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Editor

World Energy Handbook

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Part I

Introduction

World Energy Overview

Slobodan Petrovic

World energy is produced from fossil fuels: oil, natural gas, and coal, and from nuclear energy, and renewable energy sources. There are three main groups of energy sources: conventional, that is, fossil fuels, nuclear, and renewable. The renewable energy sources are hydroelectric, wind, bioenergy, solar photovoltaics, solar thermal, geothermal, and ocean energy. The contribution from fossil fuels has been continuously declining, but in 2019, oil still contributed nearly one third of all energy produced, followed by coal and natural gas. The largest contribution from other sources is energy from biomass, then all other energy sources (Table 1). The replacement of fossil fuel energy by renewable energy takes place slowly but steadily and the dominance of fossil fuel energy sources is waning year after year.

History of Energy Consumption

Going back to the beginning of the nineteenth century, the nearly only energy type used was traditional biomass, with small contribution from coal (Fig. 1). Coal was known centuries before and used in limited ways, but the significance of coal was not established until the First Industrial Revolution in the mid-eighteenth century. The consumption of coal continued to increase throughout the nineteenth century. After almost a century of dominance by the traditional biomass and coal, new sources of energy such as oil, discovered in America in 1859, natural gas, and hydropower emerged in the early twentieth century as appreciable energy sources on a global level. It should be clear that individual countries or regions might have had historically different energy mix.

In the twentieth century, coal continued its dominance, energy generated from oil and natural gas showed steady increase. In the mid-century, nuclear energy technology advanced and it became a promising new form of energy. Steady gains in the overall proportion of the global energy came from hydropower and, somewhat surprisingly, from coal. Renewable energy sources, except hydro, wind, and solar primarily, first appeared in the global energy consumption composition and showed small but steady increase throughout the second part of the twentieth and into the twenty-first century.

Energy Consumption "Mix"

In the first part of the twentieth century, at the time of writing of this handbook, the energy generation ratios between different technologies, or energy mix, reveals overwhelming dominance of fossil fuels, with a combined contribution of 80% (Fig. 2). Individual fossil fuel sources for energy generation contribute to the following ratios: oil 31%, coal 26%, and natural gas 23%. Minority contributions to global energy generation are provided by hydropower (6%), traditional biomass (6%), nuclear (4%), and renewable energy generation technologies.

The rank is shown in Table 1.

The overall energy is used as heat or electricity and the ranking is different in terms of contribution to global electricity produced (Fig. 3).

Oil, which is the dominant energy source for transportation, powering internal combustion engines, has very little (3%) impact on the production of electricity. The pie chart reveals that the largest contributor to electricity generation in the world is coal, when burned in the thermal power stations. The next largest energy sources for electricity production are natural gas – also used in thermal power stations – hydroelectric power, and nuclear power. The relative ranking of electricity generation power sources is shown in Table 2.

Fossil Fuels

In 2021, roughly 80% of the total energy consumption and 61% of the global electricity came from fossil fuels. The

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entire transportation sector around the world is dependent on fossil fuels, primarily oil burned in internal combustion engines to power vehicles, buses, trains, airplanes, and ships. Coal burned in thermal power plants provides the largest portion of the world's electricity used to power homes, businesses, industrial operations, but also in transportation for trains or to charge batteries in electrical vehicles. Natural gas is used mostly to provide heat for homes, but also for electricity generation, transportation, and manufacturing.

Table 1 Rank and contribution to global energy produced among energy generation sources

Rank	1	2	3	4	5	6
Energy source	Oil 31%	Coal 26%	Natural gas 23%	Bioenergy 6%	Hydro 6%	Nuclear 4%
Rank, contd.	7	8	9	10	11	12
Energy source	Wind 2%	Solar PV 1%	Solar thermal 0.3%	Geothermal 0.2%	Ocean energy <<1%	Gas and steam turbines <<1%

Fossil fuels were formed over hundreds of thousands of years from decomposed plants and animals. The decomposition of organic matter under heat and pressure within the Earth's crust created solid (coal), liquid (oil), and gaseous (natural gas) material with high calorific value. The process of forming fossil fuels is extremely slow – to the order of thousands of years – and any fossil fuel taken from the ground and exploited cannot be replenished because the rate of current exploitation far surpasses the rate of formation. Effectively, we are now using fossil fuel reserves created thousands even millions of years ago and eventually these fossil fuels will be depleted. There are many predictions when each of the three fossil fuel types will be depleted at the current rate of use. A historical model based on empirical

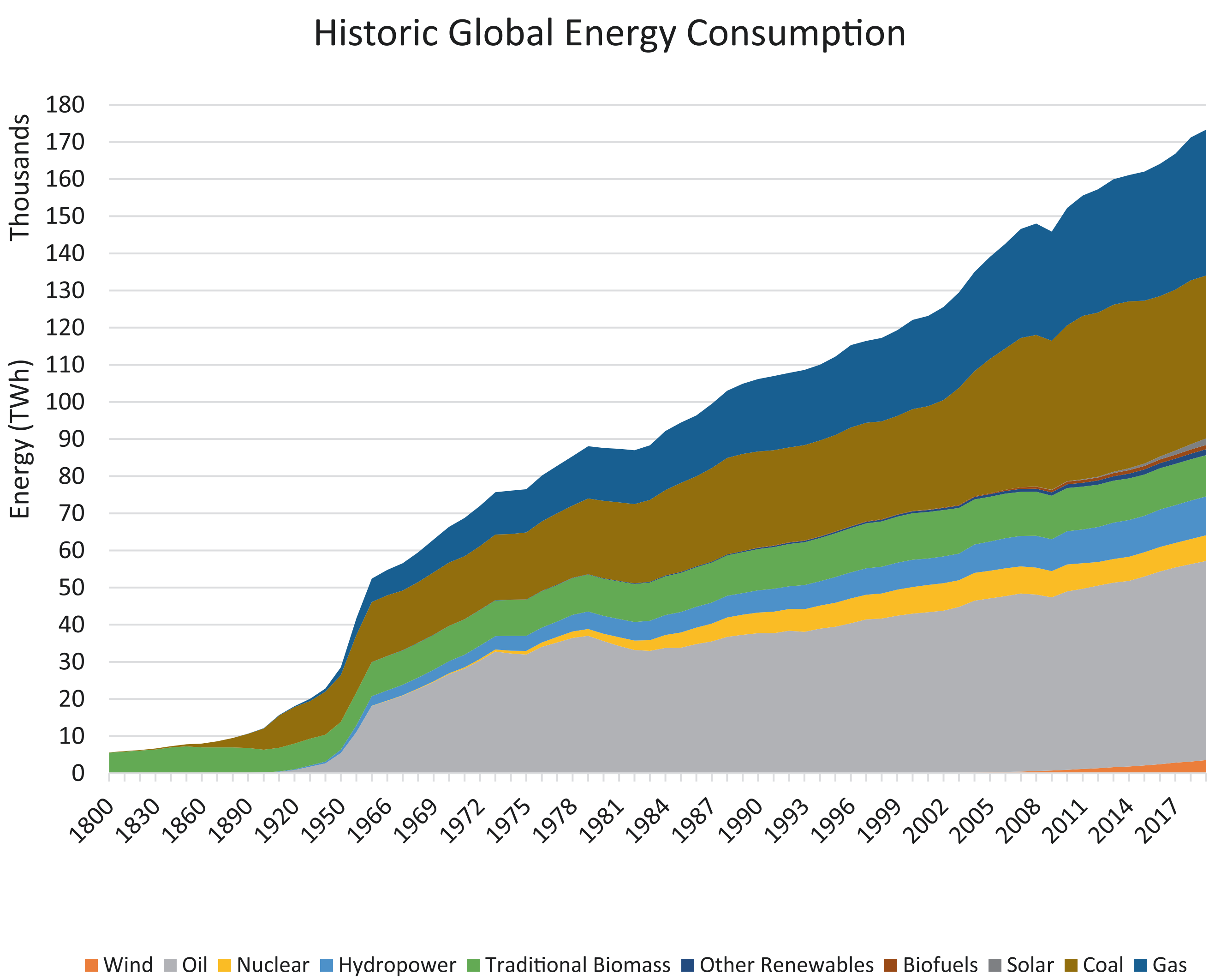

Fig. 1 Historic trend in global energy consumption distribution (1800–2021)

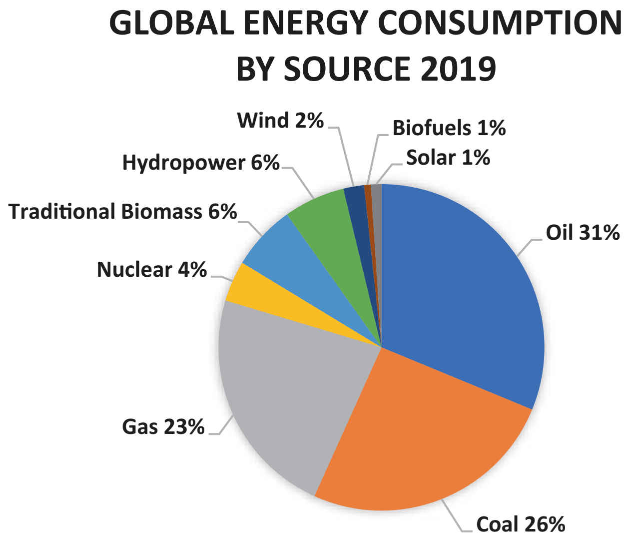

Fig. 2 Energy consumption in 2019

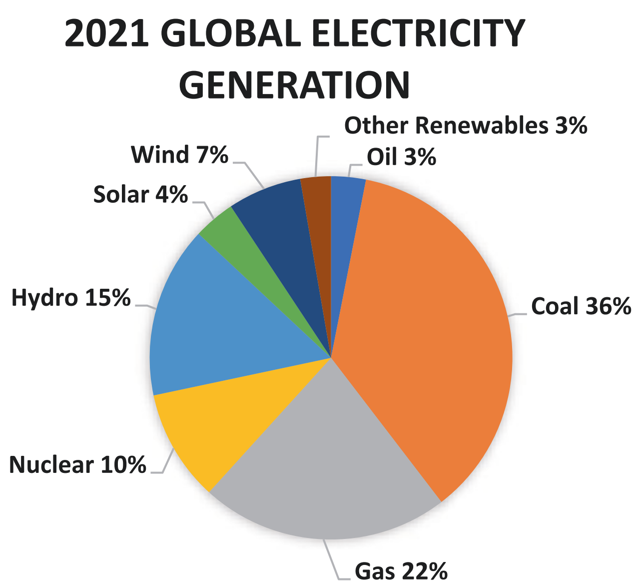

Fig. 3 Energy generation in 2021

data called Hubbert Curve claimed in 1956 that a decrease in exploitation of oil from a certain region, after a peak of used oil was reached, meant that all the reserves have already been discovered, followed by further decrease until the source is completely depleted. This suggested a far more Important conclusion that the reserves of oil, and other fossil fuels, on earth are limited, in other words, the rate of our use will lead to a rapid depletion. The actual shape of the Hubbert Curve and the timing of its peak is of course different for every region or a field from which oil is obtained, but the general principle does not change, and the amount of crude oil recovered follows a bell-shaped curve showing gradual decrease until the source is completely exhausted. As the crude oil is recovered from the waning reserves, the cost of its recovery increases until eventually, the cost of renewable energy resources such as wind, hydro, solar, and biomass becomes lower.

A convenient way to track availability of a fossil fuel is reserves-to-production ratio, R/P. This ratio effectively represents the number of years a source can continue to be exploited at a given rate of production, this, extraction. Looking at the R/P ratios reveals that oil is expected to be depleted in the next few decades, natural gas somewhat longer, while coal can remain a source of energy for at least a couple of centuries. Looking historically, crude oil reserves on earth would have been completely depleted in about two centuries, while it took several hundred thousand years for it to form.

Geopolitical Aspects of Fossil Fuels

Near-complete reliance of the world energy generation on fossil fuels and inevitable depletion in the near future (except coal) has created a long-term geopolitical instability that has led to local and global instability and numerous conflicts. It is obvious that a smart policy for any country is diversification of energy generation.

Oil

Crude oil, also defined as petroleum (meaning rock oil) fossil fuel, is a mixture of hydrocarbons that originates from the remains of marine animals and plants. During several millions of years, the organic material was buried under the layers of rock, silt, and sand and under conditions of heat and pressure. The very slow but complex processes transformed plant and animal material into petroleum used today. The oil is located in the reservoir rock and covered by an impermeable cap rock. The extraction is done by drilling through the cap rock (Fig. 4).

Crude oil contains various hydrocarbons and must be refined by separating different fractions based on boiling pints. A fractionation of one barrel, that is, 42 gallons of crude oil, typically gives 19.5 gallons of gasoline, 9.2 gallons of fuel oil, 4.1 gallons jet fuel, 2.3 gallons asphalt, 0.2 gallons kerosene, 0.5 gallons of lubricants, and 6.5 gallons of other petrochemical products.

The current global oil consumption is about 35 billion barrels per year and the reserves are estimated at roughly 1650 billion barrels, which means that at the current rate of consumption the oil will last approximately 47 years. Variations in oil production are expected in this period. First, a peak is predicted by 2035 at around 107 million barrels per day, followed by a decline to 96 million barrels per day and plateau by 2050. This trend is expected in response to a decreased demand for oil caused by an increased number of electrical vehicles (EVs).

Table 2 Rank and contribution to global electricity produced among energy generation sources

Rank	1	2	3	4	5	6
Energy source	Coal 36%	Natural gas 22%	Hydro 15%	Nuclear 10%	Wind 7%	Solar PV 4%
Rank, contd.	7	8	9	10	11	12
Energy source	Oil 3%	Bioenergy 2%	Solar thermal <<1%	Geothermal <<1%	Ocean energy <<1%	Gas and steam turbines <<1%

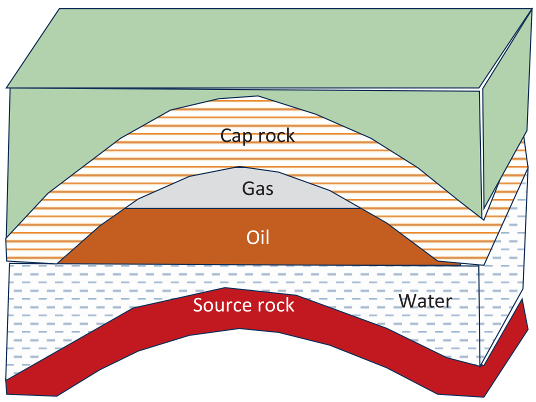

Fig. 4 Cross-section schematics of source rock and impermeable rock

Coal

The energy in coal comes from the energy stored in plants and trees that lived 200–300 million years ago, when the Earth was partly covered with swampy forests. The remains of plants decomposed and formed layer upon layer in the shallow swamp waters. Under heat and pressure from top layers and in the absence of oxygen and bacteria, this organic matter was transformed into coal. The cyclic process produced horizontal bands of peat and inorganic, sedimentary rock. Depending on the time passed, pressure, and heat, four different general categories, or "ranks." of coal were formed, lignite, sub-bituminous, bituminous, and anthracite. Anthracite is coal with the highest carbon content, between 86% and 98%, and a heat value of nearly 15,000 BTUs-per-pound. Bituminous coal has a carbon content ranging from 45% to 86% carbon and a heat value of 10,500 to 15,500 BTUs-per-pound. Sub-bituminous coal has 35–45%t carbon content and a heat value between 8300 and 13,000 BTUs-per-pound. Lignite is a geologically young coal which has the lowest carbon content, 25–35%, and a heat value ranging between 4000 and 8300 BTUs-per-pound.

The major use of coal is for the generation of electricity and about one third of world's electricity is produced from coal at 33% conversion efficiency. Coal is an impure fuel and its burning produced CO_2, SO_2, and NO_x, carcinogenic and mutagenic substances, including radioactive materials naturally occurring in coal. NO_x reacts with volatile organic compounds and ground level ozone to produce smog. Acid rain is formed when SO_2 and NO_x react with water and oxygen in the atmosphere to form acidic compounds that fall with rain. Coal ash is composed primarily of oxides of silicon, aluminum, iron, calcium, magnesium, titanium, sodium, potassium, mercury, and sulfur, plus small quantities of uranium and thorium. Typical emissions from a 500 MW coal-fired power plant in a year include 3,700,000 tonnes CO_2, 10,000 tonnes SO_2, 10,200 tonnes NO_x, 720 tonnes CO, 220 tonnes VOCs, 77 kg mercury, 102 kg arsenic, 52 kg lead.

Global production of coal is nearly 8 billion tons and the reserves-to-production ratio is estimated at over 200 years. The production is expected to hold steady at 8 billion short tons through 2040, after which a decline in coal use is predicted as it will be replaced in many applications by the renewables.

Natural Gas

Natural gas, like oil, is produced by the decomposition of marine microorganisms at the bottom of the seas. The decomposing organic matter gets covered with thicker and thicker layers of mud, silt, and sand, and an environment is created without oxygen, but with increasing pressure and heat. A slow process of decomposition takes hundreds of millions of years to produce the natural gas that we exploit today.

Natural gas production in the world is over 4 trillion cubic meters per year, while the global reserves are estimated at around 200 trillion. This suggests that the reserves-to-production ratio is roughly 50, which means that at the current level of production, global natural gas reserves will last approximately for another 50 years before being depleted.

Nuclear Energy

Electricity is produced in nuclear power plants based on the fission reaction of enriched uranium-235, in the form of UO_2 pellets enclosed in zirconium or stainless steel tubes. The reactor is started by slow-moving neutrons that cause fission of heavy nuclei into two mid-size nuclei with a release of energy. Uranium 235 can split in two different ways: one comprising tellurium and zirconium, and the other one barium and krypton. More neutrons are produced in both reactions. To control and stop the chain reaction, rods of cadmium or boron are inserted into the reactor to absorb neutrons. Enormous thermal energy created in the reaction is carried away by a cooling liquid that circulates through the reactor and creates steam to drive a turbine, which is connected to an electrical generator. A large source of cooling water is needed, such as a river or a lake. For protection from radiation, the reactor is surrounded by a reinforced concrete shell.

Nuclear power provides 10% of the global electricity generation and has the capacity of 400 GW worldwide. It is expected that the capacity would increase to over 500 GW by 2030, while some high estimates predict a rise to nearly 800 GW 2050. The conditions for such rise include implementation of novel technologies. Nuclear power plants are typically over 30 years old, while the service for some has been extended to 60 years, and to maintain the current role in the energy mix, a significant number of new power plants are necessary.

Renewable Energy Generation

Renewable energy, or sometimes called alternative energy, can be extracted for indefinite periods; it is freely available in nature and does not harm the environment. The types of renewable energy include solar, wind, hydro, biomass and biofuels, wave and tidal energy, and geothermal. The carbon emission from utilizing renewable energy is minimal compared with energy conversion from fossil fuels.

(For a more detailed description, consult *Renewable Energy Crash Course: A Concise Introduction* by Eklas Hossain and Slobodan Petrovic, Springer, 2022).

Renewable energy sources (RESs) are often called sustainable energy sources. The sustainability definition given in the Brundtland report from 1987 gives a broader meaning and calls sustainable energy as the energy that cannot be depletable on a human timescale, that does not lead to emission of greenhouse gases or other pollutants, and that does not contribute to social injustice or geopolitical imbalance.

Solar energy is the result of the nuclear fusion reactions inside the sun. The electromagnetic spectrum of solar radiation that reaches the Earth is based on the temperatures on the surface of the Sun of roughly 6000 °C. Solar energy is captured in photovoltaic (PV) devices, usually based on silicon, to produce electricity.

Solar PVs have reached a 1 TW of generation capacity in 2022. They contribute 1% to global energy and 4% to electricity production in the world. It is expected that the solar photovoltaic generation will experience an exponential growth to reach only recently unimaginable 8.5 TW by 2050.

Solar thermal technologies are converting solar energy into thermal energy and applying it for water heating, space heating, space cooling, district heating, and for industrial process heating. It is estimated that solar thermal can provide 60–90% of the hot water demand and 25–40% of the heating demand for the world. In 2019, solar thermal capacity for generating heat was close to 500 GW_{th} (thermal capacity), which generated nearly 400 TWh of energy.

Solar energy can also be used to generate electricity. In solar thermal power generation, solar radiation is first converted to heat, which then creates steam used in reactors to produce electricity. The global solar thermal power capacity was over 6 GW_{el} (electrical capacity) in 2020, which produced roughly 16 TWh of electricity. It is expected that the solar thermal power global capacity will surpass 14 GW_{el} by 2030.

Wind energy originates from the energy of the sun and differences in heating rates of the air masses. It is one of the most important renewable energy technologies. The wind turbines can be installed on the land and offshore. A special case of wind energy utilization is harnessing the power of ocean waves.

In 2022, estimated global wind capacity is over 800 GW and wind is providing 7% of the world's electricity. Wind capacity is expected to grow to 1 TW in 2022, 2 TW in 2029, and 5.9 TW in 2050. This 5.9 TW will include 1.7 TW of offshore wind.

Hydropower has the largest renewable energy technology capacity, providing around 15% of the world electricity. The origins of hydropower are in so-called water cycle, which is also getting its energy from the solar heating. On a small scale, hydropower satisfies the sustainability criteria with no adverse environmental impact. However, on a large-scale, massive dam installations result in major interruptions of Nature and the environment and can further lead to methane generation through anaerobic decay of vegetation.

In 2020, global installed hydropower capacity was 1.3 TW, which generated 4370 TWh of electricity. By 2030, hydro power is expected to surpass 1.5 TW capacity.

Bioenergy is energy derived from materials such as wool, found in the surface layer called the biosphere. The biosphere is essential for maintaining the Earth's atmosphere and is continuously replenished by the energy of the sun. Wood and other bioenergy feedstock, for example, crops, have potential to be sustainable without net increase in CO_2 emission if the rate of reforestation exceeds the rate of use. These biological materials or biomass can be burned directly to produce heat or power. They can also be converted through thermochemical (combustion, gasification, and pyrolysis) and biochemical (digestion and fermentation) routes to heat, electricity, and fuels used for transportation. Bioenergy is currently a significant energy source only in developing countries.

Bioenergy provides about 6% of the total energy produced on earth and about 25% of the world's electricity.

Ocean energy can be harnessed in three ways, as wave energy, as tidal energy, and as ocean thermal energy based on the water temperature differences. Wave energy is a concentrated form of solar energy because the winds that produce waves are caused by the atmospheric pressure differences as a result of solar heating. Ocean wave power depends on the height of a wave and the period between two successive waves. It is far more concentrated than solar or wind power as it can reach up to 70 kW per m of wave. Ocean energy depends, in addition, on the length of the coastal line where the waves occur. The global wave power resource is estimated at 2 TW, with electricity generation potential of about 2000 TWh annually.

The tidal energy is created by the gravitational pull of the moon on the world's oceans. The technology involves building a semipermeable dam or a tidal barrage across an estuary where the tide can be up to 15 m, compared with up to 3 m on a shore. Turbines used in the water passages are used to produce electricity from the rise and fall of water in the estuaries. The total power of tides across the world is 3 TW, from which up to 400 GW is exploited to produce electricity.

Ocean Thermal Energy Conversion (OTEC) produces energy from the temperature difference between surface water of the oceans in tropical and sub-tropical areas; and water at a depth of approximately 1000 m, which comes from the polar regions. A temperature difference of 20 °C is necessary for useful conversion. To convert this thermal gradient into electrical energy, the warm water can be used to heat and vaporize a liquid (known as a working fluid). This expanding vapor runs through a turbine generator and is then condensed back into a liquid by cold water brought up from the depths. The cycle is repeated.

The origin of geothermal energy is in the Earth's internal heat, which comes from conversion of kinetic and gravitational energy when the Earth was formed 5 billion years ago and from a decay of radioactive isotopes with long half-lives such as thorium 232, uranium 238, and potassium 40. These isotope materials are contained in the upper crystal rock. Heat is conducted through the main body of the Earth and exits through the surface mainly at the boundaries where the tectonic plates are in relative extension and compression. Geothermal resources include mainly hot water, but also rock several miles below the Earth's surface and can be accessed through drilling. Mile-or-more-deep wells can be drilled into underground reservoirs to tap steam and very hot water that can be brought to the surface for use in a variety of applications. The extracted hot water can be used for heating or steam can be used for electricity generation. Geothermal energy is renewable on a larger scale, but locally it can run out.

Geothermal global energy generation capacity is nearly 16 GW and it provides about 0.2% of the world's energy.

Energy Storage

One of the essential principles of energy generation and use is that the two should ideally match, which means that energy is available at the time of demand. The present energy systems do not completely meet this requirement and the effectiveness of the future energy systems depends critically on the transformation from random generation and unpredictable use to availability on demand. This can only be accomplished when energy storage becomes a central part of the overall system between energy generation and use.

Renewable energy sources (RESs) are intermittent and have a fluctuating nature. For example, the wind is not always blowing, and it changes speed, the solar photovoltaics generate electricity only during the day and when there are no clouds, and wave energy depends on the wind. Hydroelectric power is more predictable, but it still depends on the seasonal variations. Tidal power is available only at a certain time of the day. Geothermal power is reliable and predictable locally, but it is not available everywhere on earth. Biomass is similarly available only locally.

Energy production in large power plants is also not ideally matched with use. A nuclear of a coal-fired power plant requires long times to start and stop, while the demand fluctuates during those times. The only part of the overall energy system where there is a match involves energy storage. For example, in the transportation sector, fossil fuel oil is partially processed and stored in the form ready-for-use. The solution to provide a match between energy generation and consumption that the energy producers and distributors have been using is to store the energy in the electrical grid, where it is moved between the users depending on the energy demand. But, the energy grids' main purpose is to distribute energy, not to store it, and because of that, fluctuations and losses can occur and even large complete failures of the most sophisticated electrical grids. Electrical grids are not built for energy storage, and moving energy around until a user at some location needs it is certainly not the answer and does not provide energy security.

This leads to a concept of energy storage, the only sustainable and reliable way to utilize both renewable energy sources, but also conventional energy sources. The energy storage solutions include mechanical systems such as compressed air (CAES), flywheels, and pumped hydro; electrical systems such as supercapacitors and superconducting magnetic energy storage (SMES), electrochemical energy storage with electrolytic capacitors, batteries, and fuel cells; and thermal systems. Energy storage can be bulk, including pumped storage and compressed air; and distributed energy storage, including batteries, flywheels, and other.

Energy storage solutions should be matched with applications as some of them can provide large amounts of energy while the others store less energy, but can deliver it at a fast rate, which is described as high power. Pumped hydro and compressed air energy storage can store and subsequently deliver large energy, but cannot provide high power, while supercapacitors have high-power capabilities, but can store limited amounts of energy. Batteries and flywheels are available in types and sizes that cover both high energy and high-power ranges.

Global energy storage capacity is estimated to reach 12 TWh by 2026. In the energy storage mix, the dominant technology based on the overall contribution is pumped hydro. In 2012, pumped hydro contributed 98% of the overall energy storage capacity. However, the mix is changing largely due to rising popularity of different types of batteries and supercapacitors, and it is estimated that pumped hydro will contribute to about 42% of the global energy storage capacity in 2022. The pumped hydro is expected to grow in capacity from 127 GW_{el} in 2012 to 200 GW_{el} in 2026 and over 350 GW_{el} is expected by 2030. But the largest growth is the energy storage for the utility-scale batteries, where the new additions rose to 5 GWh in 2020 for a total of around 17 GW.

While the total number of installed energy storage systems is difficult to accurately track, the bulk systems have reached over 1000 systems worldwide. The mix of different technologies in terms of number of systems shows the dominance of battery technologies, primarily newer lithium–ion batteries as well as supercapacitors.

Energy Resiliency

Energy resiliency is a broad term that has many different definitions, but it can be summarized as a system's ability to anticipate, avoid, adapt, and respond to and recover from strong unexpected events. The International Energy Agency (IEA) defines energy system resilience as the capacity of the energy system to cope with hazardous events, to respond in ways that maintain essential functionality, and to learn and recover from said events. This definition alone conveys the complexity of this subject of resiliency.

A related and perhaps encompassed concept is that of energy security. This is mostly thought of as access to fuel or other energy sources. In the broad international economic landscape, fuel prices can be either stable or volatile. The depletion of fossil fuels is inevitable, but energy systems can adapt in the years leading up to this event by improving resiliency efforts. Energy security also refers to cybersecurity as more sensing and communication becomes remote and therefore more susceptible to cyber-attacks. A system's resiliency must include measures to prevent and recover from such cyber-attacks.

Energy security depends on the energy generation mix and although renewable energy generation has been added to the global power mix in recent years, the geographical regions that most need to increase their energy production have in fact low growth rates. This means that developing countries are exposed to pollution and climate change-related problems caused by the global situation with energy generation, without the opportunity to improve their economic growth. At the same time, developed countries that have created the problem in the first place are creating solutions that would benefit them. This is a trend that cannot continue. A prolonged, globally collaborative effort is necessary to properly address climate change and improve energy system resiliency across all parts of the world.

There are many types of events that can pose a threat to our energy systems. Some of them are natural disasters such as hurricanes, earthquakes, floods, volcanic eruptions, wildfires, and tornadoes. Many of these will occur more frequently as a direct result of the climate change so we need to prepare our infrastructure to withstand or quickly recover from such events. Other threats are more directly posed by human activities, including war, terrorist attacks, and labor strikes. A resilient system will be built with these threats in mind, it will be designed in anticipation of each threat, and with the capability to withstand or at least recover quickly from such occurrences. A different point of view sees the impracticality of building a system to withstand disaster events because the number and types of disrupting events is likely to evolve and change. It makes more sense instead to build systems with effective mitigation techniques to quickly restore functionality in case of any type of disturbance.

A common historical system response to disruptive events has been in so-called cascading failures, which happen when an event occurs that disrupts the flow of power in one location and the resulting displacement of power transmission can cause a number of failures in connected parts of the system. Events like these can take a long time to recover from since each failure needs to be rectified in order to restore complete functionality. However, cascading failures can be avoided by re-evaluating methods for generating, storing, and transporting energy. The most logical solution regarding resiliency is decentralizing power generation. At the moment, most individual country energy systems are centralized, meaning that the majority of energy is created in one place in fossil fuel, nuclear, or hydroelectric power plants and then transported using power lines to areas where the users are. With the penetration of more renewable energy into the energy generation mix, there is also an opportunity to utilize the nature of renewable energy sources and further localize (i.e., decentralize) energy production from solar, wind, hydro, ocean, geothermal, and bioenergy; and break up large energy infrastructure into smaller units, increasing the overall system resiliency. Each small unit or small energy system would include generation, storage, and transmission with the ability to operate independently or in tandem with neighboring systems. This decentralized power system is inherently more resilient than the current systems. In case of a disaster or local threat, a small system can quickly disconnect from other parts of the grid, preventing cascading failures, and after the disaster, it will be able recover faster by utilizing local resources. There are known examples of such systems that were successfully isolated during floods and storms and provided power to customers whose connection to the main grid was disrupted. More such systems have been constructed that are isolated from the grids and powered completely by renewables.

A critical aspect of an energy system resiliency is the need to have effective and resilient interaction among the system components, in addition to each component having its individual resiliency. This includes equipment for sensing, communication, and actuating responses. A proper answer to energy resiliency and system improvements starts with the complete understanding of the energy systems in individual countries and regions. This book is an attempt to build a database of energy systems, provide comparisons among countries and regions; and create the foundation for future growth and improvement.

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Energy Research Methodology

Slobodan Petrovic and Dawn Love-Wincensten

Many of the articles in this publication were researched and written by students getting their bachelor's or master's degrees in Renewable Energy Engineering at Oregon Institute of Technology. The in-depth research entailed in these projects was coordinated through the college library following the methodology detailed in this section. It is important to note that this research was started while the majority of the world was on lockdown from the COVID-19 pandemic. Researchers were working from home with little to no access to print research materials. Most libraries nowadays support research through IP addresses and IP proxy address access to tools such as library subscribed databases. Additional tools such as video conferencing and shared cloud stored documents were used to share information and communicate.

Using the Society of College, National, and University Libraries (SCONUL) Seven Pillars of Information Literacy Core Model,[1] a plan was built, suitable for any country listed in this resource no matter how varied the information available might be from country to country.

Identify

The projects were laid out in the beginning. Each researcher would study the energy use, consumption, production, and needs of —two to four developing countries. They worked together to identify the countries each person would take on.

[1] SCONUL Working Group on Higher Education. 2011. The SCONUL Seven Pillars of Information Literacy Core Model for Higher Education https://www.sconul.ac.uk/sites/default/files/documents/coremodel.pdf

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Scope

Scope was an aspect that perplexed researchers throughout the project. This final outcome varied greatly early on as researchers sought to determine what might be available and useful in their individual assignments. While researchers needed to provide a full picture of a country's energy resources, in many cases, the information was sparse and difficult to find. Researchers found they needed to be determined and resourceful in their information gathering in order to find useful and plentiful information.

Plan

Each researcher participating in this project needed to plan to find a collection of different resource types. The varied types strengthen the value of the information presented here. These resources are some of what was useful:

News

Current events and primary sources in the form of news sites provide up-to-date information. These resources offer a lay person perspective on the topics and events going on in a particular country of study.

Legal Information

Court cases, legislative reports, and decrees and legal research, give the researcher an administrative perspective to what is possible in a country. These are also primary sources. In the case of this project, the researchers had access to international case studies through a library resource.

S. Petrovic (ed.), *World Energy Handbook*, https://doi.org/10.1007/978-3-031-31625-8_2

Government Documents

Government documents are documents published by a government agency. In this case, researchers were encouraged to look at information from the country being studied, its neighbors, and other reports that may be available such as United Nations' (UN) documents. These documents often provided a different perspective.

Utility Company Websites

In some countries, the utility companies are run by the government. However, in those countries where private industry runs the utilities, there is often a website that talks about feasibility of resource types, and studies performed by the utility company. This is useful information, but it is important to note the obvious bias.

Research and Journal Articles

This is not a place for traditional research. However, research databases and journal articles provided background and tertiary information to support the more current information. These resources also provided a less biased perspective than some of the other sources discussed here.

Library Search

The Library provided a federated search of different types of resources, including books, research articles, news sources, and some government information. This search provided a single place for researchers to start their search and get an understanding of the breadth of information that was available. This was a primary tool in helping to plan how gathering research was to be completed.

Gather

Knowing the types of resources needed to fulfill the plan, a web-based research guide was developed to be a starting point for the researchers. This web-based page was freely accessible without researchers needing to log on to the library first. However, the various resources being accessed did require user authentication to access. The page was divided by the depth of information the resource would have. Encyclopedic type resources were first for general overview such as the Europa World Handbook or the CIA World Factbook. Following this were primary documents and news sources such as legal research and news publications. The last section focused on places to get in-depth research articles from academic journals. As noted previously, there was very little cause for researchers to use traditionally published books. This site has since been disabled due to the research guides for the university moving to a new server and format.

Each resource on the site was accompanied by a video demonstrating an example search relevant to the research project itself. While these videos were useful, they did make the page slow to load – a possible barrier for researchers working from locations without strong Internet connections or those who were sharing connections with other housemates also locked down or working from the location.

A college librarian was invited to the class to talk about available resources and how to use these. These sessions were held once per term as a reminder to the researchers. Additionally the librarian worked one-on-one with a number of researchers over the course of the research and writing process. These meetings were available by request of the researchers.

Evaluation

While it is always important to evaluate information sources, in this project, there was such a variety of resources used that evaluation and understanding of the sources' potential bias was essential. In order to do this, the CARP test[2] was used. This test is sometimes referred to as the CRAP or CRAAP test as well, and is used in many information-gathering circumstances.

Currency

This research was being done to write a book that would be published in the future. While some background research was needed, the majority of sources should be up-to-date and within the most recent couple of years.

Authority

Authority is a big issue when searching randomly on the web. While this project had a curated starting page, many researchers fall into their comfort zone of searching through a favored search engine. Authority also leads to understanding bias. For example, a source written by the country being researched will have a different bias than a source written from a neighboring country. Authority also comes to attention when looking at

[2] No Date. Evaluating Sources Using the CARP Test https://www.tbcs.org/uploaded/Library/Andrea_Lairson_Library/CARP_Test.pdf

research articles. While, in general, these are written by knowledgeable people, and have gone through deeper vetting than the average website, there are still cases where an article's author may not be the authority on a topic, and instead may have just presented information in a novel way.

Relevance and Reliability

While looking at material for researchers, a collection of out-of-print, digitized country studies were found. This collection provided a historical perspective on the places being researched, but they were comically out of date, and did not cover energy needs or use in any meaningful way. Thus, these resources were deemed irrelevant despite their potential as historical sources. In this way, researchers were able to investigate relevance.

Reliability came into view more when gathering information from individual government sites. These sites were not all equal in type or amount of information available. Some countries provided more, and some countries provided little to no information. Researchers were not able to depend on these. Similarly, some energy utility company sites were not deemed reliable.

Purpose and Point of View

The purpose of this resource is to give an overview on developing country energy resources. The purpose of a government website is to tell researchers about that government from the point of view of that government. The purpose of a travel site is to entice the researcher to travel. The purpose of a research article is to discuss and demonstrate some novel idea. Understanding why the information a researcher is finding exists in the world, helps them know how it may be useful to their own purpose.

Point of view is probably the most important part of evaluating a resource. Understanding the point of view a source is written from will tell the researcher of a potential bias. For example, The CIA World Factbook is a site with country overviews put together, but the United States Central Intelligency Agency. The resource is a good overview with facts on population, politics, brief notes on culture, language, etc. It has a very different point of view than a site published by a country's own government. While the factual information and figures given may be the same, understanding the different purpose and point of view helps researchers in determining effectiveness of the information found.

Manage

Research management was an area of emphasis in these research relationships. With the variety of information types being gathered, and the need for detailed evaluation and understanding on the resources used, it was important to organize and manage information consistently. In addition, the varied source types needed to be treated by type when being cited. This process involved reviewing each resource and determining the best way to incorporate and cite the information into the final product. In the cases of very few resources found, an effort was made to address the lack of available information in the text. The previously mentioned guide also addressed potential copyright hurdles with the types of sources covered.

Present

This resource is the presentation of the work these researchers have done. Before it came to this point though, some researchers gave visual presentation via posters as part of the annual student project symposium at the university. During 2020 and 2021, these posters were displayed digitally and are still available via the college digital repository: https://cdm17267.contentdm.oclc.org/digital/collection/symposium2021/search/searchterm/ree%20country%20studies/field/subjec/mode/exact/conn/and

By presenting the information in a variety of formats, researchers enhance the final product. The multiple modalities reach a wider audience and can reference one another for more thorough coverage.

Financing Energy Projects

Slobodan Petrovic and Sasa Z. Linic

Acronyms

ESG *Environmental, Social, and Governance*

DER *Distributed Energy Resources*. A variety of small, modular electric generation units located near the end user; used to improve the operation of the electricity network by complementing central power.

Smart growth A development strategy emphasizing mixed land uses with convenient transportation choices in existing communities, thereby alleviating sprawl and preserving open spaces.

RE *Renewable energy*

Stakeholder capitalism Business practices where companies work equally for all community members toward achieving more than just profits and stock prices.

Introduction

Energy is in high demand all over the world and is a critical element in the global economic system. While the use of fossil fuels to generate energy had dominated the overall economic developments in the twentieth century, a recent drive toward increased independency from fossil fuels creates new economic and social circumstances; and access to capital has become the foundation for securing economic and social changes. The success of economic changes on a global level and of individual energy systems depends on business effectiveness and the confidence of the investment community for developing new energy sources.

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In developing countries, the limited access to affordable energy services is the critical factor in slow economic growth and continuing poverty. Access to renewable and inexpensive energy sources is vital to overcoming the poverty, promoting economic growth, creating employment opportunities, providing basic social services, such as health, and stimulating sustainable human development. Energy financing plays an important role in enabling technologies for energy generation and storage.

Historical Overview

While the modern history of substantial use of energy is relatively short, the origins go back to ancient times and there are indications that throughout the Roman times, first energy financing resources were established in form of concessions (Rhodes and Osborne 2004) (*Contract of Eretria* – third century BC). In the medieval epoch, the financial mechanisms focused mainly on local priorities such as water supplies and roads.

In the eighteenth century, industrialization and growing innovation stimulated creation of many forms of modern funding, including a wide range of subsidy mechanisms. In the late nineteenth century and the beginning of the twentieth century, water supplies and railways were the most lucrative and money-making investments, securing long-run profitability and return on investment for shareholders. In industrialized countries, natural resources such as coal, wood, oil, and natural gas which dominated the energy market, were financed, distributed, and controlled through private equity.

At that time, at the turn of nineteenth to twentieth centuries, electricity first experienced an unprecedented growth after the construction of the first hydroelectric power plant on Niagara Falls, on the border of the United States and Canada. The conversion of mechanical energy into electricity in the hydroelectric power plant used history-changing

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interventions by the great Nicola Tesla and was financed by George Westinghouse. By the early twentieth century, as electricity became an unavoidable necessity, allocation of substantial capital followed, and very soon, public interest in energy increased.

Then came the Great Depression in the United States and brought insolvency of private firms, along with soaring energy prices, triggering governmental interventionism, particularly in the ownership of utilities. This was followed by the New Deal enacted by President Franklin D. Roosevelt, the regional and rural policies were introduced that made access to electricity a community goal, justifying public investment and ownership. In the early part of the twentieth century, many other countries, such as the Soviet Union, nationalized their electricity sectors.

Following decades of nationalized energy control, the shift in energy financing occurred in the early-to-late 1970s by returning electricity industry back to the private sector. This was followed by uncertainty over the future energy structure, and recovery of investment costs in electricity infrastructures caused considerable instability in financing electricity infrastructure. In developed countries, investors' uneasiness, and lack of public funds caused increased public debt to GDP ratios. Furthermore, the geopolitical circumstances suppressed the ability of the public sector to deliver efficient investment spending and optimal allocation of resources, which have led to re-examination of the role of state in infrastructure investment. This worldwide shift forced many countries to seek solutions in privatization and liberalization, opening the era of transnational private equity energy sector investments.

Defining Energy Infrastructure

Energy infrastructure sector can be described as the dominant part of economy encompassing supporting networks and services that are vital for the proper functioning of global economies. While the nature of energy-related businesses varies, there are several common factors linking them together to create a broad category defined as infrastructure.

The energy infrastructure refers to existing facilities such as power plants, energy storage, and distribution, including electrical power grids; and as such comprised heterogeneous assets. The infrastructure by definition is a foundation for energy generation and delivery and is constantly evolving, although sometimes at a slow pace. In recent years, exploring and inventing new sources of energy generation and storage has sparked another shift in the infrastructure and investment tools.

The energy infrastructure is also an arrangement of generation, transmission, and distribution of electricity; physical networks of oil and natural gas pipelines; oil refineries; and other transportation elements such as marine and rail transportation (Park and Clinton 2004). As per its definition, it signals consequently that energy infrastructure is made up of highly heterogeneous assets. From an investment viewpoint, energy infrastructure is an established asset-based business providing essential services that are generally costly and difficult to replace. The energy infrastructure, along with its economic and financial characteristics, is part of the assets that typically generate relatively stable cash flows and incorporate many product types, depending on the national economies and geographical location. These assets include:

- Public service – Assets provide essential services that support the functioning of society and the economy (Weber et al. 2016).
- Inelastic demand – Assets are typically protected from macroeconomic cycles, even when prices increase (Inderst 2010).
- High barriers to entry – Assets typically require initial diverse funds which act as a strong barrier to entry and discourage potential competitors from entering the market (Porter 1998). Historically, there has been little or no competition in power market delivery, while the energy infrastructure assets profit from a natural monopolistic or "quasi-monopolistic" market positioning.
- *Regulation* – Because quasi-monopolistic advantage provides essential services, energy infrastructure assets are subject to regulations that prevent monopoly powers from charging users excessive prices.
- *Inflation protection* – Energy assets may provide protection against inflation because their revenues are often linked with inflation-adjustment mechanisms (Weber et al. 2016).
- *Long duration* – Based on the relations with socioeconomic factors such as population growth and demographic trends, absolute economic expansion energy-related assets tend to be long lasting.
- *Predictable cash flow* – Energy infrastructures are long-range assets with high development costs, but reasonably low operating costs. Combined with the inelastic demand pattern and pricing power, the result is a very consistent, long-term cash flow.

Based on the uncertainty of gains that can be obtained through technology advancement, the energy infrastructure is relatively immature compared, for example, with real estate, but nonetheless there are models of its risk-return profile as an asset class and the equivalent attractiveness for investors. As a result, energy infrastructure continues to be an expanding area of global interest, both in the developed world and in emerging markets. However, the key factor for an investor is in the end not the specific subsector, but rather the asset's risk-return profile, which largely depends on the distinctive characteristics of the investment opportunity in question.

Energy Financing

Energy capacity on a global or local level reflects relationship between finance and energy; and indicates total commitments undertaken by various industries, communities, and other stakeholders. To further support energy projects and encourage growth, financing mechanisms are transparent, standardized, and traceable; and based on analysis of market trends.

As described earlier in the text, the model of ownership of energy assets changed several times in the last hundred years. In the United States and largely around the world, the financing model started with private equity in the nineteenth century, then through state interventionism, ownership, and involvement of public funds during the Great Depression, and finally back to private equity after the energy crises in the late 1970s. Because the strategic nature of the energy infrastructure assets and projects have always been controlled by the governments.

Funding for energy infrastructure is constantly evolving. Because capacity and diversity growth will continue into the foreseeable future, mechanisms and instruments in financing have been innovative and adaptive. Efficiency in financing demands a better understanding of the correlation between various types of financial programs, their accessibility, and limitations, as well as preparedness to invest. Oil and liquid natural gas (LNG) were largely financed by the companies and by consumers, while a small portion comes in the form of bank loans. In addition, such concept also depends on having a healthy system of secondary financial sources and intermediaries. Diverse investment vehicles play important roles in facilitating financial dynamics, and encouraging investment, based on profit expectations and risk profiles. There are often significant funding challenges which can potentially impede development. For example, the financial crisis from 2008 and resulting regulations limited banks on their lending capabilities. Such regulatory frameworks directly and indirectly effect earnings and ability to secure new developments, or financing by raising funds via equity, debt, or a mixture of both.

In the recent years, a shift a has been taking place from conventional fossil-fuels toward environment-friendly renewable energy solutions. It is broadly agreed that availability and allocation of capital for investment in low-carbon energy represents a key barrier for climate change mitigation despite greater awareness by policymakers and investors in global environmental issues (Polzin 2017; Polzin et al. 2019).

Sustainable Energy for All (SEforALL), an international organization that works in partnership with the United Nations, summarized Sustainable Development Goal 7 (SDG7) and pointed out that for global energy access by 2030, it is necessary to secure $45 B annually (Sustainable Energy for All 2020). Others have projected that up to 10 times larger investment may be needed to meet sustainability goals outlined in the Paris accord (McCollum et al. 2018).

Over the past three decades, energy infrastructure ventures have been increasing in size and popularity, but this investment area remains relatively underrepresented. Bloomberg New Energy Finance (BNEF) (Bloomberg NEF 2020) highlights that total funding for renewable energy in the last decade has been growing at a remarkable rate. As the ESG investors, that is, those who include environmental and social factors into their selection of investments, move primarily to big industries, there is a pressure on fund managers to focus on energy and sustainable development. Those investors are now requiring a positive impact on society and environment, in addition to profitability. The shifts in investment directions have in return created market volatility for energy-related companies and changes in industry models for profitability and cost of capital.

Furthermore, the changes reflect on the cash flow to keep companies operating, commitments to customers, and overall funding capacity. According to Bloomberg (NEF 2020), higher risks are expected in the foreseeable future. Global uncertainty has made an impact on the borrowing costs, while energy producers and distributors face credit risks from non-payment by customers under financial stress. Unpredictability in power demand caused primarily by social and political disruptions, uncertainties over future pricing in the energy market, and wider exposure to energy distribution has created alternative financial instruments, complementary to donations and subsidies, as part of an effort toward a smarter "funding mix." These financial instruments, in the form of loans, equities, quasi-equities, and guarantees, increase the impact of funding, and also promote more responsible, result-oriented use of funds by companies and governments. However, the potential of these instruments has still not been demonstrable because ESG investors, unlike market speculators, consider long-term benefits that become fully realized in time.

Financial Mechanisms and Instruments

Rapid technology advancements and overall uncertainty based on external factors continue to change the rules of financing on a global level. At the same time, innovative financing creates ability to transfer funds all around the globe. Rapidly changing business landscapes make new challenges for companies, whether they are giant multinationals or small firms, profit- or not-for-profit-oriented. Despite diversity of partnerships and alliances, the two fundamental factors remain financial mechanisms and financial instruments.

Financial mechanisms include policy tools explaining how necessary funding is received to hold a business, organization, or a program operational.

Financial instruments describe monetary contracts between parties, for example, a financial asset of one entity and a financial liability or equity instrument of another entity. Based on asset-class, if an instrument is debt-based, it is called a loan, deposit or certificate of deposit, bonds, T-bills, and commercial papers. On the other hand, equity-based instruments are stocks.

Grants and Loans

Challenging projects in developing or least developed countries (LDCs) require various financial instruments that address financial reality of a host country and availability of funds. Multilateral institutions (mostly under the umbrella of the United Nations) developed mechanisms to support a shift to low-emission and climate-resilient programs. Funds (grants and loans) are available to developing countries, least developed countries, and countries with economies in transition to meet the objectives of the international environmental conventions and agreements. All national programs must fulfill the following criteria to qualify:

- Ratification of the international conventions under which funds operate and/or eligibility of the recipient for the United Nations development program (UNDP) assistance.
- Demonstration by the recipient country that the program is approved and conducted on a national level and enjoys the priority status.
- Priority assignment of the fund aimed at addressing environmental problem.
- Open involvement of public in project design and implementation.

The key factors affecting the fund selection include financing mechanism (equity, grant, or loan), project size, country eligibility; sector (e.g., agriculture, energy, energy efficiency, renewable energy, forestry, transport, water, waste management), and field (adaptation, mitigation, capacity building). A program must also be defined in partnership between Ministry of Finance, Ministry of Energy, and approved by the Cabinet of Prime Minister/Cabinet of the President.

Climate Bonds

Climate bonds are fixed-income financial instruments related to climate change projects. They offer investors a way to accomplish financial gains while at the same time making a positive impact on the environment. Climate bond market contributes to a broader shift toward socially conscious investing by increasing options available to investors and enabling a country to raise capital on the international market in a transparent, low-risk process. The access to funds is enabled in cooperation with qualified international accredited bodies. The two types of climate bonds are "green bonds" and "certified climate bonds."

Co-investment – Any form of minority (up to 50%) equity financing alongside main investor. This form brings diversification opportunities for smaller investors, while at the same time dilutes risks for large investors. It brings together matching aptitudes of funds and governments, and is seen as a way to increase efficiency, its likelihood to deliver a high performance.

Blended finance is the mixture of development finance and philanthropic driven funds for the mobilization of additional finance toward sustainable development in developing countries. In practice is a mixture of grants with (a) loans, or (b) guarantees, or (c) equity, including "convertible loans to grants," "convertible grants to loans," or "partially repayable loans."

The main benefits of blended finance for developing or least developed countries include greater flexibility of the instrument, sustainability of the instrument (due to the revolving effect), leveraging of other public and private funding opportunities.

Blending instruments permit flexibility, as the amount of funds can be adapted to the needs of the project and, consequently, the execution of the project accelerated. The transfer of knowledge is also recognized, especially when the instrument includes a form of technical assistance (in most cases offered by iNGO or multilateral international organization and their bodies).

Royalty-based financing is a model related to performance where the investor lends money to investees against its future revenue streams, to be returned in previously agreed percentages of gross-revenue. It is a more pragmatic way of funding projects, as it focuses on their success and does not jeopardize their development in the initial phase.

Conclusion

Contemporary approach to energy finance is a multidisciplinary exercise incorporating environmental challenges and harmonizing the interest of policymakers and investors.

Designing stable energy systems depends on effective usage of financial instruments. This is of the greatest importance for developing and least developed countries, which, under the normal circumstances, can neither borrow funds on the international capital markets, nor attract national or international investors, despite having the highest energy potential.

To improve the chances of funding energy projects for those countries, it is critical to understand the nature of forces keeping those countries on a low pace of overall industrial development, which in turn is closely tied to large energy projects. Enabling easier access for these countries to available capital and increasing the level of transparency may have positive implications on a broader level.

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Part II

Africa

Angola

Slobodan Petrovic and Gudrun Albrecht-Smith

National Energy Introduction

Angola is a country on the west coast of central Africa, about 700 km south of the equator. It has a total area of 1,246,700 km^2 (481,353 mi^2) and a total coastline of 1600 km (994.2 mi) and thus, is one of the largest countries in Africa. The highest mountain peak (Morro de Môco) is at 2619 m. There are direct national borders with the four neighboring countries Congo, Congo (Dem. Republic), Zambia, and Namibia [3]. Luanda is Angola's capital and largest city. Angola is one of the least densely populated countries in the world. It has population density of 14.8 per km^2 [11] (Fig. 1).

At the beginning of the twenty-first century, the population density was well below the average for Southern Africa [13]. Although the inhabitants are from varying African tribe heritages, the most common language is Portuguese [11].

Energy Policies

In 1998, Angola enacted the "General Environmental Law." It defines the basic concepts and principles of protection, preservation, and conservation of the environment, promotion of the quality of life, and the rational use of natural resources [2]. The "Petroleum Activity Law" of 2004 covers the rules to access and conduct petroleum activities in Angola [10]. The "National Development Plan 2013-2017" was created in 2012. It is the overall medium-term development framework within which all sector goals are formulated for this period. The NDP links into the national vision or Long-Term Development "Angola 2025." A policy governing sustainable energy for all by 2030 was enacted in September of 2016 [2] and the first law to regulate natural gas exploration, production, monetization, and commercialization was enacted in 2018 [10].

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Trends in Generation Technologies

Angola is set to become the largest producer of crude oil in Southern Africa. It has also set the foundation for the sustainable development of renewables, through investments and supportive measures. Angola has a particularly strong hydropower generation potential that remains underutilized [2] (Fig. 2).

Domestic Resources

Angola is the second largest oil-producing country in sub-Saharan Africa and an OPEC member. Due to a significant drop in oil prices and limited foreign currencies in the Angolan market, very limited investment in either new or mature exploration and production fields has occurred since 2014 [10]. Angola's hydropower potential is huge, currently, only 20% is exploited. Solar is also a prominent energy source. In addition, there is a substantial opportunity to develop wind energy [12]. In June 2019, Italian energy company Eni collaborated with Angola's national hydrocarbons company Sonangol to develop Solenova, a joint venture to implement renewable energy projects in the country [18].

History of Energy

Petroleum was first discovered in Angola in 1955, which allowed the country to become one of the largest exporters of petroleum in sub-Saharan Africa. A state company was set up in 1977 to engage in joint ventures and production-sharing agreements, while management of the oil business was left mostly in foreign hands. In 2002, the overall state of the economy has improved, owing to the income generated from the country's petroleum industry. A large share of the country's total power-generating facilities remained out of use into the early part of the twenty-first century because of political instability.

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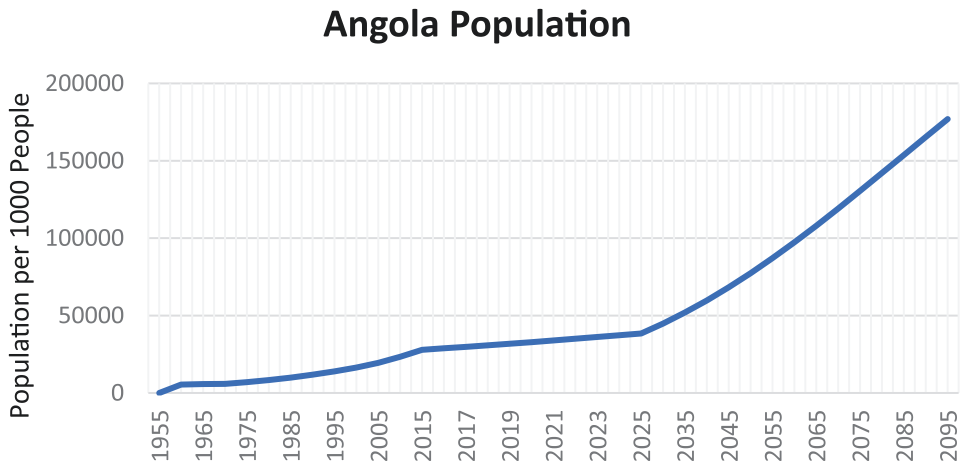

Fig. 1 Angola population and future estimates [11]

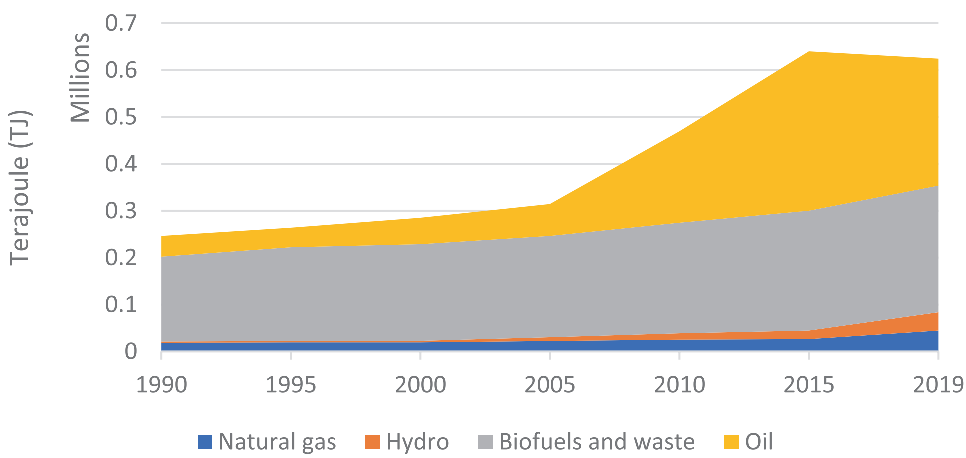

Fig. 2 Trend in energy supply sources [2]

Energy Generation Mix

Angola's current energy mix consists of 68% hydropower, 31.3% other fossil fuels, and 0.7% hybrid (solar/fossil fuel) [16] (Fig. 3).

Energy Consumption Mix

In 2019, Angola's energy consumption comprised 43.3% oil, 43.3% biofuels, 7.1% natural gas, and 6.3% hydro [16] (Fig. 4).

Fossil Fuels

In 2014, fossil fuels provided 48.3% of the total energy consumption in Angola. The contribution to overall energy consumed increased from 22.8% in 1995 to 48.3% [14] (Fig. 5).

Oil

Angola has 8423 million barrels (1200 metric tons) of proven oil reserves as of 2016 [6]. Without new investment in Angola's mature oil fields, production is expected to decline due to high cost of production.

Coal

Angola does not currently explore or invest in any potential coal reserve discoveries. No coal production, import, or use has been reported [14].

Natural Gas

Angola had 11 trillion cubic feet or 311 billion cubic meters of proven gas reserves in 2017 [6]. In 2019, Algeria produced 88 billion cubic meters of dry natural gas [14].

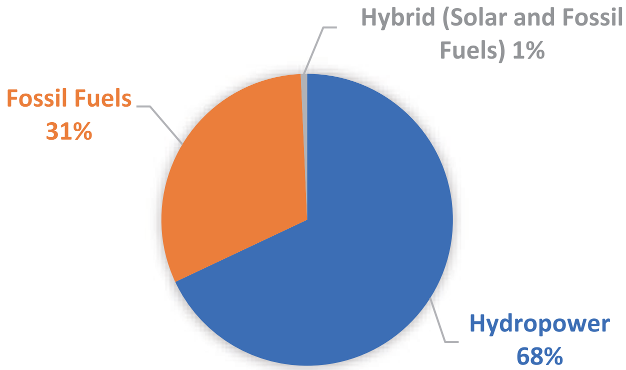

Fig. 3 Energy generation mix, 2019 [16]

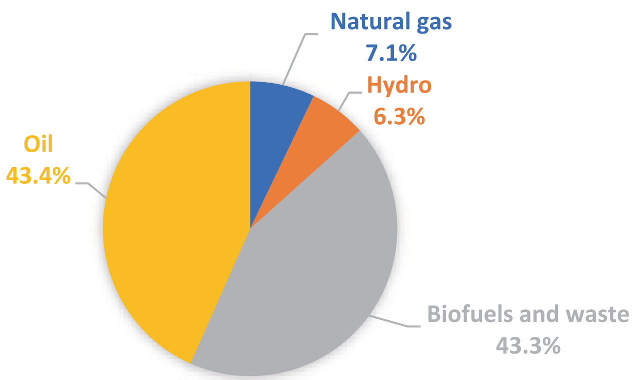

Fig. 4 Energy consumption mix in 2019 [2]

Nuclear Energy

Angola has radioactive minerals in its territory and joined the International Atomic Energy Agency (IAEA) in 1999. Since then, it has started to increase, promote, and develop nuclear science and technology applications [20]. To date, Angola does not generate electricity from nuclear sources [14].

Renewable Energy Generation

Photovoltaics

Angola has very limited solar PV installations. There are no reports of any installations in the MW range. The largest project, a 380 MW solar PV installation [16], is expected to be completed by 2025. There are also plans to install 30 MW off-grid solar PV.

Wind

Angola's wind power generation potential is estimated at 3.9 GW [10]. The first wind power plant with the capacity of 100 MW was constructed in 2016 [7]. There has been no further announcement regarding that project, and, to date, there has been no wind electricity generated in Angola [14].

Hydro

Angola's hydropower potential is estimated at just over 18 GW. Most of the capacity is located on the Kwanza River, the country's largest river.

In 2019, the installed hydropower in Angola was over 3 GW and annual energy generation is over 9 TWh. Construction of a 2 GW hydropower plant started in July 2017 and is expected to be operational by 2024 [2, 16]. Besides large hydro projects, 100 locations suitable to produce 600 MW from mini-hydro plants have been identified [16].

Ocean

Based on a theoretical resource assessment of wave energy of coastal waters, at the southern African coastline, the wave power potential at the Algerian coast is 10–20 kW/m for about 40% of the year [15]. Currently, there are no ocean energy or tidal wave energy plants off the Algerian coast.

Geothermal

There is no indication that Angola has explored its geothermal potential. It does not produce energy from that renewable resource [14].

Biomass

Biomass currently plays an important role in meeting the bulk of the energy needs of Angolan households [2]. More than 55% of Angola's land area is forested and the rural population uses its biomass as fuel [21]. It is expected that by 2025, 500 MW of energy will be produced from forestry, agriculture, livestock, and solid waste sources. In 2020, biomass was used to produce 0.2 billion kWh of electricity [14].

Biofuels

In 2009, Angola started a project for growing sugar cane on a 30,000-hectare site in the country's first-ever biofuel project. Another project is expected to produce 1.1 billion tons of biofuel annually [9].

Carbon Footprint

In 2020, CO_2 emissions for Angola were 22.5 million tons [14].

CO_2 pollution shows recent improvement (Fig. 6) from its all-time high of 33.07 million tons in 2016 [14].

Electrical Grid

In 2019, nearly 47% of the population in Angola had access to electricity [22]. As part of its long-term development strategy, the government of Angola plans to expand electricity access to 60% of the population by 2025 [12].

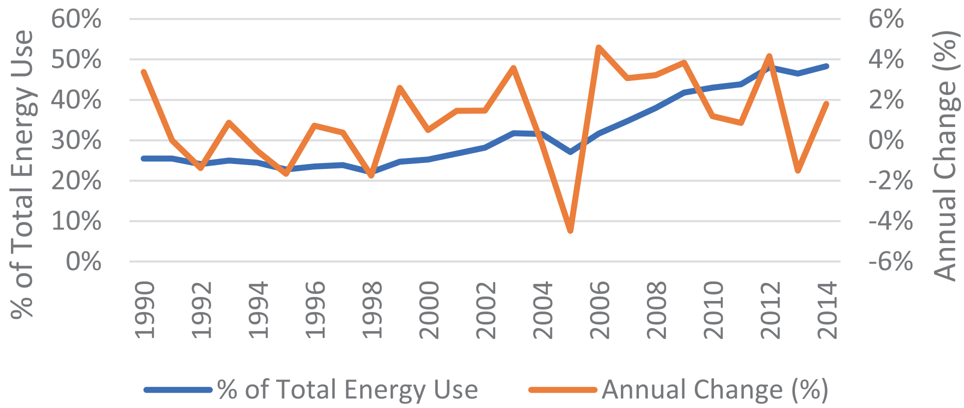

Fig. 5 Fossil fuel consumption since 1990 [8]

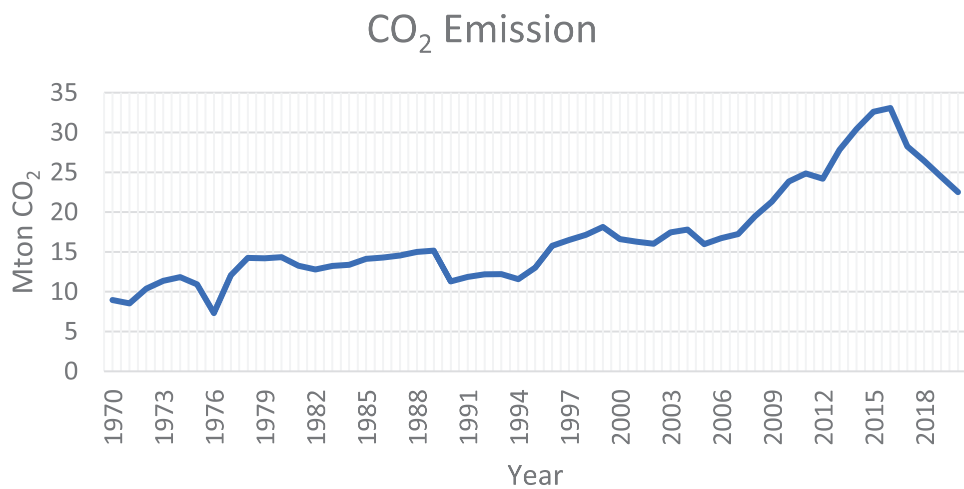

Fig. 6 Historical CO_2 emission [14]

Climate and Natural Disasters

About 80% of disasters in Angola are related to water, either due to floods or droughts. Floods have caused the most casualties and material damage, especially to social infrastructure. On average, almost 1.9 million people are estimated to be directly affected by drought per year, causing hydroelectric losses (deficit compared to current average production).

Grid Resiliency

Power transmission infrastructure in Angola and losses are estimated at 35%. The high rate of loss is due to illegal connections, non-payment, non-enforcement of payment requirements, and the fact that approximately 80% of electricity customers are unmetered.

Reliance on Foreign Fossil Fuels

Angola is one of the leading fossil fuel exporters in Africa and does not rely on foreign fossil fuels [6].

Relations with Global Community/ Socioeconomic Influence

Angola ratified the Paris Agreement in November 2020. It has some of the most ambitious targets for transition to low-carbon development in Africa. Not enough data has been collected to create an accurate greenhouse gas emission inventory and there are concerns about implementation in the absence of considerable international financial support [19].

Education

The Ministry of Education launched the training program on renewable energy, in Luanda in 2009 [4]. According to UNESCO, Angola has 12,747 students studying abroad, an increase of 9.38% compared to 2016 statistics [5]. During the twenty-first century, private Angolan universities began increasing, of which many were linked to universities in Portugal. To increase the domestic and international competitiveness of Angola and its people, the country's higher education sector called in 2015 for a quality increase in the standards of Angolan universities and colleges [1]. The Lusiada University of Angola offers renewable energy scholarships, but the scholarships listed are for universities outside of the country [17].

Summary

Angola relies heavily on crude oil production and its extensive hydropower resources to generate power. The nation's electricity grid is fragmented, in need of an upgrade, and interconnected to neighboring countries only where hydropower interconnects, which leaves much of Angola's rural areas without electricity. Currently, Angola does not utilize its solar potential and exploits only about 20% of its hydropower potential. Wind energy is also underutilized. Plans have been made to improve its renewable energy output, but without foreign investment, or another oil boom, Angola will have difficulties implementing its ambitious plans.

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Botswana

Slobodan Petrovic and Niels Williams

National Energy Introduction

Botswana has a very strategic central geographical location in southern Africa. The country has a huge potential to export electricity to its neighbors if its current energy resources are fully exploited. While the generation of power has been overly skewed toward coal, diesel, and imports from the Southern African Power Pool (SAPP), the Government of Botswana has embarked on a renewable energy push meant to diversify the energy mix.

There has been a gradual increase in budget allocations to the power sector, and the regulatory regime has become more receptive to investors. The government's investment has reinforced and expanded the backbone grid infrastructure to accommodate the feed-in power by any Independent Power Producers.

The solar PV subsector is of particular importance within the broader renewable energy policy, owing to Botswana's tremendous potential for solar energy utilization. There are extensive areas where solar energy projects can be developed, including in the rural areas or large-scale solar farms. In both scenarios, the additional investment would be accommodated to promote energy independence and meet the country's power peak demand.

Energy Policies

Botswana's energy policy is anchored on three key aspects – increasing access to electricity through the Rural Electrification Project, security, and stabilization of the power supply, and onboarding Independent Power Producers, especially within the Solar PV sector (BPC 2020). The stabilization of electricity supply involves expanding the existing generation and transmission infrastructure, while the security of the power supply involves measures that reduce dependence on power imports from the Southern African Power Pool (SAPP). The National Policy on Renewable Energy also outlines a target of 15% renewable energy within the energy mix by 2030 (BPC 2020).

Trends in Generation Technologies

As illustrated in Fig. 1, the bulk of the power is drawn from the Morupule coal-fired thermal plants and imports from the Southern African Power Pool (SAPP). There are two diesel operating stations – Orapa and Matshelagabedi, which serve the primary function of emergency power supply or when the Morupule plants are undergoing planned maintenance (BPC 2020) (Fig. 2).

Taking a deeper look at historical power generation figures, Botswana's annual generation has plateaued around the 3700–4000 GWh range. For the long-term target, the government has set a target of 1.5 GW of new capacity by 2040 (Reuters 2021).

Domestic Resources

Botswana has ample domestic resources capable of meeting the power demand. The most significant resource is coal, whose reserves are estimated at 212 billion tons. Also, with many parts of the country experiencing an annual Direct Normal Irradiation equivalent of 3000 kWh/m^2/a, Botswana is primed for solar power.

History of Energy

Botswana's energy sector has been tied to South Africa and its southern African neighbors since its humble beginnings in the 1950s. Before 1950, Tati Concession Company (TCC), using coal from South Africa and Zimbabwe, was the only power generator in the country and supplied Francistown only (Kanduza 2009). Since the Union of South Africa ran a highly developed power sector with surplus power, there was

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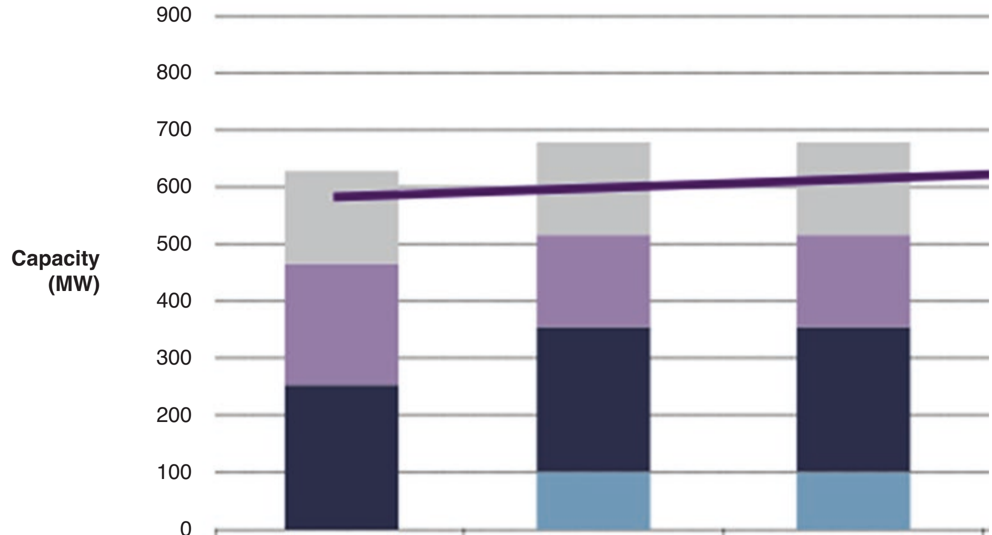

	2019	2020	2021
Emergency (Diesel)	160	160	160
Imports	200	150	150
Morupule B	260	260	260
Morupule A	0	100	100
Peak Demand	596	605	614

Year

Fig. 1 Power generation trends and outlook

Fig. 2 BPC annual statistics 2019

	2019	2018	2017	2016	2015	2014
Total unit sales (GWh)	3,294	3,336	3,349	3,479	3,495	3,449
Total generation (sent out) and imports (GWh)	3,925	3,844	3,928	4,043	4,024	3,704

a consensus to avoid developing Botswana's domestic resources further and instead import the electricity, just like many other commodities (Kanduza 2009, p. 40). The purchase of TCC by Glazer Brothers, a speculating company from South Africa, marked the entry of colonial henchmen into the nascent power sector. In 1970, through an Act of Parliament, the Botswana Power Corporation was formed and charged with the generation, transmission, and distribution of electricity (BPC 2021).

Breakdown of Energy Generation "Mix"

Energy Generation Mix

Botswana's energy mix consists of three primary energy sources – the Morupule A & B coal-fired plants, which, based on their capacity factors, have a 360 MW capacity, the Orapa (90 MW) and Matshelagabedi (70 MW) diesel plants, and 150 MW imports (BPC 2020) (Fig. 3).

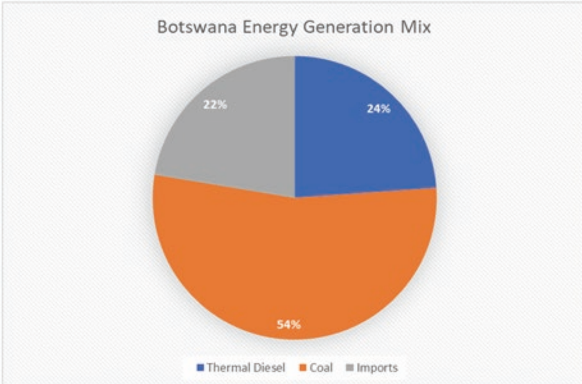

Fig. 3 No source given

Energy Consumption Mix

No information was provided by the author.

Fossil Fuels

Oil

As of 2019, Botswana had an average monthly fuel consumption of 100 million liters (Gamba 2019). Botswana Oil Limited, the state-owned company charged with the security of fuel supply and management of the Government's strategic fuel storage facilities, reported trading in a combined 87.3 million liters of fuel in the 2017/2018 year (BOL 2019). Botswana imports all its petroleum products, which include petrol, diesel, and illuminating paraffin. The fuel import bill amounted to P500-million (about US$50 million) every month, with the average basic fuel price (BFP) being P5,00 per liter (Gamba 2019). Botswana sources its petroleum products from South Africa. Botswana Oil Limited is in the process of diversifying the fuel import sources and expanding storage plants to achieve and maintain supply. The alternate sources of fuel that have been identified include Mozambique, Zimbabwe, and Namibia (Memo 2020). While Botswana does not have any definitive oil reserves, the country has expanded oil exploration efforts. Licenses now allow for oil and gas exploration in the Okavango Delta. The company behind the project, ReconAfrica, has indicated the potential oil and gas deposits in a formation known as the Kavango Basin (Barbee and Neme 2021).

Coal

In the financial year ending 2018, the total coal usage amounted to 1171 ktoe, in what was the largest source of energy in the country (IEA 2021). In 2020, Minergy Inc. exported the first consignment of coal (2650 tons) from the Masama mine to South Africa (Benza 2019). The mine produces up to 70,000–80,000 tons of clean, saleable coal per month. There are two operating coal mines in Botswana – the state-owned Morupule Coal Mine and Minergy Inc.'s Masama Coal Mine. The mine is estimated to produce up to 3.5 million tons per annum (Mtpa) (NSenergy 2020). Botswana has enormous coal resources estimated at 212 billion tons. While this potential is still largely unexploited, there are concrete plans to develop a thriving coal export market (NDP 2020).

Natural Gas

The key type of recoverable natural gas reserves found in Botswana is the Coal Bed Methane (CBM), located mostly in the central Kalahari region. The size of the reserves is estimated at 10.8 tcf, which is enough to kickstart a major extraction development (KEB 2020).

Renewable Energy Generation

Photovoltaics (PV)

Botswana is in the process of streamlining the regulatory structure to allow for the feed-in of solar power. As such, currently, there is no large-scale generation of power from solar PV. The energy mix is wholly made up of coal, diesel, and electricity imports (BPC 2020). While no major commercial solar operations are undertaken in Botswana, there is a 1.3 MW Phakalane Solar Plant operated by the Solar Projects Section of the BPC (2020). The plant was constructed in 2012 by the Japanese government through the JICA agency (Sunday Standard 2012). It was a pilot project meant to kickstart the development of a thriving renewable energy sector in Botswana. With an annual Direct Normal Irradiation of 3000 kWh/m^2/a, Botswana has a huge potential to generate enough solar power to meet its domestic demand and export to neighboring countries (International Trade Administration 2021). Overall, the country gets more than 3200 hours of sunshine per year. As highlighted by the Botswana Power Corporation, the main priority is to engage the Independent Power Producers (IPPs) to facilitate a faster production of solar power. In the short term, there are concrete plans to develop 2 50 MW solar PV projects and Grid Tied Solar projects to 12 Villages, with a total capacity of 35 MW (BPC 2020). The completion date is set for August 2022.

Wind

Many parts of Botswana experience relatively low average wind speeds, which range from 2.0 to 3.5 m/s (Get.Invest 2021). These speeds would be insufficient to facilitate the development of large-scale wind power projects. The country has identified a range of small-scale projects which can be developed in a broader energy plan stretching out to 2040. These projects would collectively generate 50 MW (Reuters 2021).

Biomass

Biomass makes up 29.16% as a proportion of the overall energy used in Botswana (Danish Energy Management and Esbensen 2017). Charcoal and firewood are critical sources of energy for rural and low-income urban communities. As such, woody biomass has a strategic role in the overall energy mix. In many rural areas, it has been observed that woody biomass accounts for 38% of total final biomass energy consumption (Danish Energy Management and Esbensen 2017). There is a considerable potential of close to 200 tons per annum for the use of fuelwood resources in generating energy (UNDP 2012).

Biofuels

As of 2016, there was a production of about 15,000 liters per month of biodiesel that made use of waste vegetable oil drawn from multiple food processing outlets (NDP 2020). Also, approximately 70% of households in urban areas use LPG. The Glen Valley Wastewater Treatment plant is the largest, although its primary function is treating sewerage and wastewater. The plant was constructed by the local government and commissioned in 1997. It averages a total production of 876,000 m^3/year of biogas (NDP 2020). Regarding the usage, 26% of the gas produced is used to maintain the temperature of the digester and for incineration. The production of biofuels in Botswana is relatively small-scale in nature. As of 2020, there were fifteen known biogas plants, of which two are for research purposes, and two others are wastewater treatment plants (NDP 2020). The rest of the plants provide limited energy, mostly for cooking and lighting. Botswana has a huge potential in producing biofuels, particularly due to the large cattle population, estimated at more than 2,220,000. Biogas can be reliably and sustainably produced from the cow dung. Abattoirs and sewage plants also offer such potential (UNDP 2012). Details of biofuels goes here.

Energy Storage Technologies

Country Current Implementation of Energy Storage Techniques

The use of vanadium redox flow technology and its connection to the grid offer an efficient way of complementing Botswana's nascent renewable energy sector. Such units have been coupled with 11-kWp solar arrays for an independent power producer (Tisheva 2017).

Country's Future Storage Direction

The development of Concentrated Solar Power is a key avenue that Botswana looks to take advantage of not just as a form of generating clean energy but also as a form of energy storage. The initial plans are for a 200 MW capacity of CSP (Reuters 2021). Feasibility studies have pointed to the CSP potential that lies in the diamond mining area of Jwaneng and the Northwest copper mining region. The Botswana Power Corporation acknowledges the challenges faced in expanding the current grid network. This challenge offers an opportunity for an off-grid electrical microgrid. The development of this network, particularly in the rural areas, would hasten access to electrical power for many communities. One such system has been developed by New Southern Energy (N.S.E.) to power two safari lodges (Trickett 2017).

Carbon Footprint

Most Recent Carbon Output

Botswana recorded 6.32 million tons of Carbon output in 2019, in a data analysis provided by the Global Carbon Project (Ritchie and Roser 2020). This figure marked a notable reduction from the 7.03 million tons recorded in 2017.

Historical Trends of Carbon Footprint

The per capita carbon emission levels in Botswana have been on a general upward trend since the late 1980s. For instance, in 1989, the carbon footprint stood at 1.15t, and by 2017, it had risen to 3.2t (Ritchie and Roser 2020). That said, standing at 0.02% as of 2016, the country still accounts for a negligible share of the global carbon emissions.

Types and Main Sources of Pollutants

Half of Botswana's total carbon emissions came from coal usage, with the remaining half being split between oil and cement production (Ritchie and Roser 2020). The economic activities that yielded the emissions, mining, fuel burning, vehicular emissions waste, and household fires are noteworthy.

Air Quality

Botswana has a mean annual concentration of PM2.5 is 23 μg/m^3, which is above the recommended maximum of 10 μg/m^3 (IAMAT 2021). This makes the country relatively polluted despite having a population of just two million. Among the pollutants, sulfur oxide emissions from the copper–nickel smelter at Selebi Phikwe and elevated concentrations of nitrogen oxides during peak traffic hours exacerbate the already poor air quality (Wiston 2017).

Energy Resiliency

Electrical Grid

Botswana's power grid was first developed in the late 1940s to facilitate the importation of electrical power from South Africa (Kanduza 2009). In the 1970s, the role of designing, constructing, and maintaining the grid was bundled together with the generation of power and altogether entrusted to the BPC. In 2019, the Corporation embarked on the Northwest Transmission Grid Connection Project, which is the most ambitious grid improvement and expansion project to date (BPC 2020). The project aims to provide reliable power to the northwestern areas of the country, in what will be of great support for the local economy, especially the mining and tourism sectors. The Reinforcement of Bulk Supply Points in the southern part of the country has led to the development and refurbishment of the Mochudi, Ramotswa, Tlokweng, and Gaphatshwa 132/33/11 kV stations at a total cost of around P463.5 million (BPC 2020). Other network rehabilitation programs are also ongoing throughout the major urban areas owing to the deterioration of the secondary distribution network. The grid network in Botswana is relatively stable and consists of 11 kV primary distribution power lines, and the range rises to 400 kV for the primary transmission network. Other than the power drawn from the Porupule Stations, the primary transmission network is key and strategic in importing power from the regional power pools (Get. Invest 2021). The BPC expects to reduce the distribution of high voltage faults from an average of 270 per month to 198 (BPC 2020). The Corporation is expecting a reduction from an average per month. Distribution low voltage faults are expected to reduce from an average of 4690 per month to 3192 per month. Finally, despite the power supply challenges facing the Southern African Power Pool (SAPP), the long-term bilateral contracts that determine the importation of power are critical to stabilizing the domestic good and avoiding load shedding (BPC 2020).

Climate and Natural Disasters

Botswana is highly susceptible to hot climate and droughts. In 2015/2016, the country experienced its worst drought in three decades, and it resulted in a significant dry-up of the Gaborone Dam, threatening water availability in the capital city (Nonjinge 2018). From the current climate change models developed, especially regarding global warming scenarios of 1.5–3 °C above pre-industrial levels, Botswana is projected to experience extreme changes in temperature and precipitation. Such changes can affect some critical sectors, such as agriculture (AAAR 2018). With half of Botswana's total carbon emissions coming from coal usage and the remaining half being split between oil and cement production, Botswana is bound to increase its total carbon output even further (Ritchie and Roser 2020). The role of carbon in the energy mix can only be tempered by developing a thriving renewable energy sector. Botswana draws much of the domestic energy from fossil fuels. There is limited use of renewables, especially in the large-scale generation of power. As such, the impact of climate change on renewables is little. However, given the risk posed by droughts to such sectors as agriculture and livestock farming, there is an inherent challenge that must be recognized when seeking to generate power from woody biomass and biofuels such as biogas.

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

Botswana is heavily reliant on South Africa for the importation of petroleum products and the export of coal (Memo 2020). Any economic volatility or shock in South Africa would be felt in Botswana as well. This has been experienced before with regard to electricity imports from the Southern Africa Power Pool. Diversifying the import and export destinations for the energy products is vital in removing any potential choke points. While the export of energy products is not extensive in Botswana compared to the import of such products, there are strategic plans in place for the export of coal products. With 212 billion tons of potential coal reserves, the sale of such a resource is important. Additionally, while the state-owned Botswana Oil Limited has seen petroleum sales rise gradually over the years, Botswana Power Corporation power sales have stagnated around 3100 GWh to 3400 GWh over the past decade (BPC 2020).

Relations with Global Community/ Socioeconomic Influence

The formulation of Botswana's Intended Nationally Determined Contribution (INDC) was particularly important given the proportion of fossil fuels that the country uses per capita and the extent of air pollution in the major cities. The country set out a target to reduce the overall emissions by 15% by 2030 (INDC 2015). Through this effort, Botswana reaffirms its role among the community of nations, especially regarding the sustainability of the environment.

Botswana has engaged extensively with the United Nations and ratified major Protocols and Treaties (UN 2021). The engagement has particularly been based on Botswana's National Development Plans, in which the UN has provided multilateral support to realize the goals stipulated. Botswana also served as a member of the UN Security Council from 1995 to 1996.

Botswana has demonstrated a keen interest in advocating for human rights, democracy, and the rule of law on the international stage. This interest has informed the diplomatic relations the country has forged around the world. In 2014, after repeated cases of rights violations by the government of North Korea, Botswana cut all diplomatic ties between the two countries (MoFAIC 2014). The same position has been applied to Iran, where the relations are muted. Botswana does, however, maintain cordial relations with both Russia and China.

While the Botswana government does not bar relations based on political ideologies, the preference for relations with democratic countries has been demonstrated. However, given the trade relations and intricacies of labeling the political ideology, Botswana does maintain cordial relations with communist, socialist, and democratic regimes (MIAC 2021).

The development of the Botswana energy sector is part of the government's Vision 2036, which seeks to have a 50% proportion of renewable energy within the energy mix by March 2036 (BPC 2020). As part of the global community and climate change advocate, the Climate Change Policy and Institutional Framework outlines the need to cut greenhouse gas emissions by 15% (INDC). This target can be achieved most probably, through the use of solar power, given the annual Direct Normal Irradiation equivalent of 3000 kWh/m^2/a that the country already enjoys (International Trade Administration 2021).

Summary

The decarbonization of the Botswana power supply offers the growing renewable energy sector a big boost. There are concrete legislative and policy instruments geared toward promoting electricity access, and the role of renewable energy has been recognized as being of vital importance going forward. With the technical challenges that continue to face the Morupule stations, and the energy deficit already facing the Southern Africa Power Pool, the need for cheap and clean energy cannot be overstated. Additionally, with the limited potential for hydro and wind power, capital investment into the Botswana renewable energy sector can be fine-tuned and streamlined for solar PV. While meeting the current peak demand has already proven challenging and necessitated load shedding, increasing the domestic power generation from renewables will ensure energy demand is met, energy independence guaranteed, and greenhouse gas emissions reduced.

Current Energy Situation (Recap of Generation Methods, Energy Trends)

Botswana holds a great potential to meet the domestic as well as regional power demand. This potential is exemplified in the huge coal reserves and solar isolation – two resources that have not been fully exploited. The country draws much of its power from the coal-fired Morupule plants, the standby diesel plants, and imports from the Southern African Power Pool. Over the past decade, power consumption has plateaued. The Botswana Power Corporation is undertaking key projects that will expand the power grid and stabilize the power supply.

Future Energy Situation (Private Business Interest, Government Direction)

The BPC has laid out coherent plans to improve access to electricity and to diversify the energy mix. These plans have been backed by a more accommodative regulatory structure that seeks to onboard Independent Power Producers in developing the infrastructure necessary to generate power from renewable sources such as solar PV. The Government of Botswana has an obligation to reduce the emission of greenhouse gases as per the 2015 Intended Nationally Determined Contribution submission. Collaboration with the private sector will be key in meeting that Paris Accord target.

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Congo

Slobodan Petrovic and Jack Zoucha

National Energy Introduction

Home to over 100 million people, the Democratic Republic of Congo (DRC) is the largest and fourth most populous country in Africa [1]. The Kingdoms of Luba and Lunda ruled the country until the 1870s until it was acquired as King Leopold II of Belgium's personal property under the Congo Free State. Over the next 30 years, the local population was forced to produce rubber, and by 1908 when Leopold was forced to give up the land to Belgium, millions had died as a result of disease and abuse. From 1908, the DRC was a Belgian territory, known as the Belgian Congo, until independence was gained in 1960. The DRC continued to be marred by conflict and corruption as late as 2006, and still faces significant violence in the east from the overspill from continuing conflict in Rwanda and Uganda [1].

Despite having the 15th largest population in the world, the DRC ranks only #106 in electricity production and consumption and is one of the lowest in electrification rates at only 9% of the population [1]. The DRC faces numerous challenges in the electricity sector, including limited access, due mainly to an underdeveloped, dysfunctional grid – in fact, a significant portion of consumers are connected illegally to the existing grid, with only 500,000 customers able to be accounted for in 2018 [2]. Due to both the size of the country and the terrain, most of the country remains unconnected to a common grid and will most likely remain that way for the foreseeable future – with over 67% of the country (>1.25 million km^2) covered by forest, making many regions of the country accessible only by air [3].

Energy Policies

In Article 48 of the DRC Constitution of 2006, access to electricity is guaranteed as a right to the entire Congolese population; however, the actual situation is quite different, with less than 20% of households in urban areas and only 0.4% of households in rural areas having access to electricity. National policies have long prevented the expansion and modernization of the grid, with an antiquated, colonial-era legal framework governing the electricity sector up until 2014 [4]. After the DRC's independence, Ordinance Act 70-033 established the Société National d'Electricité (SNEL) as a state-owned, vertically owned utility company, with a complete monopoly on electricity production and distribution [3]. The company was privatized in 2008 under Act 08-007, with the DRC state as its single shareholder, but remained a de facto monopoly in all things electricity in the DRC [4].

Faced with a combination of a rapidly increasing population and a booming mining industry, the 2014 Electricity Law was passed, liberalizing the electricity sector, and opening the market to any operator interested in the production, transportation, distribution, import, export, or commercialization of electricity in the DRC [4]. Due to a huge potential for hydropower, the bill was also created to protect Congolese interests on both local, regional, and national levels, while still attracting foreign, public, and private investments. The new legal framework comprises a Minister of Electricity, a national regulation board, the Electricity Regulation Authority (ARE), and a state-owned body responsible for the electrification of rural areas, also including a special National Electrification Fund to help sponsor investment into rural electrification [4]. Additionally, the DRC's Modern Villages program aims to electrify more than 100 villages using hydro-based green mini-grids; however, implementation has been slow despite the added incentives, including certain tax benefits [2].

Trends in Generation Technologies

The energy sector in the DRC has been historically dominated by bioenergy, with over a 95% dependence on

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biofuels – considering such a low percentage of the population has access to electricity, the primary energy uses in the DRC are heating and cooking, traditionally accomplished with biomass like wood, followed by industrial and residential electricity demand [5]. The electricity sector in the DRC is almost exclusively run by hydropower, ranking #4 globally at just under 98% of total installed capacity [1], with most of the remaining being produced by oil.

There are no nuclear energy installations in the DRC, coal has never made an entry into the electricity sector, and less than 0.1% of installed capacity comes from other renewables like solar PV, wind, or geothermal. The steeply rising demand for electricity from the mining industry created an energy deficit in the DRC, moving the DRC from a net energy exporter to a net importer until the recent completion of significant hydropower projects [6].

Domestic Resources

The country is extremely rich in resources, with copper being the largest export and over 70% of the world's cobalt supply coming from Congolese mines in 2019; however, majority of this mining is privately exploited, and therefore not properly reflected in the GDP or the economy in general. There is also significant arable land with a large potential for farming, but poor land and water management on top of territory conflicts have made agriculture an afterthought in the DRC economy [7]. The country hosts an extremely large biodiversity and is home to the world's second largest rainforest, with the wood from the forests being the primary source of energy for much of the population.

There are also plenty of energy resources available within the country, including huge reserves of oil and natural gas, a significant amount of recoverable coal reserves, and an estimated potential of well over 100 GW of hydroelectricity [3, 6, 7]. Less than 3% has been successfully exploited so far, still managing to provide almost all of the country's electricity, and it is estimated that hydroelectricity, if properly developed and exported, could reliably provide revenues of more than 6% GDP, an economic boost of more than US$5.7 billion per year [3]. The DRC is also central in many continent-wide energy plans that have been developed by both inter-African organizations and interested foreign parties, eventually providing power to most of the South African (SAPP), West African (WAPP), East African (EAPP), and Central Africa (CAPP) power pools, along with the Comité Maghrébin de l'Electricité (COMELEC) in northern Africa [3].

Breakdown of Energy Generation "Mix"

Energy Generation Mix

Renewable energy sources make up more than 99% of the total energy supply and over 98% of installed electrical generating capacity in the DRC [1, 3, 7] (Fig. 1). The majority of energy consumed in the DRC is biomass, like wood from the vast forests, used in both heating and cooking. With such a low access to electricity, heating and cooking make up most of the energy demand in the DRC, with more than 95% of the population dependent on bioenergy, including biomass and biofuels [5]. There are other forms of generation that go mostly unreported, like residential PV units, solar thermal water heaters, or other household or rural systems that are not connected to the main grid, but are insignificant in comparison to the overall energy mix.

Hydropower has made up more than 98% of the DRC's total electrical supply since before 1990 [7] (Fig. 2). Fossil fuels make up about 2% of total installed generating capacity, mostly as self-producers [1], but have traditionally only been used in drier years to compensate for drops in production from hydropower due to the cost of importing refined petroleum products [8].

Energy Consumption Mix

Electricity consumption has been increasing rapidly in recent years, due mainly to the increase in mining activities in the country. A sharp increase in demand for access to electricity has gone largely unrecognized, with the residential demand staying relatively consistent, though many of the DRC's development plans will make electricity consumption increase significantly in the next 20 years as median income rises, electricity access improves, and mining continues to increase [5] (Fig. 3).

Fossil Fuels

Oil

Currently, Congolese oil production is limited to the offshore production in the Coastal Basin, yielding less than 25,000 barrels per day, all of which is exported [9, 10]. There are currently only three major oil companies with extraction operations underway in the DRC; Anglo-French firm Perenco conducting offshore oil extraction in the Atlantic Ocean off

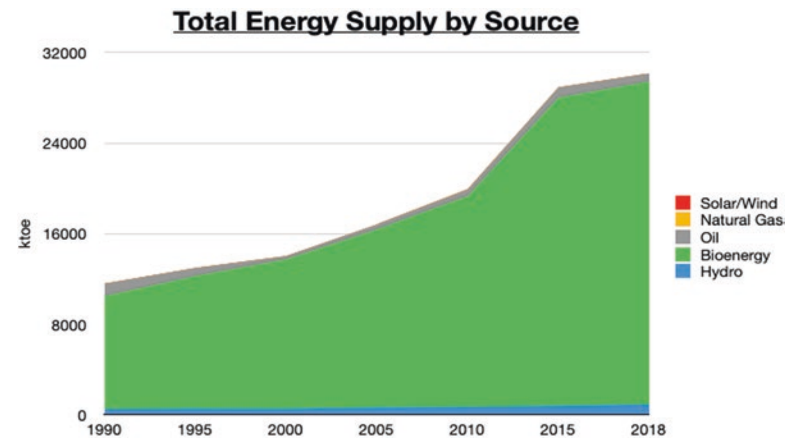

Fig. 1 The DRC energy generation by source, including transportation, cooking, heating, and electricity [7]

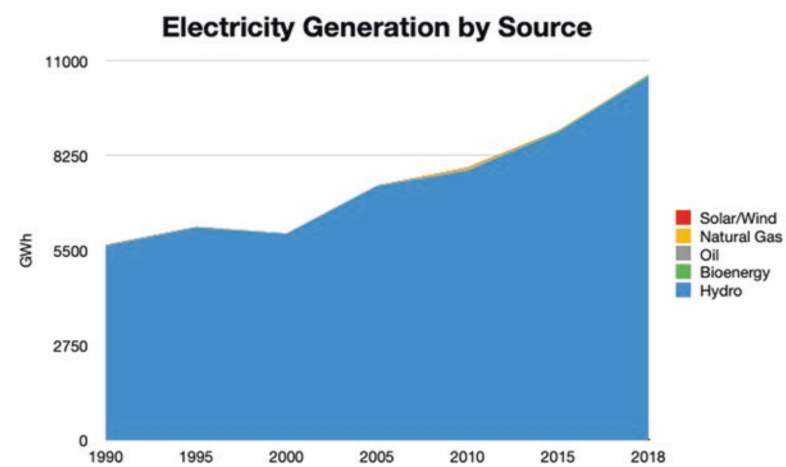

Fig. 2 The DRC's electricity generation by source, dominated by hydropower [7]

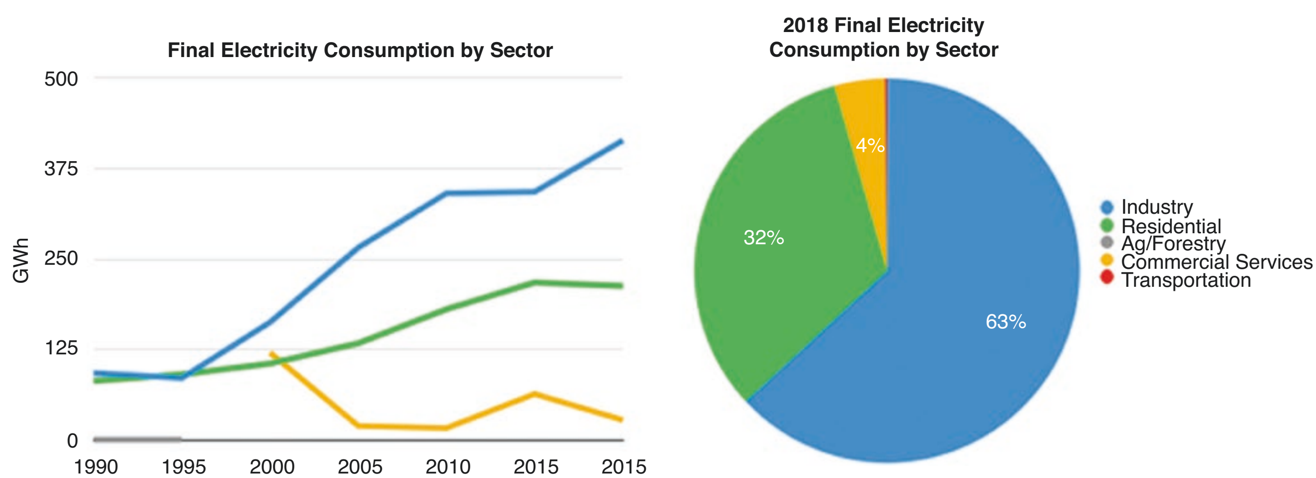

Fig. 3 DRC electricity consumption by sector, increase from mining activities noticeable in 1995 from copper, 2015 from cobalt [7]

the coast of Muanda in Kongo Central; French oil company Total, and the DRC parastatal Cohydro, which are conducting exploratory and preliminary extractive operations in the Eastern DRC [3, 9]. Perenco is currently the only company actively producing oil in the DRC, operating 11 fields onshore and offshore with the capability of commissioning around 25 wells per year [10].

Recent oil discoveries show that the DRC has the 2nd-highest crude oil reserves in Central or Southern Africa, behind only Angola [9]. The DRC has proven reserves of more than 180 million barrels [1, 3, 9], though estimates of total petroleum reserves are as high as 3–5 billion barrels [9]. Despite the huge oil reserves in the DRC, there is no oil refinery in the entire country, forcing the export of all oil produced internally, and the import of any refined petroleum product that may be required [1, 9]. The total gross production from Perenco is routed to the Kalamu floating terminal off the coast of the DRC and transported to foreign refineries from there [10].

The country still consumes over 20,000 barrels of refined oil products per day [1, 9], less than the average production of just the Muanda region. The DRC does not currently have any oil-powered thermal power plants, and most refined oil imports can be attributed mainly to the consumption of gasoline, aviation fuel, kerosene, and petroleum-based lubricants in the transportation industry [3]. There are no prominent plans to explore or install any oil-based thermal plants in the DRC any time in the near future, but improved infrastructure plans along with increased manufacturing in the country will most likely lead to a sharp increase in refined petroleum products as the demand for transportation also rises [5].

Oil exports have been a reliable source of income for the DRC, and further development of the vast oil reserves throughout the country could provide further economic development for the country. Investing in oil refineries could provide even further economic potential by reducing or eliminating required imports of refined oil products and providing another exportable product in high demand globally. The DRC is also planning to offer 19 onshore oil and gas sites in the 4th quarter of 2021, the first ever increase in site offerings and the first ever open market for oil since the country adopted a new petroleum law in 2015 [11].

Coal

The DRC currently has no domestic coal production or exportation, and the only reported coal imports are for industrial purposes [3, 7] and charcoal used for cooking by approximately 35% of the population [5]. There have never been any coal-powered thermal plants in the DRC, and there are no plans in place to start now. Like oil, there are deposits of coal throughout the country, estimated to be at least 88 million tonnes of bituminous-type recoverable reserves [3].

Coal consumption has increased dramatically in recent years in the DRC, jumping from 6.35 thousand tonnes being consumed in 2013 to 35.38 thousand tonnes in 2018 [12], increasing at rates similar to mining and other industrial activity in the country. It is clear that coal has no place in the DRC's energy future, but with current development goals in place both domestically and internationally, coal consumption and imports will still continue to increase exponentially if economic and industrial activity reach stated goals [5]. The increased carbon output from industry could easily be offset by providing clean cooking access in both rural and urban areas – already a part of many development goals by outside agencies, even if it is not currently a domestic priority [5].

Natural Gas

Along with the large reserves of crude oil and coal, the DRC may hold more than 30 billion m^3 of methane and natural gas, located in three major deposits [9]. Additionally, Lake Kivu in eastern DRC has up to 60 billion m^3 of methane dissolved in its waters, leaving a huge potential for electricity. While the high levels of methane in the lake (also known as "Killer Lake") do pose a threat to local populations, the lake also generates as much as 250,000 m^3 of methane annually [9]. In fact, a company is already extracting and producing methane on the eastern (Rwandan) side of the lake, and an accompanying power plant that has a current capacity of 34 MW, with a planned second phase to add an additional 75 MW [13]. Given that the lake is split almost equally between the DRC and Rwanda, there is still a huge opportunity for the DRC to take advantage of the natural gas reserves in the lake and be able to supplement any variability in the hydropower supply with local natural gas.

The DRC has not imported or exported any natural gas since at least 2015 [1, 7], and has no reported production or consumption of natural gas either, including biogas. It remains a large and untapped resource, with the potential to power vast regions of the country that are to date without power. The possibility of rapid renewable deployment also leaves plenty of room for natural gas to become the mainstream solution for flexible and easily dispatchable sources of electricity for any potential lapses in renewable energy sources.

There are currently no plans in place for the development or construction of any gas-powered thermal plants anywhere in the DRC. Additionally, no plans were readily available for the development of any natural gas extraction or production facilities, despite the economic possibilities and the proven effectiveness just across Lake Kivu. Natural gas will be integral to any electrification strategy, even with such a huge potential of hydropower in the DRC. Climate change has already proven to be a factor in hydropower output throughout the country [8], and the rainfall is only going to continue decreasing as climate change worsens.

Nuclear Energy

The DRC does not have any nuclear power plants in the country, and there have never been any plans for nuclear development in the DRC [1, 4, 7]. Given the political instability within the country and around the region, it could prove to be an extremely risky endeavor. The country currently contains two research reactors, TRICO I which is now in permanent shutdown, and TRICO II which is in an extended shutdown, with a restart possible [14]. Like coal, nuclear sources most likely have no place in the DRC's energy future.

There is at least one significant uranium deposit in the DRC, located at the Shinkolobwe mines in the southern part of the country, which actually provided a majority of the uranium for the Manhattan Project in the United States during World War II [14, 15]. Some mining continued until the DRC's independence, when the mine shafts were sealed and guarded. The deposit has continued to be unofficially mined for cobalt since at least 1997, raising international concern about the unsanctioned uranium that may be finding its way out of the country [14]. In 2004, the Congolese president again officially closed the Shinkolobwe mines after a UN report described the situation as "anarchistic," although the local government never enforced the ban and illegal mining continues in the area [15].

In 2009, the French company Areva, signed a uranium exploration agreement with the DRC government, focused primarily on Shinkolobwe, but has since stated that it will not actualize any plans for mining while the country remains politically unstable [14]. The DRC has been working with the International Atomic Energy Agency (IAEA) since 2019 to improve its legislative framework, particularly in the healthcare and agriculture sectors, and has been receiving legislative support since 2017 from other entities in an effort to bring its national legal code in line with accepted international safety and security standards [16]. There are no public estimates available for how much uranium may be deposited around the DRC, but updating the country's legal standards are a positive step toward the future export of nuclear fuel to other countries, especially after the country's stability can be established and maintained.

Renewable Energy Generation

Photovoltaics (PV)

With an average solar radiation ranging from 3.25 to more than 6 kWh/m^2/day, the DRC has immense potential for implementing solar photovoltaics (PV) and solar heating systems throughout the entire country [3]. However, there was only 20 MW of estimated total capacity by the end of 2020 [17], producing just over 10 GWh [6]. Most of this estimated capacity comprises single-module systems, often powering only a few lights and possibly a battery. There are over 800 systems in larger, official installations, totaling more than 83 kW in 2016 [3], still far short of the solar potential of the DRC.

Despite a poor record of PV installation, the increase in mining in the southern parts of the country has led to a renewed interest in bridging the energy gap with solar energy. There are many construction plans already in the works, with the potential to add more than 2 GW of solar capacity by the end of 2025. The biggest project includes over 1 GW of solar farms surrounding the capital city of Kinshasa, carried out in two phases by the US-based company Sun Plus [18]. The first phase of the BOOT (build, own, operate, transfer) solar project was launched in August 2020, installing several PV plants with a combined 600 MW of capacity [19], with the second phase still in development. The total cost of the "Kinshasa Solar City" is estimated to be around US$1 billion, supplied entirely by Sun Plus. The city-wide project network has a power purchase agreement signed by national utility SNEL with a 25-year deal that will see the power company buy 100% of the electricity generated for $0.095/kWh [18, 19].

In June 2021, SNEL made two more purchase agreements for large-scale solar PV plants. The first, funded by an international consortium led by the UK government-backed Gridworks, will see three large-scale, off-grid utilities to supply power to the cities of Gemena, Bumba, and Isiro, located in the northern region where there is no access to the national power grid [20]. The initial investment is promised to be at least US$100 million, and is expected to be completed by the end of 2024. Moyi Power, the company in charge of construction, currently anticipates an initial deployment of 14 MW of PV capacity and 40 MWh of battery storage aiming to connect more than 23,000 households and commercial consumers across the three sites in the first 5 years, expecting to double the size of the plant every 3–5 years in order to keep up with demand [21].

The other project, meant specifically to keep up with increasing mining activity, will see two 100 MW plants constructed in the southeast region where most of the mining occurs. The total investment will be more than US$300 million, carried out together with developer Financing Access, which is partnered with US-based investment fund Green Power Capital (GPC). The facilities will have the potential to supply over 500 GWh of energy to the DRC's power grid, enough to meet the demand of both the mining companies and more than one million people in the region [22].

Both the size and geographical features of the DRC make it well suited for decentralized energy systems, especially in urban areas. The country is almost 70% forest, and space for large-scale PV plants is limited. The largest potential consumer base for PV in the DRC is most likely urban and peri-urban households [23]. The higher spending power and larger energy demand of the urban population create a huge potential for smaller home systems in the DRC, similar to rural areas in neighboring countries, but are more densely grouped, leading to lower peripheral costs. These households offer the potential for pay-as-you-go models, as they are also targeted intensively by mobile telecom operators through mobile money agents [23], and with the lack of a national electric grid, could be one of the easiest ways to reach electrification goals in the DRC.

Wind

Throughout the DRC, wind speeds tend to be low, averaging only 1.4 m/s [3]. There were no reported wind installations in the country [3, 5, 7, 17], and no immediate plans could be found for future construction. While average wind speeds have been measured up to 6.6 m/s in the Ugoma mountains, it is uncertain how much wind energy is commercially viable in the DRC, especially with the abundance of other renewable sources available. Like nuclear energy, wind does not have much of a stake in the DRC's energy future and will mostly be ignored. There may be minimal applications for stand-alone turbines or micro-grids for residential systems, but the scarcity of wind energy in the DRC will also likely make it much more expensive than other off-grid technologies.

Hydro

The DRC has huge hydropower resources, and even though it accounts for more than 97% of the country's electricity supply [1, 3, 7], it is estimated that less than 3% (2760 MW) of the potential hydropower has been exploited in the DRC [3, 5, 6]. At least 100 GW of potential hydro capacity has already been identified in the country, with the possibility to produce more than 700 TWh/year [24], accounting for almost 8% of total global technical potential [25]. In particular, the Inga site on the Congo River has an estimated potential of more than 44 GW (more than twice the capacity of the world's current largest dam, the Three Gorges dam in China); however, less than 2 GW is currently being utilized [24]. The two largest dams in the DRC are both installed at the Inga site – Inga 1, built in 1972 with a capacity of 0.35 GW and Inga 2, completed in 1982 with a capacity of 1.4 GW [3, 25]. Both stations are struggling with maintenance and equipment failures, currently providing just over half of their rated installation capacities [26].

Many of the SNEL's hydropower stations are in poor condition and in need of repair or complete replacement (rehabilitation). Many of hydropower plants in the DRC are currently operating at less than 62% of installed capacity (Table 1). With more than 70% of hydro turbines in need of rehabilitation and an estimated cost of more than US$800 million, the DRC's current hydropower infrastructure is mostly out-of-date, inefficient, and costly. It also fails to cover much of the country, concentrated primarily in the West, where the capital of Kinshasa is located, and Southern regions, where mining continues to increase. Given the geography of the country, nationwide transmission would be difficult and expensive, but the economic potential of exporting over 500 TWh/year could more than make up for further investment into electricity transmission lines, especially to neighboring countries, providing an economic boost of more than US$5.7 billion per year [3].

There have also been numerous examples of private hydropower plants in the DRC in recent years, made much easier by the 2014 Electricity Law. A 10.5 MW hydropower project in the Kwilu province is being built for a total cost of $57.4 million, of which $42 million is funded by the Government of India (GOI). Another plant in the Kasai province, also being built with the GOI's assistance, will have a capacity of 64 MW at an estimated cost of $280 million, of which $250 million has been funded by the GOI [6].

The future projects are solely owned by Virunga Sarl, a company that constructs and operates hydro plants and distribution systems in the Virunga National Park area. The Virunga region has eight potential hydropower sites with an estimated potential of more than 100 MW. Only two of these sites, a 13.8 MW plant at Matebe and a 0.38 MW plant in Mtwanga, are currently operational, but a third site at Lubero is being developed with a capacity of 12.8 MW. The smaller Mtwanga plant supplies power specifically to a local soap factory and supports more than 400 jobs, but the company also offers incentive schemes for residential customers. High upfront costs have prevented extensive use, with only around 4000 customers, a frequent problem with the widespread poverty found in the DRC [6].

Public hydro infrastructure in the DRC is outdated and inefficient. The private hydro is too expensive for most of the population and there needs to be a better way to take advantage of its greatest resource. Similar to solar projects discussed previously, some form of public–private partnership seems to be the most promising development strategy. Since there is a major lack of funding and technical expertise in the country, both major causes of the degradation of the public hydro infrastructure, acquiring an outside owner–operator is the best option for the DRC. The private companies have a hard time selling the energy when they do invest, and purchase agreements with the national utility could provide the guaranteed income they are looking for.

The final plan for the Inga site, the Grand Inga dams, involves building five additional dams just west of Inga 1 and 2, for an additional capacity of 40 GW (Fig. 4). Inga 3 and Inga 4 have already been designed and Inga 3 was supposed to be completed in 2017 [3, 8], but after years of financial setbacks, instability, and corporate conflicts, it still remains to be built. In August 2020, a consortium of Chinese and Spanish companies was approved by the DRC government to continue with the building of Inga 3, now a combination of Inga 3 and Inga 4, which will have a capacity of more than 11 GW [27]. The cost is projected to be at least US$14 billion, and after the COVID-19 pandemic, some uncertainties have arisen. The DRC government is trying to implement the project in phases, as two separate dams as originally planned, but the Chinese companies have so far rejected the plan [27].

Table 1 SNEL's Public Hydropower Portfolio, 2020 [26]

Region	Hydropower Station	Year commissioned	Installed Capacity (MW)	Available Capacity Feb 2018 (MW)	Generators	Last Rehabilitation	Generators in need of Rehabilitation	Estimated Cost of Rehabilitation ($M USD)	Acquired Funding?
West	Inge 1	1972	351	227	6	2017	2	70	N
	Inge 2	1981	1424	830	8	Ongoing	6	248	Y
	Sanga	1932	12	0	6	Ongoing	3	n/a	Y
	Zongo 1	1955	75	31	5	None	5	187.5	N
	Zongo 2	2018	150	150	3	–	–	–	–
South	Nseke	1956	260	186.3	4	Ongoing	1	n/a	Y
	Nzilo	1952	108	100	4	None	4	125	Y
	Mwadingusha	1930	67.8	0	6	Ongoing	6	n/a	Y
	Koni	1950	42.1	36	3	Ongoing	2	37.5	Y
East	Ruzizi 1	1958	29.8	13	4	2011	3	51	N
Isolated	Tshopo	1955	19.7	12.65	3	2013	2	40	N
	Mobayi/ Mbongo	1993	11.4	3	3	None	3	25.2	Y
	Bendera	1959	17.2	0	2	Ongoing	2	n/a	Y
	Kilubi	1954	10.8	3	3	None	3	24	N
	Mpozo	1932	2.2	0	2	None	2	n/a	–

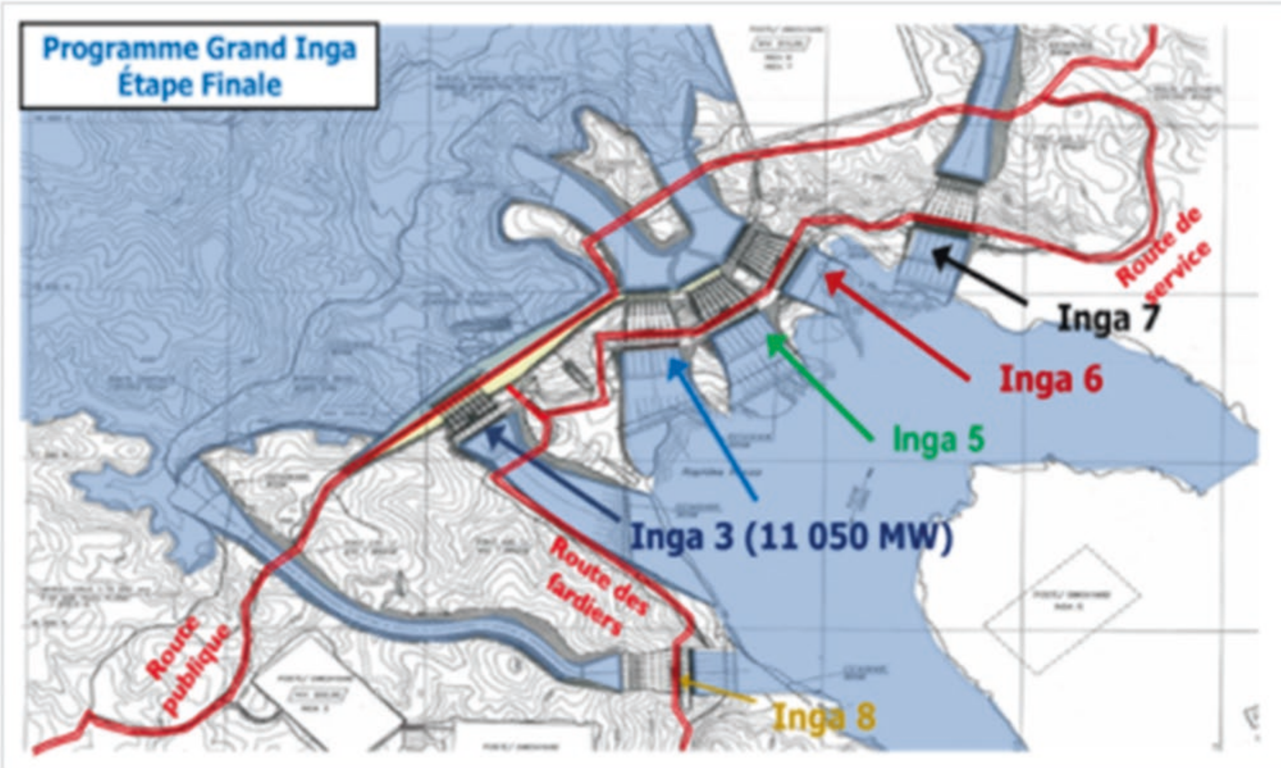

Fig. 4 DRC government plans for Grand Inga dams (Inga 3 and 4 have been combined as Inga 3) [25]

The remaining dams are designed to be built in a specific order, and construction cannot continue on any part of the Grand Inga while political and corporate interests collide. While a public–private partnership seems to be the best solution for both parties, conflicting interests have proved to be the primary obstacle to further hydro development in the DRC.

Ocean

With only 37 km of coastline, there is not much potential for any forms of ocean energy in the DRC [1]. Since 2011, there has been a Common Interest Zone agreement with Angola for the mutual development of offshore resources, not leaving much room for any future development of offshore energy sources. The only real use of the DRC's coastline is oil drilling, with Atlantic fishing accounting for less than 2% of total fish harvests in the country [28]. There are no current or future plans for the development of any ocean energy source, and it is unlikely the ocean will play any role in the DRC's energy future, beyond minimal sustained oil production.

Geothermal

The DRC currently has no reported geothermal power generation or consumption [5, 17], but the eastern part of the country contains a huge potential along the East African Rift, where volcanoes and active hot springs present a potential of at least 6500 MW [29]. The temperatures in the hot springs range from 35 to 90 °C, with flow rates anywhere from 11 to 162 L/s [3]. In 1952, a geothermal plant with a capacity of 0.2 MW was installed to support mining operations in the area, but was shut down soon after due to lack of maintenance [30].

More than 200 hot springs have been mapped in the DRC, but only around 30 have been investigated in-depth [31]. Without further exploration, it may be impossible to know the true potential of the DRC's geothermal resources, but the government has established the Comité de Pilotage pour le Développement des Ressources Géothermiques du Nord-Kivu (CPDRG), in hopes of reviving interest in geothermal energy and furthering both public and private development of geothermal resources [31]. The same volcanic activity that causes the natural methane production and storage in "Killer Lake" could also be used elsewhere in more direct energy applications, for both electricity and heating.

Biomass

Biomass is, by far, the most important energy source in the DRC, accounting for more than 90% of the country's total energy use, primarily in households for things like heating and cooking [5, 26]. Rainforests cover almost 67% of the entire country, and the wood and charcoal from those forests are the main source for primary energy in both rural and urban populations. These resources can be considered renewable, as long as they are responsibly managed – but that has failed to happen so far in the DRC. Although deforestation rates may be considered modest compared to the Amazon, the annual rate of tree cover loss regularly surpasses 1 million hectares/year. In 2019 alone, almost 500,000 hectares of primary forest disappeared, second only to Brazil for total deforestation that year [32].

While local agriculture and fuel collection are widely considered as the major driver for forest clearing in the DRC, more recently established activities like logging, mining, and commercial agriculture have yet to be accurately quantified [32, 33]. Small-scale clearing for agriculture was the largest direct driver, contributing to more than 80% of total forest loss; however, as mining and other economic activities increase with the demand for many of the minerals mined in the DRC, the exploitation of the forests is only expected to increase in coming years. What is even more challenging, the population of the DRC is expected to be almost 200 million people by 2050, potentially doubling local agriculture and fuelwood demands and further depleting the forest.

Only three small-scale biomass projects were identified in the DRC: the SNV, a non-profit from the Netherlands, runs four small diesel engines powered by palm oil, providing electricity to 72 households in Gemena; the Compagnie des Cultures de Binga runs a biomass power station fueled by palm oil by-products in the city of Binga, and finally the Sucrerie Kwilu-Ngongo runs a 9 MW biomass power station running on sugar bagasse in Kwilu-Ngongo [26]. While all three projects have found great success, identifying and producing any biomass than could be consistently supplied and mobilized limit the potential of any scale-up proportionate to electricity demand. The sugar mill could potentially increase sugar production for additional energy generation, but a lack of transmission lines going in and out of the sugar mill eliminates any benefit for an upgraded capacity.

There are significant biomass resources in the DRC, but given the threats already facing one of the most biodiverse habitats on Earth, it is just too risky to let the forests make up any part of the electrification efforts in the county. Traditional biomass is already vital to the DRC's population for cooking, and until conservation efforts can be put in place, any further exploitation of the ecosystem need to be mitigated. While the DRC also has solid potential for energy production strictly from forestry and agricultural waste, but there has never been any kind of study done, and there are currently no plans for the development of any kind of large-scale biomass projects. Biomass will continue to play a huge role in the DRC's energy consumption until access to both electricity and alternate cooking methods has expanded greatly, but economically and environmentally, biomass should have no role in the DRC's electricity future.

Biofuels

With the huge biomass resources available in the DRC, the potential for the development for biofuels is also immense. There are favorable conditions for many biofuel sectors, including oilseed crops (palm kernel, rapeseed, soybean, sunflower, etc.), sugarcane waste for the production of methanol/ethanol, and forestry and agricultural waste could be combined with an abundant supply of natural methane in Lake Kivu for the production of biogas [31]. Biofuels could provide a dramatic reduction in dependence on imported petroleum products, and even provide another economic export for the country, but should not be considered as a priority in the DRC's energy future, especially with the dangers that commercialized oilseed or sugarcane farming could do to the struggling forests in the country.

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

Although battery storage is common throughout the DRC, there are currently no large-scale energy storage installations in the country and no plans for any on the national level [25]. Private companies have expressed their intent to build energy storage alongside other projects, but there is no national electricity source, like major PV or wind installations, that would be improved with the use of any kind of energy storage. Moyi Power said it intends to build 40 MWh of battery storage connected to a 14 MW PV system [21], but no other plans for major installations could be found. The majority of energy storage is built into micro-grids or single-home PV units, but given that SNEL only has 500,000 connections, it is more than feasible that the DRC could be the first country where virtual grids surpass a physical one [34].

Country's Future Storage Direction

Between the size and geography of the DRC, the lack of any existing national electric grid, and a major lack of financing within the country, it is difficult to imagine a fully connected power grid in the DRC, leaving micro-grids to be the most likely option. The government's Modern Villages development program is already promoting the use of hydro-powered micro-grids [2], and it is clear that private corporations invest heavily in micro-grids, in favor of retaining primary control over all components [2, 6, 9, 26, 34]. Depending on the power source, battery storage might not even be useful or financially worthwhile for many off-grid systems, especially the increasingly common run-of-river micro-hydro stations [26, 34, 35], but could also provide stability to fragile grids across the country.

There may be a lack of energy storage within the country, but the DRC is key in maintaining the world's lithium–ion battery supply, accounting for over 70% of the total global supply of cobalt in 2019 [7]. Despite the high price of cobalt – over US$75,000/ton – we have yet to find an effective replacement for powering everything from phones to laptops to electric cars [36]. The DRC still contains more than half of the world's untapped cobalt sources, and until a replacement battery technology becomes widely accepted, mining is only bound to increase across the country [7, 36].

Other than limited battery storage, there are currently no other reported installations of wide-scale energy storage anywhere in the country, but then a huge investment in energy storage may not even be necessary or practical in the DRC. On a national level, the completion of the Grand Inga dams would give the country a huge supply of easily accessible energy storage. The construction requires the flooding of the Bundi Valley, forming a 22,000-hectare reservoir for the dams [37]. It may not be exactly the same as pumped hydro storage, but responsible control of such a huge reservoir could guarantee reliable electricity for decades to come. The latest design plan allows for independent phases to be run by separate operators, spreading out purchase agreements and priorities, and lowering the risk of corruption or misuse of such an expensive, and valuable, resource [25]. Flooding the valley could displace as many as 35,000 local inhabitants [37], but the potential social and economic gains from completing the project could very well justify any relocation programs required.

Energy storage, more specifically batteries, will likely play an important role in the electrification goals of the DRC, especially with the importance that localized micro-grids will most likely play in any development plans. They may not be useful for every application in the country, given the abundance of hydropower, but could provide much-needed stability to both urban and rural households, especially as small-scale solar PV modules penetrate energy markets across the DRC.

Carbon Footprint

Most Recent Carbon Output

Greenhouse gas (GHG) emissions – from carbon dioxide, methane, nitrous oxide, and fluorinated gases – are usually measured in tonnes of carbon dioxide equivalents (CO_2e), where "equivalent" means "having the same warming effect as CO_2 over a period of 100 years." In 2019, the country released more than 2.2 million tonnes CO_2e, which may seem like a lot, but accounted for less than 0.01% of total global emissions [38]. While the total carbon emissions have been sporadic, per capita GHG emissions have been almost halved to less than 2 tonnes per capita since 1990, even with the random spikes in output since then [38].

Historical Trends of Carbon Footprint

DRC has a very sporadic emissions record, ranging from less than 1 to almost 5 million tonnes CO2e, without an easy explanation as to why [38] (Fig. 5).

Electricity generation makes up less than 6% of the country's total emissions, due partly to the lack of electrification in the country, but mostly because over 98% of generated electricity comes from hydropower, a carbon-neutral resource except for the massive amounts of concrete required for construction [39]. Less than 150 tonnes CO_2e are emitted for every GWh of electricity generated in the DRC, much lower than the global average of 475 tonnes/GWh [40], another sign of an electricity sector dominated by renewables. If the DRC can continue to increase electricity production, emissions per unit energy will drop even lower since a large majority of planned capacity installations will be hydro or PV.

Types and Main Sources of Pollutants

Land-use change and forestry are the primary contributors to the country's GHG emissions, followed by agriculture and energy [39], with over 70% of total emissions just from forest lands, including land conversion and the burning of biomass obtained from the forest [41].

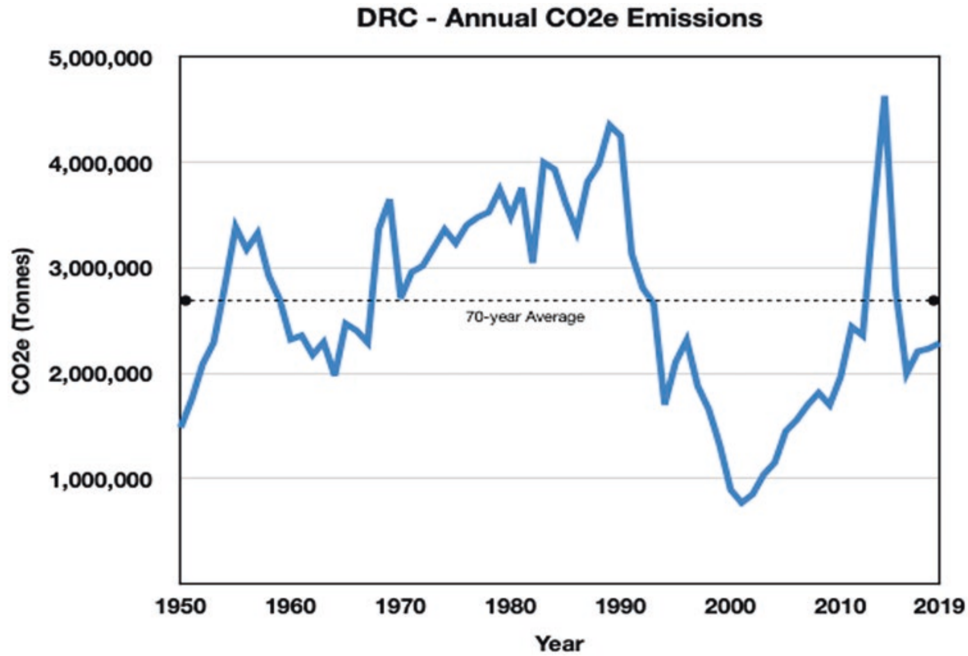

Fig. 5 Annual CO_2e emissions in the DRC [38]

Air Quality

Despite the small CO2e emissions from the DRC, the air quality is historically poor, due mainly to burning, mining and mineral processing, and forestry [42]. Particulate matter (PM2.5, PM10) makes up the majority of the pollutants throughout the DRC, with PM2.5 levels often rising more than 10× higher than the WHO recommended limit of 10 µg/m^3 [43]. Pollution levels this high can be extremely dangerous to at-risk individuals and should be considered a public health priority. Cleaner cooking methods, increased access to electricity, and better forest management can all drastically reduce air pollution, especially from biomass combustion [43].

Energy Resiliency

Electrical Grid

All aspects of the national electric grid are operated by the state-owned Société National d'Electricité (SNEL) and regulated by the Electricity Regulation Authority (ARE) since 2014 [2, 4]. The national grid was originally designed to supply only two major areas: the capital of Kinshasa in the western part of the country and the mining activities in the southern region [37]. Presently, three main subnetworks correspond to the geographical distribution of electricity-generating centers, with a direct connection between the south and the west – leaving the east mostly isolated, and the northern regions without any kind of organized grid [27, 36], with only 121 cities, towns, and villages being electrified by a national grid [37]. SNEL has just 500,000 registered connections, although the actual number of users may be much higher with 3–5 households connecting illegally for every formal customer, a practice that is encouraged by the fact that approximately 95% of SNEL customers are unmetered, only paying a flat monthly fee. Overall, it is estimated that less than half of the energy produced is actually monetized, contributing greatly to a lack of funding for repairs [34].

The West-Southern transmission grid was built to connect the capital with the Inga dams, now also servicing major urban and mining centers in the former province of Katanga in the south and distributes more than 90% of the country's entire generating capacity [26]. The main transmission network is made up completely of high voltage lines with a total length of 6937 km, including a 1827-km high voltage DC line running directly from the Inga power stations, with other transmission lines at 50, 70, 110, 120, 132, and 220 kV being used sporadically along the way [37]. The only other major grid is located in the eastern part of the country, covering most of the Kivu provinces, but the rest of the DRC is powered through isolated or stand-alone grids [26].

There are four total international transmission lines currently operating between the DRC and other SAPP nations, connecting to the Republic of Congo (Brazzaville) to the west, Zambia to the south, and Rwanda and Burundi to the east [26]. If the DRC hopes to develop its hydropower resources further, it will also need to invest heavily on upgrading and stabilizing the transmission network both locally and internationally. The transmission and distribution networks are both in poor condition, suffering from theft and a lack of maintenance – in fact, SNEL's poor infrastructure causes grid outages over 75% of the time [34]. Most of the grids were built during the construction of the associated power station, and many have not been touched since [26]. Additionally, the sheer number of illegal connections often overloads transmission lines, putting further strain on an already-fragile grid, and decreases the electricity supply quality that reaches registered customers [34]. The size, geography, and lack of funding in the DRC will make it extremely challenging to establish a stable national grid, and a stronger focus should be placed on isolated mini-grids and stand-alone systems to reach electrification goals in the country.

Climate and Natural Disasters

The DRC covers a huge amount of land, split by the equator, and experiences a wide variety of climates. The tropical rainforests that cover most of the country dictate the majority of the climate, keeping it hot and humid for most of the year. The DRC only has two real seasons, wet and dry – wet season is April to October north of the equator, but south of the equator is the exact opposite, with wet season running from November to March. Cooler and drier climates can be found in the southern highlands, and cooler, but wetter climates can be found in the eastern highlands [1].

While there are no recurring natural disasters, there is a history of almost all of them in the DRC. The DRC experiences infrequent, but violent, volcanic activity and earthquakes in the eastern region, tied to the East African Rift [31], but since 1990, floods have been the most devastating, followed closely by widespread epidemics that often sweep the country [44]. The rainfall common to tropical areas can put a major strain on local, underdeveloped infrastructure, and mismanagement of forest lands has only made flash flooding worse [45]. Other parts of the country are experiencing extended drought, and wildfires have started taking a noticeable toll on the population for the first time since at least 1960 [44]. Prolonged drought could lead to a drastic reduction in hydropower output, vital to the country's electricity supply, making the goal of widespread electrification even more difficult. It could also lead to an increase in biomass consumption and burning, inciting further damage to the local environment.

Despite the extremely small carbon footprint of the DRC, the country is the 12th most vulnerable country to climate change and the 5th least prepared [46], a combination that could prove disastrous in the future. Climate change impacts can already be seen around the country, with excessive heat waves, violent rain, soil degradation, a prolongation of the dry season, an increase of droughts during the rainy seasons, and floods. At our current rate of climate change, the DRC could see over 100% more dry days during the rainy season, average temperatures rise as high as 4 °C in some areas in the country, and a rapid increase in extreme weather events, including flooding, wildfires, and epidemics [46]. The DRC's vulnerability to climate change is only aggravated by extreme poverty, environmental degradation, and a low adaptive capacity [44], and it will be key to get pre-emptive infrastructure and policies in place to combat both the causes and effects of climate change.

Grid Resiliency

Climate change will clearly have an impact on electricity generation and transmission in the DRC, but the current condition of the grid is far more alarming – the lack of electrification is only the beginning of the problems facing the grid. Theft, vandalism, aging equipment, and failing safety measures all plague the national electric grid, and a lack of technical expertise makes it almost impossible to maintain. Overall, the infrastructure is in poor condition, with much of it being 50+ years old without ever receiving any major repairs or maintenance [37]. Failing infrastructure leads to major grid outages over 75% of the time [26], and a huge number of illegal connections overload transmission lines, causing further strain on the grid and decreasing the supply quality to registered, paying customers [34]. Of the more than 2600 kW of hydropower capacity currently installed, less than half is typically available due to aging infrastructure and a lack of maintenance of both the generating units and the transmission lines at many of the existing hydro plants [26, 34].

Poor electricity quality and reliability cause major problems for many industries and services that depend on electricity, including mining, healthcare, and technology businesses across the country. In fact, 1 out of 2 businesses identify electricity as a major constraint to growth and almost 9 out of 10 experience regular outages [26]. In the capital city of Kinshasa, peak demand is more than 1000 MW, but the network is currently limited to about 500 MW due to deterioration of the grid and capacity limitations on Inga 1 and 2. SNEL is forced to conduct daily load shedding to cope with the deficit, causing over 2/3 of power outages in the city [26]. Frequent and/or prolonged power outages can result in major economic losses and can make it difficult to attract and retain major businesses in industry, causing further economic damage down the line. Both residential and industrial demands are forecast to grow rapidly, but if the rising demand is not met with an equal increase in supply and major improvements to electricity infrastructure – from generation to transmission to distribution – electricity service is only going to deteriorate further [26].

Without a reliable grid, it will be extremely difficult to continue adding customers to reach electrification goals, and the DRC will never be able to exploit the full economic potential of its hydropower without stable connections to transmit the power through. Investments into the electricity sector in the DRC should focus heavily on strengthening the existing grid in order to improve electricity reliability and quality and be able to keep up with growing demand. Additionally, a national focus on education and upkeep of the electric grid should be a top priority, to avoid a similar deterioration in the grid in another 50 years. If the DRC hopes to make electrification rates almost 10× higher, there will need to be a workforce both large enough and knowledgeable enough to plan, construct, and maintain a much larger electric grid.

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

The DRC does produce a modest amount of crude oil, mostly on the small area of Atlantic coastal region, but there are currently no refineries in the country [1, 9]. Gasoline and diesel fuel make up more than 95% of the fossil fuel consumption in the country [1], primarily for transportation and diesel generators [9]. All development goals for the country call for major increases in economic activity, which will be accompanied by an increase in transportation demands, and therefore petroleum imports. The DRC also has no plan to take advantage of its wide range of biofuel sources [31], cementing a complete, increasing dependence on foreign fossil fuels.

There could be substantial economic benefits from building a small refinery somewhere in the country, preferably close to reserve sites to mitigate any environmental risk. The DRC already produces and exports more than enough crude oil to meet their own demands [1] and could easily increase production as demand increases. Many of the smaller nations surrounding the DRC also lack modern refineries, and local production of refined petroleum products could provide the DRC with another exportable commodity [9], while heavily reducing its dependence on foreign fossil fuels. Combined with an infrastructure plan for sustainable production of biofuels from agriculture and forestry waste, the DRC could obtain energy independence in all energy sectors.

Relations with Global Community/ Socioeconomic Influence

The DRC is a part of numerous international organizations, including the African Union, the United Nations (UN), the International Monetary Fund (IMF), the World Bank, and the World Health Organization [47]. The country is closely allied to other South African nations as a member of the South African Development Community (SADC) and the South African Power Pool (SAPP). While internal conflict has been limited since at least 2006, there has been continuing problems with spillover conflict from Rwanda, Uganda, and Sudan, predominantly in the eastern parts of the country [26]. The country has a long history of conflict with opposing ethnic groups in Rwanda, stemming from the 1994 genocide in Rwanda, eventually leading to the First and Second Congo Wars, sometimes known as the "African World War." The war officially ended in 2003, but conflict has continued unchecked as Rwandan, Congolese, and UN peacekeeping troops have failed to defeat rebel Rwandan forces [48]. Today, this conflict is fairly localized in the eastern regions, but still plays a major role in the lack of stability and economic activity in the DRC.

The DRC ratified the UN Framework Convention on Climate Change in 1997, the Kyoto Protocol in 2005, and the Paris Agreement in 2015 [39]. The country's Nationally Determined Contribution (NDC) conditionally pledges a 17% reduction in greenhouse gas emissions from 2021 to 2030, dependent on at least $21.6 billion in external financing [39, 41]. The DRC received more than US$621 million in aid from the US government [48] and over US$3 billion in total global aid in 2019 alone [49] – more than 6% of the country's GDP. There is a lot of work to be done repaying international relationships, but improving electrification and increasing economic activity could lessen the burden of the DRC to foreign entities and improve existing relations, or possibly even forge new ones.

Education

No type of specific renewable energy program could be found in the DRC; however, the largest electrical engineering program in the country, located at the University of Kinshasa, requires six hydropower classes [50], most likely due to its dominance in generation throughout the country. The country's low electrification rates have prevented any extensive implementation of energy education on a national level, with only two major universities currently investing in electrical engineering programs [50, 51].

More locally, a small vocational program, École du bâtiment professional (EPROBA) bought a solar energy system in 2014, and has since been using it to train new students how to install and maintain small solar systems across the country [52]. Beginning in 2020, environmental education is also now required to be included in primary school programs across the country, aiming to help inspire children in the fight to protect the environment [53], but education about the environment cannot stop after primary school. In order to take full advantage of its renewable energy potential, the DRC needs to seriously and deliberately invest in technical education programs for its youth and vocational programs for other working adults. Otherwise, public–private partnerships will be the only way the DRC is able to meet both electrification and economic development goals – eliminating most of the country's control over its resources and economic future.

Summary

Current Energy Situation

The DRC currently ranks only #106 globally in electricity production and consumption and is one of the lowest in electrification rates at only 9% of the population. Due to both the size of the country and the terrain, most of the country remains unconnected to a common grid and will most likely remain that way for the foreseeable future. Renewable energy sources have historically made up more than 99% of the total energy supply, with hydropower accounting for over 98% of the generating capacity. Fossil fuels make up most of the remaining energy supply, primarily as gasoline and diesel for transportation.

Electricity consumption has been increasing rapidly in recent years, due mainly to the increase in mining activities in the country. A sharp increase in demand for access to electricity that has gone largely unrecognized also threatens to drastically increase residential demand across the country. Presently, the grid comprises three main subnetworks, with a direct connection between the south and the west of the country, leaving the east mostly isolated and the northern regions without any kind of organized grid. Theft, vandalism, aging equipment, and failing safety measures all plague the national electric grid, and a lack of technical expertise makes it almost impossible to maintain. Failing infrastructure leads to major grid outages over 75% of the time and a huge number of illegal connections overload transmission lines. Of more than 2600 kW of hydropower capacity currently installed, less than half is typically available, also due to aging infrastructure and a lack of maintenance.

Future Energy Situation

Despite the major challenges currently facing the DRC's energy sector, the renewable potential in the country is enormous. Well-planned and properly developed hydropower could be the key to meeting electrification and development goals, both nationally and throughout South Africa. There is more than 100 GW of possible capacity already mapped out across the country, and fully exploiting this resource could help provide a much-needed boost in economic activity. The Grand Inga dams could produce more than enough power for any increased demand in all the country's largest metropolitan areas, and neighboring countries have already expressed their interest in buying any remaining power.

There is also huge reserves of oil and natural gas in the country, with Lake Kivu actively creating a sustainable, easily accessible supply of natural methane. The oil is going to be exploited eventually, and with the addition of a refinery, the established production could easily cover the nation's consumption. Natural gas-powered thermal plants could provide quickly dispatchable generator sources in heavily populated areas and also sustain the electricity supply if climate change significantly affects hydro output in the future. It could even be used during downtimes to export even more energy to neighboring countries, especially in the eastern part of the country which the future Inga dams will most likely not supply.

Additionally, there is also a huge potential in solar PV to supply a significant portion of the country's electricity demand, especially for industrial and mining applications, and in many areas that are unlikely to ever be connected to a national grid. Given the size and geography, mini-grids and stand-alone PV systems hold the greatest potential to reach the DRC's electrification goals and added battery storage could add some much-needed reliability to the grid.

Electricity demand is expected to rise in urban and rural households, along with increases in industrial and mining activities, and the DRC needs to be just as focused on rehabilitating the grid as it is on increasing capacity. Looking even further into the future, there needs to be national initiative to train a domestic workforce to repair and maintain the energy infrastructure, from generation to transmission to distribution. If forced to rely too greatly on private partnerships, the DRC will fail to reap much of the economic benefit from the vast stockpile of energy resources located throughout the country. Electricity access may be one primary in many of the development goals for the region, but the country should also make their future interests a priority in any major construction or infrastructure plans.

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Egypt

Slobodan Petrovic and Andrew Boules

National Energy Introduction

With more than 100 million people, Egypt is the largest country in the Arab World in terms of population. Egypt's rapid population growth has posed a seemingly insurmountable energy challenge to the Egyptian leadership. This challenge manifested itself after the 2011 political uprising in long vehicle lines at gas stations and rolling power blackouts due to insufficient electricity generation capacity, especially in the summer, when cooling energy demand is at its highest. This triggered successive Egyptian governments to take corrective actions. For example, long-standing massive energy subsidies are now being gradually phased out and large investments are being pumped into increasing traditional and renewable power generation capacity. In 2022, Egypt's generation capacity is almost twice its peak load, prompting another problem: an electricity oversupply.

The discovery and development of the massive Zohr natural gas field off the Egyptian coast in the Mediterranean Sea has expanded available energy resources and even turned Egypt from a natural gas net importer to a net exporter.

By operating the Suez Canal, Egypt plays a key role in global energy resource transit. It is estimated that 9% of the world's seaborne oil and 8% of global liquefied natural gas flowed through the Suez Canal and SUMED (Suez-Mediterranean) pipeline in 2017 [2]. When the Suez Canal was blocked for 6 days in March 2021 by a stuck container ship, there were serious concerns about soaring energy prices worldwide.

In 2020, Egypt was Africa's largest non-OPEC oil producer and the second largest natural gas producer in the continent after Algeria. Egypt mainly relies on fossil fuels to meet its energy demand, with more than 90% of electricity generation coming from oil and natural gas. In fact, Egypt is the largest consumer of fossil energy in Africa, with 22% of the continent's petroleum and other liquids consumption and 37% of dry natural gas consumption in 2016 [3]. In addition to fossil fuels, Egypt also possesses significant renewable energy resources, mainly hydroelectric, wind, and solar. Furthermore, Egypt is implementing a program for nuclear electricity generation in collaboration with Russia.

Energy Policies

Egypt has had to deal with mountainous energy challenges over the past decade due to high fuel subsidies, growing population, decreasing fossil fuel production and political and social unrest. As of June 2014, Egypt owed about $7.5 billion to foreign oil and gas companies [1]. Gulf countries such as Saudi Arabia and the United Arab Emirates have been providing large energy aid to Egypt in the form of financial aid as well as fuel supplies. Realizing that relying on foreign aid to alleviate energy strain is not a sustainable solution, the Egyptian leadership has taken a number of steps to turn the energy scene around. Following a $12 billion loan program with the International Monetary Fund that started in 2016, the Egyptian government has pledged to end fuel subsidization within 3 years and halve electricity subsidization by 2020. The price of one liter of 92-octane gasoline rose from about $0.33 in 2010 to about $0.54 at the time of writing this report. Fuel prices are now reviewed on a quarter-annual basis and are changed based on global market prices. The government has been steadily increasing electricity prices for residential, commercial, and industrial sectors since 2016 and is planning to completely abandon electricity subsidization by the fiscal year 2024–2025 [4].

The Egyptian government announced a new strategy to promote renewable energy (RE) in February 2008. The strategy had an ambitious goal of generating 20% of total electricity from renewable sources by 2022, and 42% of total electricity generation by 2035 [5]. Wind energy was supposed to generate 12% of total electricity. One-third of the planned RE capacity would be state-owned and financed by both the government through the New and Renewable Energy

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Agency and international financing institutions. Two-thirds of RE capacity would be private sector projects, supported by a three-phase policy [1]:

- Phase One: competitive bids to complete RE projects from private sector are solicited through the issuance of tenders under a build, own, operate (BOO) scheme [6].
- Phase Two: Feed-in Tariff (FIT) is implemented, mainly for small-scale and medium-scale projects.
- Phase Three: investors are allowed to build and operate their own RE plants to satisfy their energy needs or sell electricity to other customers through the national grid.

In October 2014, a new presidential decree approved the issuance of fixed feed-in tariffs for solar and wind projects; tariffs are valid for 25 years for solar projects and 20 years for wind projects [1]. Tariffs would be adjusted when the following limits are reached: 300 MW of small PV (less than 500 kW), 2000 MW of medium PV (500 kW–50 MW), and 2000 MW of wind. Tariffs are paid according to plant capacity [1]. By the end of 2019, the Egyptian Electricity Transmission Company (EETC) finalized Power Purchase Agreements (PPAs) under the FIT program for 1465 MW of solar PV (32 solar plants in Benban Solar Park in Southern Egypt) and 500 MW of wind energy [6].

Egypt has adopted an aggressive approach to expand its conventional electricity generation capacity. In October 2018, the country completed the construction and grid connection of three massive combined-cycle power plants with a total capacity of 14.4 GW (4.8 GW each) in a record time of 27.5 months, boosting total generation capacity by about 40% in slightly over 2 years [7, 8].

In April 2014, the government approved the use of coal for industrial purposes, sparking heated debate on the potential negative environmental effects. Coal is mainly used as a source of energy for the cement industry, since cement plants are energy-intensive and were occasionally cut off from energy supply to preserve natural gas for power generation [1].

In September 2018, Egypt signed a deal with a Chinese energy consortium and an Egyptian construction company to build what was going to be the second largest coal-fired power station in the world (6 × 1100 MW). However, the Egyptian government announced in February 2020 that the plan would be indefinitely postponed and renewable energy projects would be pursued instead [9, 10].

Although Egypt has considered the use of nuclear energy since the 1960s, it was not until 2015 that the Egyptian government signed an agreement with the Russian corporation Rosatom to build four 1200-MW nuclear plants in Dabaa in northern Egypt. In February 2021, Egyptian and Russian officials reported that the COVID-19 pandemic slowed down project preparations and that a construction permit for the first plant is expected to be issued in July 2022 [11].

Egypt announced a National Energy Efficiency Action Plan (NEEAP) in 2012 with the target of reducing energy consumption by 5% between 2012 and 2015 compared to the average energy consumption of the preceding 5 years. However, no designated agency was tasked with the formulation, adoption, and implementation of energy efficiency measures and policies. In addition, the plan was hindered by the lack of a general legal framework for enforcement of energy efficiency measures, the lack of an overarching energy efficiency strategy and the lack of follow-up. Although energy efficiency codes for residential buildings, commercial buildings, and governmental buildings were mandated in 2006, 2009, and 2011, respectively, those codes are seldom implemented or enforced. Some energy efficiency measures were taken such as the enforcement of minimum energy standards and mandatory labeling schemes for electrical appliances and the distribution of solar heaters and compact fluorescent lamps [12].

In 2018, Egypt announced a second National Energy Efficiency Action Plan (NEEAP II, 2018–2020) to address the shortcomings of the original plan [13].

Trends in Generation Technologies

Egypt's energy generation is characterized by 90% of generation coming from gas, steam, and combined-cycle systems (Fig. 1).

Figure 1 shows Egypt's installed energy generation capacity in mid-2020.

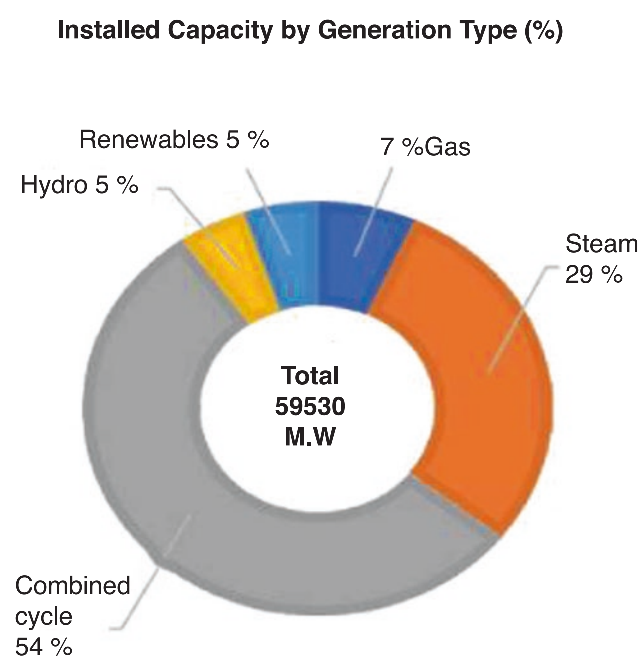

Fig. 1 Breakdown of installed capacity by technology as of June 30, 2020 [6]

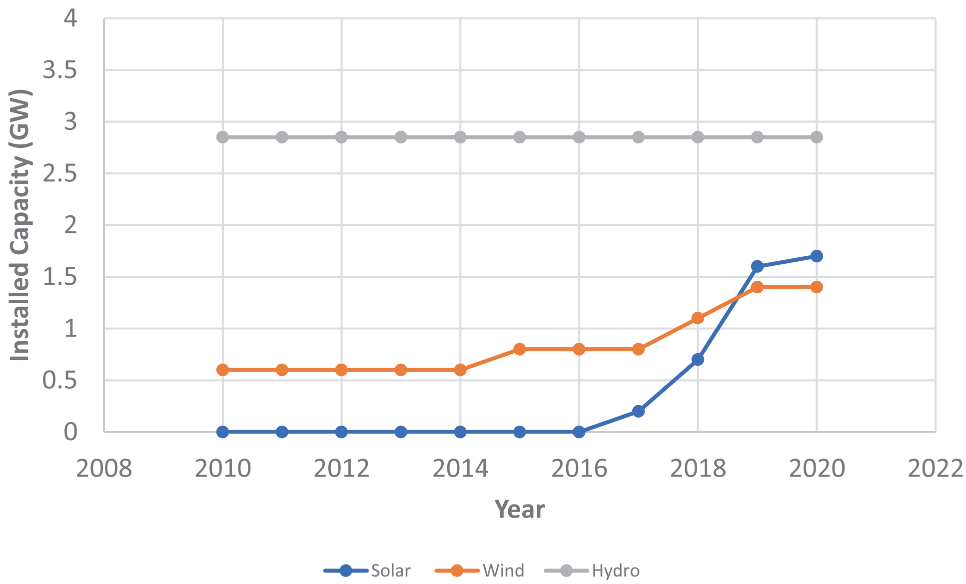

Fig. 2 Development of hydro, solar, and wind generation capacity from 2010 to 2020. (Data from Refs. [14, 33])

The world has been attempting to break away from fossil fuel and further the use of renewable energy, and Egypt has been no exception. Over the last 20 years, there has been a strong emphasis on expanding the utilization of the country's renewable resources. In 2008, the government announced a target of generating 20% of electricity from renewables by 2022.

Although the government invested heavily in adding solar and wind capacity, renewable capacity still accounts for a small fraction of the total capacity (Fig. 2). Due to enormous parallel investments in fossil-fuel power plants, for example, 14.4 GW of combined-cycle capacity was added in less than 3 years between 2015 and 2018. In 2020, renewable energy capacity accounted for about 10% of the 60 GW total installed capacity (3 GW of hydro, 1.7 GW of solar, and 1.4 GW of wind). Only 12% of energy was generated by renewables (8% hydro, 2% wind, and 2% solar) [38]. It is unlikely that the target of generating 20% of energy from renewables will be met in 2022.

Figure 2 shows that the government has heavily invested in increasing its solar and wind generation capacity in the last 10 years. PV generation capacity went from virtually non-existent in 2016 to close to 1.7 GW in 2020. Also, wind generation capacity increased by more than 100% from 2014 to 2020. Hydro generation capacity has been fully utilized with little room for further development.

Egypt plans to increase renewable generation to 42% of generated energy by 2035, with solar PV and wind spearheading renewable generation (Fig. 3). It is expected that Egypt's renewable generation capacity will increase from 6 GW in 2021 to about 10 GW in 2026.

Domestic Resources

Egypt possesses extensive fossil fuel resources. According to the US Energy Information Administration (EIA), Egypt is Africa's largest non-OPEC oil producer and third largest dry natural gas producer after Algeria and Nigeria [1]. Egypt mainly relies on fossil fuels to meet its energy demand, with more than 90% of electricity generation coming from oil and natural gas. In fact, Egypt is the largest consumer of fossil energy in Africa, with 22% of the continent's petroleum and other liquids consumption and 37% of dry natural gas consumption in 2016 [3]. In addition to fossil fuels, Egypt also possesses significant renewable energy resources, mainly hydroelectric, wind, and solar, which contribute to about 10% of total electricity generation. Hydroelectric power alone accounted for about 7% of total electricity generation in 2016 [3]. Furthermore, Egypt is implementing a program for nuclear electricity generation in collaboration with Russia.

History of Energy

The use of electricity in Egypt dates back to 1893. Electricity was entirely supplied by private owners for almost 70 years until President Gamal Abdel-Nasser nationalized private companies in 1962. From the beginning of electricity use in Egypt until nationalization, private owners had built about 3000 MW of generation capacity. Nationalization meant the government was the sole owner of electricity generation and distribution companies. That changed in 1996 when a law

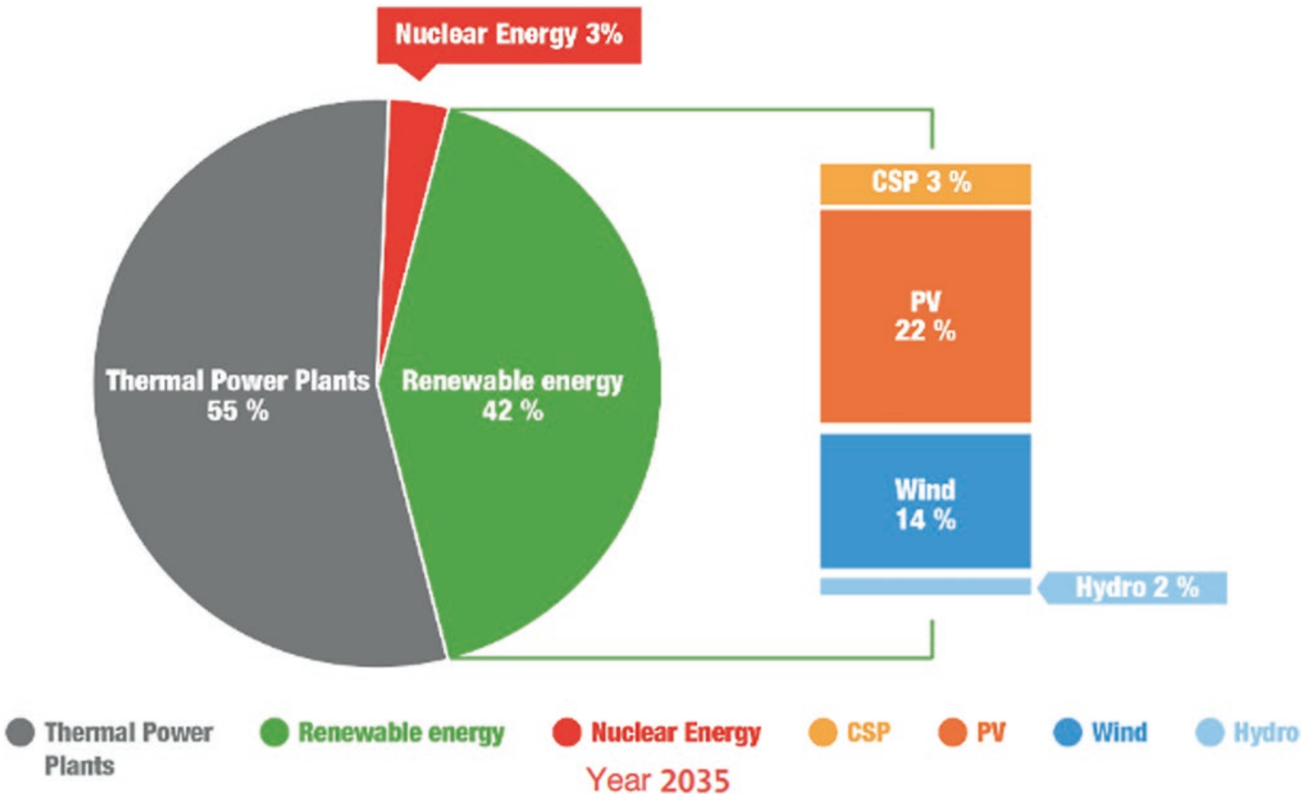

Fig. 3 Egypt's renewable energy targets for 2035 [25]

allowing local and foreign investors to build, operate, and maintain power stations was passed.

Fossil fuel exploration efforts in Egypt commenced more than a century ago. Oil exploration in Egypt began in 1908, although significant discoveries were not made until the 1970s. Oil production peaked in the 1990s and Egypt was a net oil exporter. In 2010, however, Egypt turned into a net oil importer due to increased consumption as well as decrease in new discoveries and maturing fields.

Early natural gas discoveries were made in the late 1960s. In 2015, the discovery of the giant Zohr natural gas field in Egyptian territorial waters in the Mediterranean Sea drastically changed the energy scene in Egypt and the Middle East. With an estimated 30 trillion cubic feet of reserves, the field has turned Egypt into a net natural gas exporter and is believed to be capable of delivering all of the country's natural gas needs for decades to come.

Egypt is among the first countries to utilize renewable energy. Heron of Alexandria designed the first windmill in Roman Egypt in the first century, the first known attempt of harvesting wind energy. In 1910, an industrial-scale solar thermal system was built in Maadi, Cairo, for operating irrigation water pumps. By the end of 2020, Egypt's solar PV and wind generation capacity were about 1.6 GW and 1.4 GW, respectively.

Breakdown of Energy Generation "Mix"

Energy Generation Mix

Egypt's electricity generation is dominated by fossil fuel. Figure 1 shows that as of June 30, 2019, fossil fuel technologies (gas, steam, and combined cycle) accounted for 91.4% of electricity generation capacity. Of the fossil fuels used for electricity generation, natural gas is the most used fuel. In the fiscal year 2018–2019, natural gas accounted for 92.8% of fossil fuel consumption for electricity generation. Heavy fuel oil and light fuel oil accounted for the rest [6]. Figure 1 also indicates that about half of renewable electricity generation capacity is hydroelectric (Aswan High Dam Hydroelectric Power Plant). The other half is mainly generated by solar and wind.

Energy Consumption Mix

Figure 4 shows that out of a total primary energy consumption of 3.65 exajoules in 2020, fossil fuels accounted for 94% of that consumption [14]. It should be noted that energy consumption from non-fossil resources is calculated based on an input-equivalency basis; the amount of fuel that would be required by thermal power stations to generate the same

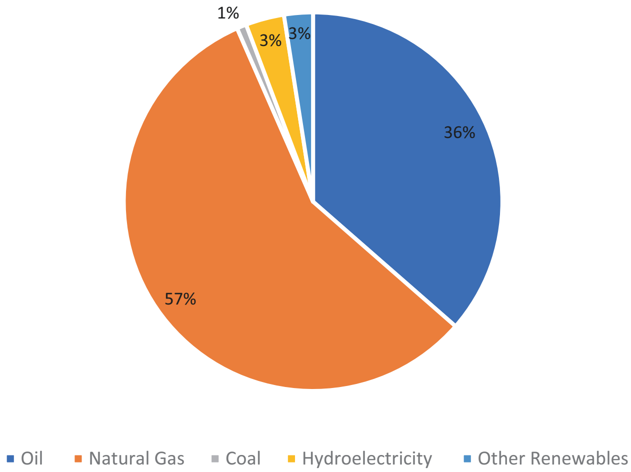

Fig. 4 Breakdown of primary energy consumption by fuel, 2020. (Data from Ref. [14])

amount of electricity [14]. It can be shown that natural gas is the most consumed fossil fuel and is used for more than 90% of conventional electricity generation. Also, natural gas is used in numerous industries such as steel and fertilizers. Oil consumption accounted for roughly one-third of total primary energy consumption in 2020. Oil is mainly consumed by the industrial and transportation sectors.

Renewables accounted for 6% of total primary consumption, half of which came from hydro and the other half came from solar and wind.

It is worth noting that although Egypt's primary energy consumption grew by an average of 2.3% per annum from 2009 to 2019, the consumption shrank by 5.8% in 2020 compared to 2019 [14], highlighting the negative impact of the COVID-19 pandemic on the economy.

In 2020, Egypt's per capita primary energy consumption was 35.7 gigajoules, compared to 265.2 gigajoules in the United States.

Table 1 shows the final energy consumption of various energy sources in 2017 in kilo tonnes of oil equivalent (ktoe).

Fossil Fuels

Oil

The search for oil resources in Egypt began as early as in 1908, although significant discoveries were not realized until the mid-1970s. Egypt became an important oil producer in the 1980s. However, total production was small compared to other Middle Eastern countries such as Libya, Saudi Arabia, and Kuwait. The vast majority of the country's production comes from fields in the Gulf of Suez and the Western Desert. Exploration and production activities are carried out in collaboration with major European and American companies [15].

Table 1 Final energy consumption of various sources in 2017

Source	Final consumption (Ktoe)
Oil	37,028
Natural gas	21,960
Electricity	13,630
Coal	224

Data from Ref. [1]

Table 2 Proven oil reserves in Egypt

End of 2000	**3.6** thousand million barrels
End of 2010	**4.5** thousand million barrels
End of 2020	**3.1** thousand million barrels
2020 share of global total	**0.2%**
2020 reserve/production ratio	**14**

Data from Ref. [14]

Table 2 shows that proven reserves declined by about 1.4 thousand million barrels from 2010 to 2020. In addition, Fig. 5 shows a steady decline in production from 2015 to 2020. These declines in reserves and production are the result of lack of new discoveries and maturing oil fields [17].

Egypt's production reached a peak of around 900,000 barrels per day in the 1990s and was a net exporter of oil. In 2010, production fell to just over 700,000 barrels per day, as shown in Fig. 5. Drop in production, coupled with an increase in consumption (estimated at 3% per year between 2005 and 2015) due to rapid population growth and increased economic activity, turned Egypt into a net oil importer in 2010 [1]. Figure 7 shows that with the exception of 2011, Egypt has been suffering from a net oil deficit (production is less than consumption) in the last 10 years. Figures 6 and 7 show the effect of the COVID-19 pandemic on production and consumption, respectively. In 2020, production plunged to less than 620,000 barrels per day, on average, and consumption dropped to about 650,000 barrels per day, on average. Production reached 556,440 barrels per day in December 2021 [16].

Figure 6 shows that oil consumption has been steadily declining since 2016. This could be explained by two main factors. First, there is a national trend to use more natural gas and less oil for electricity generation, especially after the discovery of the major Zohr gas field in 2015. Second, fuel subsidy reforms have encouraged businesses and individuals to be more prudent with their fuel consumption.

Coal

Coal plays a marginal role in the Egyptian energy scene. Egypt's coal reserves are estimated at 21 million tons, most of which is located in Sinai [21]. This is a minuscule amount compared to the total global reserves of 1074 billion tons [14]. Figure 4 shows that coal accounted for only 1% of

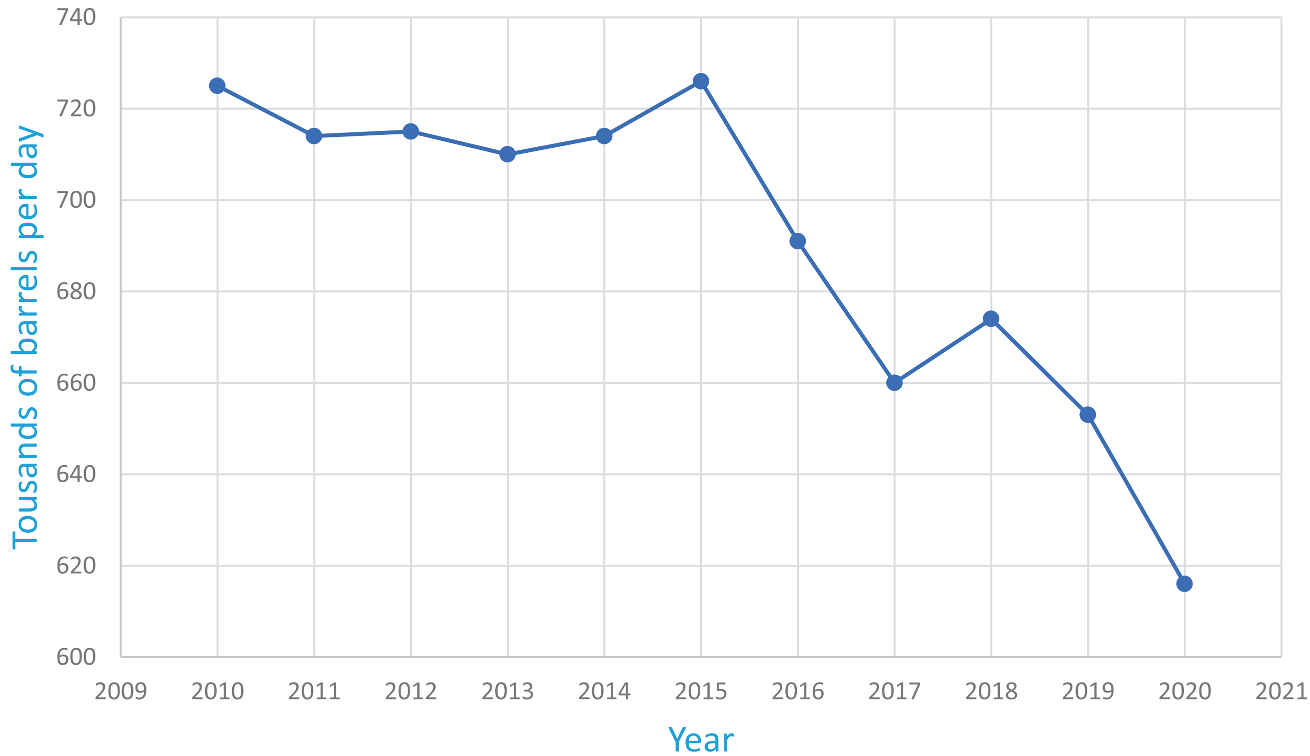

Fig. 5 Egypt's oil production from 2010 to 2020. (Data from Ref. [14])

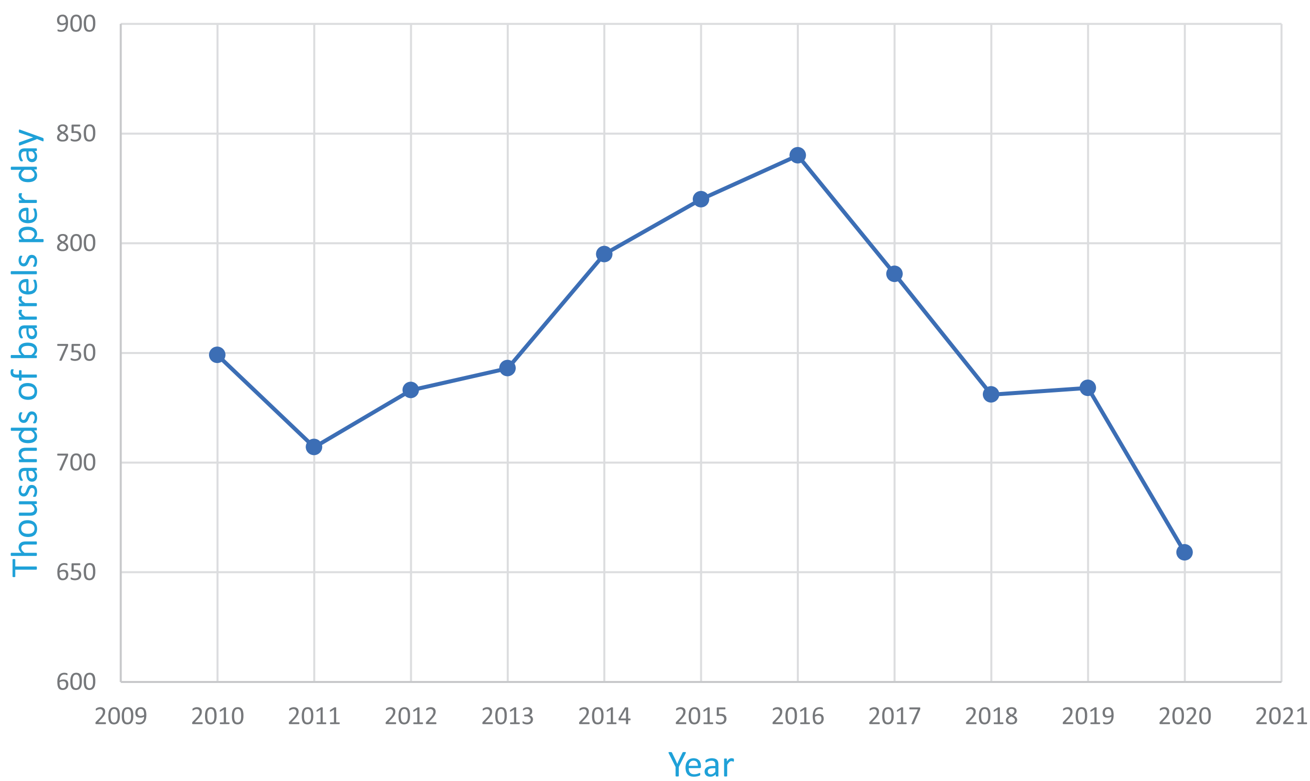

Fig. 6 Egypt's oil consumption from 2010 to 2020. (Data from Ref. [14])

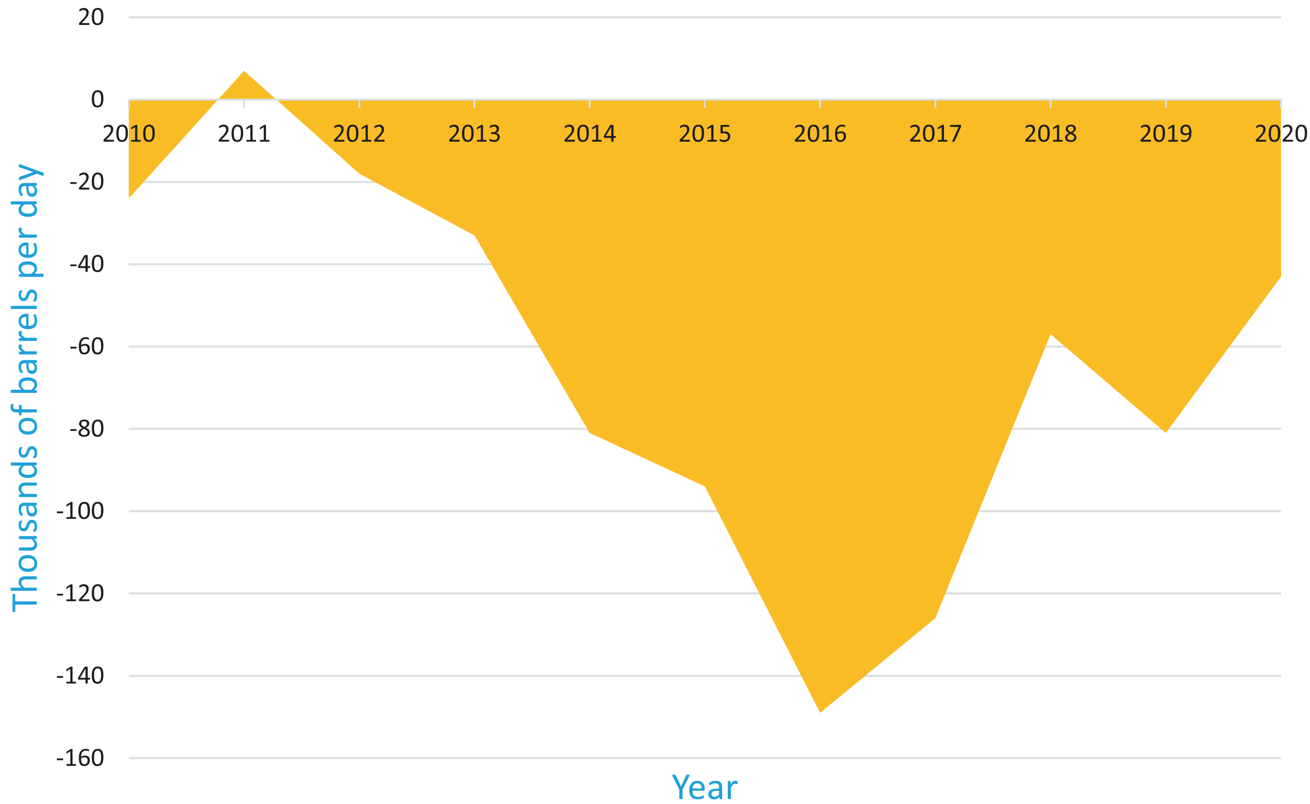

Fig. 7 Egypt's oil surplus (+) or deficit (−) from 2010 to 2020. (Data from Ref. [14])

Egypt's primary energy consumption in 2020. As of the time of writing this report, there is no operational coal-fired power plants in Egypt. Egypt's coal production fell from 64 thousand short tons in 2000 to zero short tons in 2019 [22], meaning that all of Egypt's coal needs have to be imported. In 2019, Egypt imported 6.32 metric tons of thermal coal [23]. Cement industry is the main coal consumer.

The marginalization of coal as a source of energy resulted from a national policy that favors natural gas and renewable energy for new power plants. According to the Ministry of Electricity and Renewable Energy, a planned coal power plant in Oyoun Moussa, Suez, will be replaced with solar and wind power plants. In addition, plans to construct a 6 × 1000 MW coal-fired power plant in Hamrawein in the Red Sea governorate were postponed. A final decision regarding that plant will be made based on the development of future loads [6].

Natural Gas

By the end of 2020, Egypt's proven natural gas reserves stood at 2.14 trillion cubic meters (75.5 trillion cubic feet), accounting for 1.1% of global proven reserves. At a total production of 58.5 billion cubic feet in 2020, reserve to production ratio is 36.6 [14], meaning that current proven reserves will suffice for over 36 years at 2020 production rate.

In 2015, the Italian oil and gas operator, ENI, discovered the Zohr gas field in the Mediterranean Sea. With an estimated 30 trillion cubic feet of reserves, the field is believed to be the largest-ever gas discovery in Egypt and the Mediterranean Sea. Production from the field commenced in 2017 and reached 2.7 billion cubic feet per day in August 2019 [18]. The field is large enough to supply Egypt with all of its natural gas needs and nearly two-thirds of its energy needs for decades to come, as well as turn the country from a net gas importer to a net gas exporter [19]. Figure 8 shows that in the last decade, production reached a trough in 2016 before reaching a peak in 2019 after production from Zohr field was ramped up.

Figure 9 shows that consumption increased significantly over the latter half of the past decade. This can be explained by increased power generation capacity, mainly reliant on natural gas, and increased industrial activity. Figure 10 shows that Egypt turned into a net natural gas importer in 2014, due to drop in production. It can be shown that natural gas deficit lasted until 2018, when Egypt turned into a net exporter again. This can be explained by the increased production after Zohr field discovery and development.

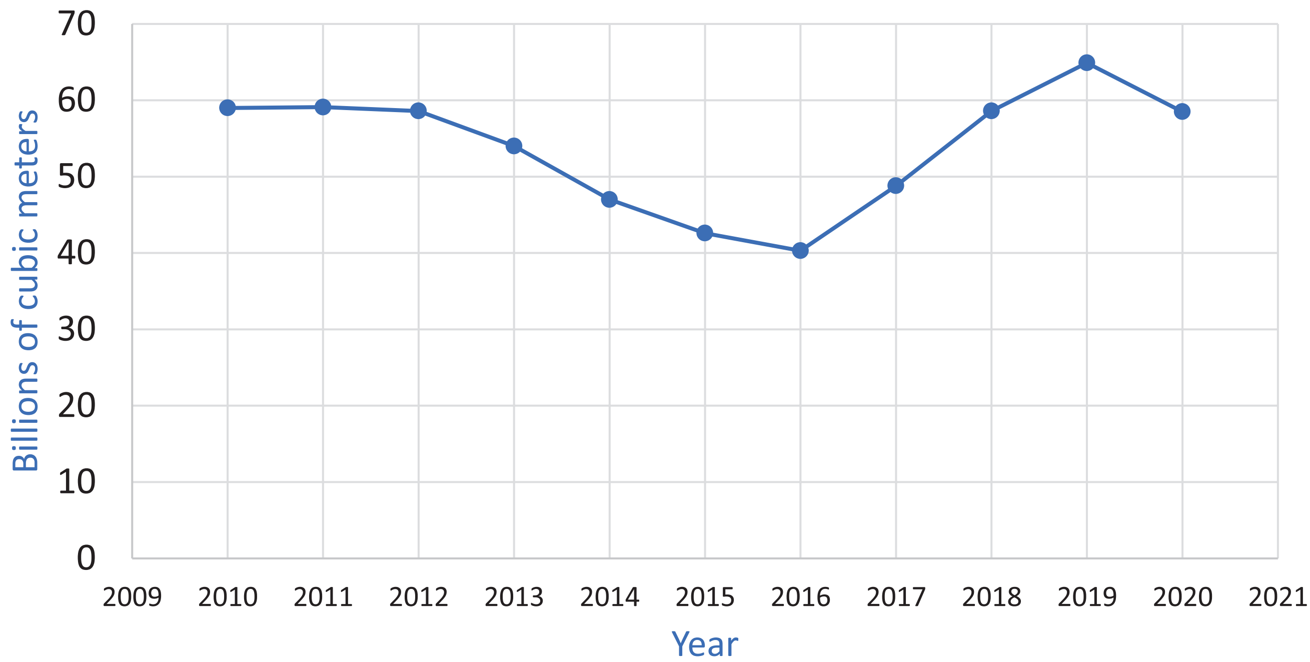

Fig. 8 Egypt's natural gas production from 2010 to 2020. (Data from Ref. [14])

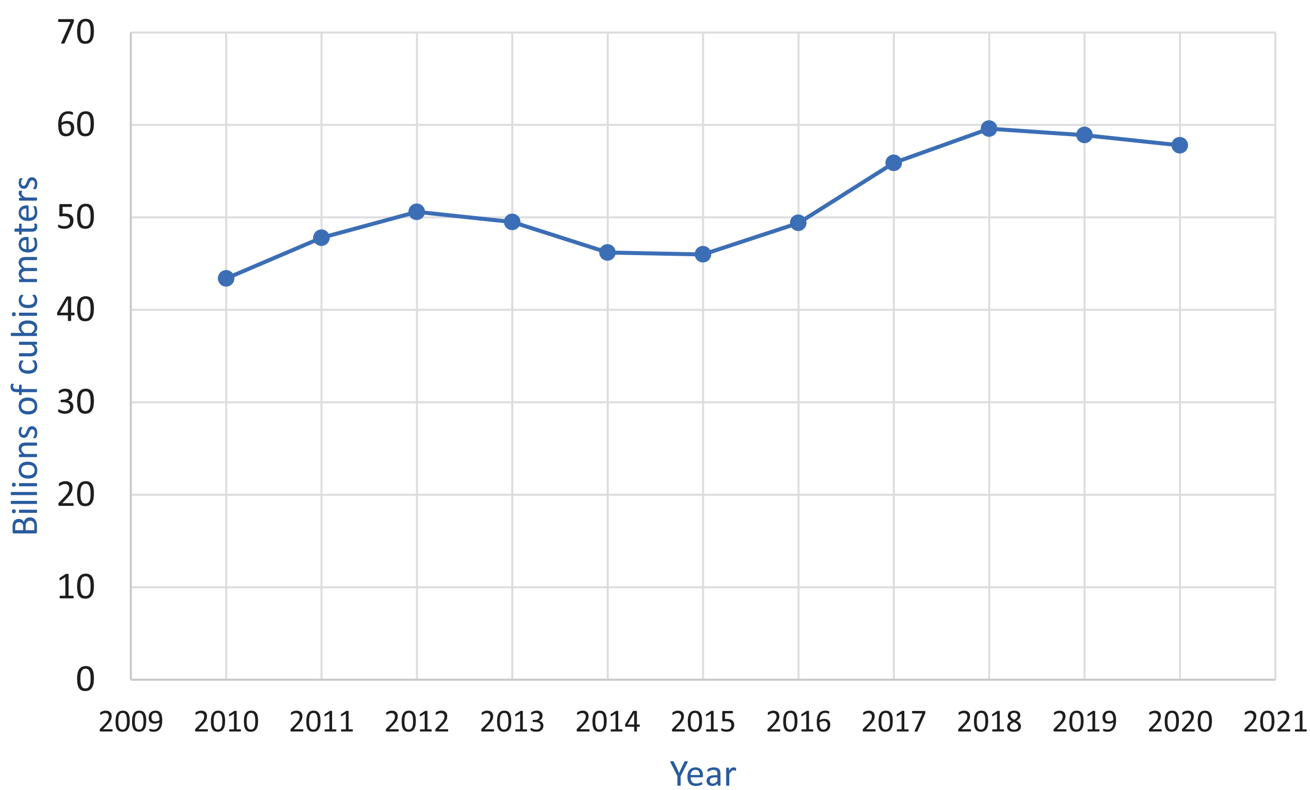

Fig. 9 Egypt's natural gas consumption from 2010 to 2020. (Data from Ref. [14])

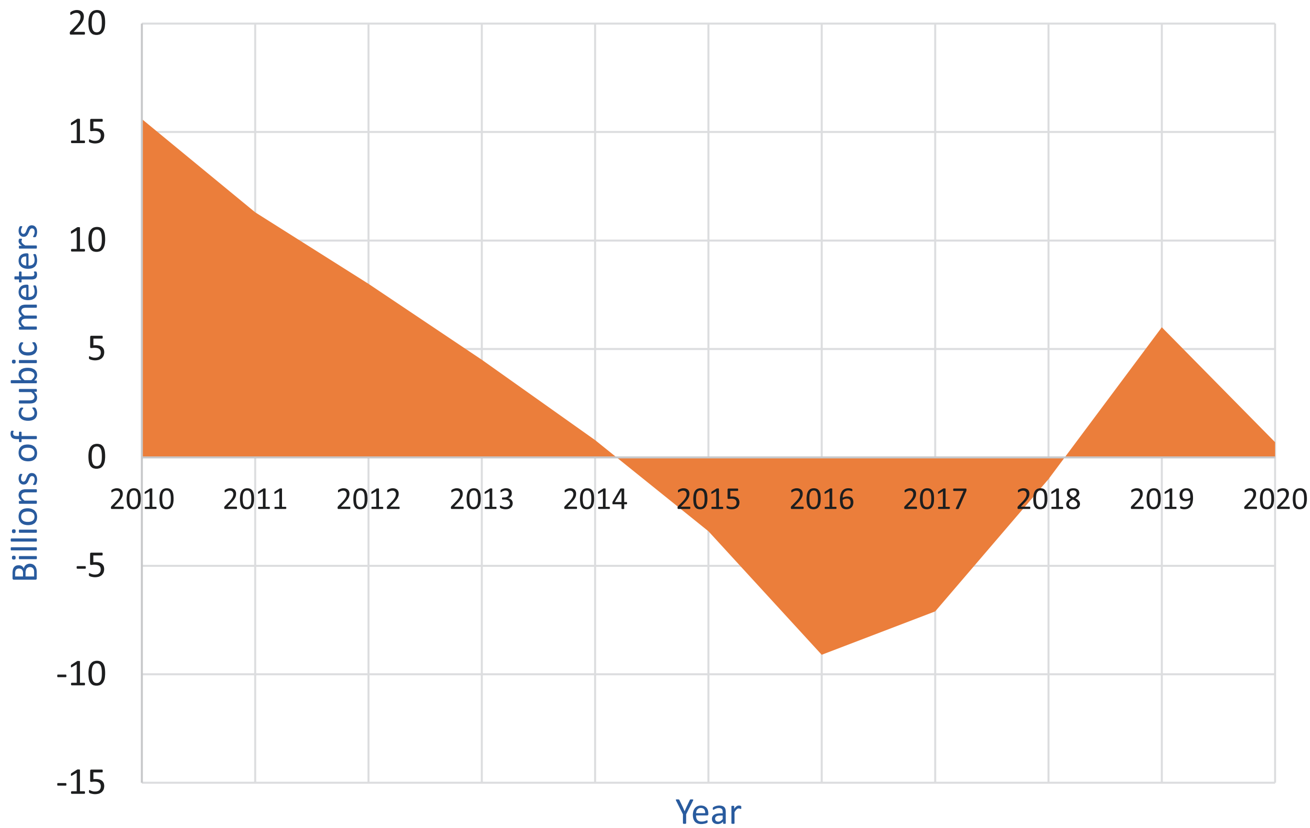

Fig. 10 Egypt's natural gas surplus (+) or deficit (−) from 2010 to 2020. (Data from Ref. [14])

Nuclear Energy

Egyptian interest in nuclear energy dates back to 1955, when the atomic energy committee was established. Egypt started operating a 2-MW research reactor in 1961. It was constructed in collaboration with the Soviet Union. Egyptian nuclear energy aspirations came to a protracted hiatus due to war and political turmoil in the 1960s and the 1970s [20].

In 1976, the Nuclear Power Plant Authority (NPPA) was established. Talks with several countries about prospective reactors took place, but all plans were suspended after the 1986 Chernobyl reactor disaster [20].

The Egyptian nuclear energy program was revived in 2008 when Egypt agreed with Russia to build and operate nuclear energy power plants after President Mubarak visited Russia. In 2010, a legislative framework to regulate nuclear energy facilities and activities was signed into law. Earlier nuclear energy plans with Russia came to a stop due to the 2011 political uprising [11, 20].

In 2013, Egypt approached Russia again to carry on with earlier nuclear energy agreements. In 2015, an intergovernmental agreement was signed with Russia to build and operate four VVER 1200-MWe reactors in Al Dabaa in Northern Egypt. The deal includes fuel supply, management of used fuel, personnel training, and development of regulatory infrastructure. In 2016, the two governments agreed on a $25 billion loan to cover 85% of the cost of the four reactors, with repayments to start upon commissioning over a period of 22 years [11].

In 2021, officials from the Egyptian and Russian governments reported that the COVID-19 pandemic slowed down site preparations. It is expected that a construction permit for the first reactor will be issued in 2022 [11].

Aside from the Russian reactors in Al Dabaa, Egypt has nuclear cooperation agreements with China and South Korea. In 2015, the Egyptian government announced that a second set of reactors would be put out to international tender. In 2016, the NPPA started a project in El Nagila area in Port Said governorate to select a suitable second site for more nuclear reactors [11].

Renewable Energy Generation

Renewable energy generation in Egypt comes mainly from hydro, solar PV, and wind. Figure 11 shows that hydro accounts for roughly half the generation capacity. Solar PV and wind combined account for the other half. Generation

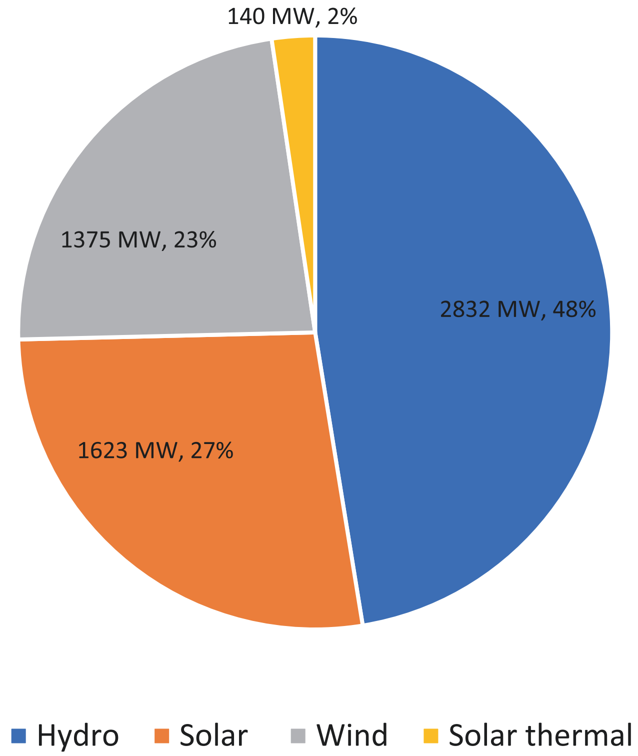

Fig. 11 Breakdown of Egypt's renewable energy generation capacity at the end of 2020. (Data from Ref. [25])

Table 3 Summary of Egypt's hydroelectricity power stations

Station name	Commissioning date	Capacity (MW)
Aswan High Dam	1967	2100
Aswan Dam 1	1960	280
Aswan Dam 2	1985/1986	270
Esna	1993	86
Nagaa Hamadi	2008	64

Data from Ref. [1]

capacities of solar PV and wind are roughly equal. Consumption of energy generated by renewables apart from hydro increased by about 900% from 2011 to 2020, although it accounted for only 0.3% of total primary energy consumption [14].

Photovoltaics (PV)

Egypt is located within the global solar belt. The country receives 2000–3000 kWh/m^2/year of direct solar radiation [24]. The sun shines 9–11 hours per day [24], with very few cloudy days, especially in the south. Egypt's location and climate makes it a prime spot for solar photovoltaic projects. To fulfill its goal to have power generation of 22% of aggregate generated energy from PV by 2035, Egypt approved a Feed-In Tariff (FIT) program to encourage investments in PV and approached major international financial institutions to finance solar projects.

In 2019, the Benban solar park was completed in Aswan in southern Egypt over an area of 37 square kilometers. With a nameplate capacity of 1.5 GW, it is among the largest solar parks in the world. The park comprises 32 individual plants, with individual capacities ranging from 20 to 50 MW. The park cost was $4 billion and was financed by the European Bank for Reconstruction and Development, the International Finance Corporation, and other international financial institutions [24]. It operates under a FIT program. Thanks to the completion of the Benban solar park, Egypt's installed PV capacity rose from 0.2 GW in 2017 to more than 1.6 GW in 2020 (an 800% increase). PV projects of a total capacity of 820 MW are currently under development [25].

Wind

With an average wind speed of 10.5 m/s at a height of 50 meters, the Gulf of Suez is an excellent location for wind energy projects. Current wind generation capacity is 1375 MW [25], compared to only 600 MW in 2014 [14]. Wind power is generated by three major wind farms:

1. Zafarana Wind Farm (545 MW): the project was implemented in several stages starting from 2001 until 2010, through governmental cooperation protocols with Germany, Denmark, Spain, and Japan. The farm comprises 695 turbines with capacities ranging from 600 to 850 kW [26].
2. Jabal Al-Zayt Wind Farm (580 MW): the farm comprises three plants that were completed in cooperation with the KfW Development Bank, the European Investment Bank, the European Commission, the Japanese International Cooperation Agency, and the Spanish government. The farm comprises a total of 290 turbines of 2 MW each [26].
3. Gulf of Suez Wind Farm (250 MW): the first wind farm owned by the private sector. It was built under a BOO (Build, own, and operate) system by a consortium of Egyptian, French, and Japanese companies [26].

At the time of writing this report, Egypt has concrete plans for more than 2400 MW of wind energy; of which 500 MW is under construction, and more than 1700 MW is under development under the BOO system [26].

Hydro

Hydroelectric generation capacity accounts for roughly half of all renewable generation capacity and about 5% of total generation capacity at the end of 2020. Current hydro generation capacity is 2832 MW. Most of Egypt's hydroelectricity generation comes from the 2100-MW Aswan High Dam hydro power station. The station comprises 12 generators, 175 MW each, and was commissioned in 1967. Table 3 is a summary of Egypt's hydroelectricity power plants.

Egypt's 2020 hydroelectricity generation was about 15,000 GWh [25]. Technically feasible hydroelectricity generation potential is estimated at 50,000 GWh per year. Future plans include increasing hydro generation capacity through upgrading existing hydropower facilities [27]. In addition, there is a plan to build a 2400-MW pumped storage power plant in Attaka, Suez, with an estimated investment of $2.7 billion and a scheduled commissioning date of 2024 [28].

Ocean

Egypt possesses vast coastlines with a total length of about 3000 kilometers on the Red Sea and the Mediterranean Sea. However, no reported attempts have been made to utilize wave or tidal energy. More research is needed to assess the feasibility of wave and tidal energy production. Research should determine whether average energy influx in the Egyptian territorial waters is large enough to justify investment and investigate technical, environmental, and financial aspects and challenges.

Geothermal

The New and Renewable Energy Authority (NREA) has signed memorandums of understanding with a local petroleum company and a local observatory to carry out technical and economic feasibility studies for geothermal energy projects and prepare an atlas with potential locations. Four promising locations have been identified, namely, Gulf of Suez, Western desert, Red Sea, and South Valley [25].

Biomass

Although Egypt produces a considerable amount of biomass (theoretical energy content estimated at about 116 TWh in 2013) [29], biomass electricity generation capacity was only 11.5 MW at the end of 2020 [25]. In 2019, the government announced plans to build $2 billion worth of biomass power plants [30].

Biofuels

Although Egypt produces large amounts of solid waste and agricultural waste, the biofuel industry in the country remains largely underdeveloped. One 2017 study estimated that Egypt has the potential for producing 16.53 million tons of ethanol from waste, worth $1.5 billion [31].

The Ministry of Environment plans to implement a pilot project to produce biodiesel from jatropha seed oil, as well as projects to produce biogas from rice straw and agricultural waste [32].

Energy Storage Technologies

Country Current Implementation of Energy Storage Techniques

Egypt does not currently use energy storage technologies.

Country's Future Storage Direction

The only concrete plan for a large-scale energy storage project in Egypt currently is a 2.4-GW pumped hydro plant in the Gulf of Suez region, scheduled for commissioning in 2024. The project aims at storing energy from solar and wind during off-peak hours and using it to meet peak load.

Large-scale battery storage systems have been considered. A council of several ministries is being set up to assess the feasibility of such projects [34]. However, it is highly unlikely that large-scale battery storage will be used in Egypt in the near future due to the following reasons:

1. *Cost*: The technology is still prohibitively expensive.
2. *Oversupply problem*: While this technology is usually deployed by countries facing electricity shortages at certain times of the day or year, Egypt has been actually grappling with a major oversupply problem. With generation capacity that is almost double peak load, the government had to put caps on generation from some renewable energy projects.
3. *Low levels of renewable energy penetration*: Energy storage is crucial in countries with high levels of RE penetration due to the variable nature of RE supply and to match supply with demand. Currently, Egypt's RE capacity accounts for 10% of overall generation capacity. If Egypt is able to meet its announced RE goal of generating 42% of its energy from renewables by 2035, the use of large-scale battery storage will be justified.

Battery storage could be a viable solution for off-grid locations for the time being, but it is not needed at this point on a large-scale level.

Carbon Footprint

Most Recent Carbon Output

In 2020, the country's carbon dioxide emissions accounted for 0.6% of global emissions, with about two tonnes per capita. This low level of emissions highlights Egypt's status quo as a developing country. To put things into perspective, the United States's carbon dioxide emissions were 13.5 tonnes per capita in 2020, about seven times that of Egypt.

Historical Trends of Carbon Footprint

Figure 12 shows carbon dioxide emissions steadily increased from 2010 to 2019, reflecting increasing population and increasing economic activity, before decreasing in 2020, likely due to the COVID-19 pandemic. Between 2009 and 2019, Egypt's carbon dioxide emissions increased by 2.4% per annum, slightly higher than a global average of 1.4% per annum for the same interval.

Types and Main Sources of Pollutants

Figure 12 shows the main sources of carbon emissions in Egypt in 2018. Electricity generation accounted for close to half of the country's total emissions, followed by transportation and industry sectors (Fig. 13).

Egypt's population is forecast to reach 120 million in 2030. A report by Britain's Standard Chartered Bank predicted that Egypt will be one of the world's top ten economies by 2030 [36]. Therefore, it is reasonable to assume that carbon emissions are poised to significantly increase over the next decade. In fact, Egypt aims at ramping up its electricity generation capacity from 60 GW in 2022 to 90 GW in 2030 to meet its economic growth needs. By how much power generation carbon emissions will increase depends on which scenario the country adopts to increase its generation capacity. One study predicted that if the country sticks to its plan of generating 42% of its power from renewables in 2035, carbon emissions from electricity generation will increase very little over the next decade. If the country, however, chooses to walk away from a green scenario and adopts a diversified scenario with high coal usage or a fossil-fuel scenario (which may be tempting given recent large natural gas discoveries), emissions from power generation will increase by more than three times by 2030 (see Fig. 14).

Air Quality

Cairo, the capital of Egypt, is one of the most polluted cities in the world. Cairo air is ranked second worst for PM10 (particulate matter that is 10 micrometers in diameter or less), 14.2 times the WHO-recommended safe limit. The city's air contains PM2.5 (particulate matter that is 2.5 micrometers in diameter or less) that is 11.7 times the WHO-recommended safe limit [37].

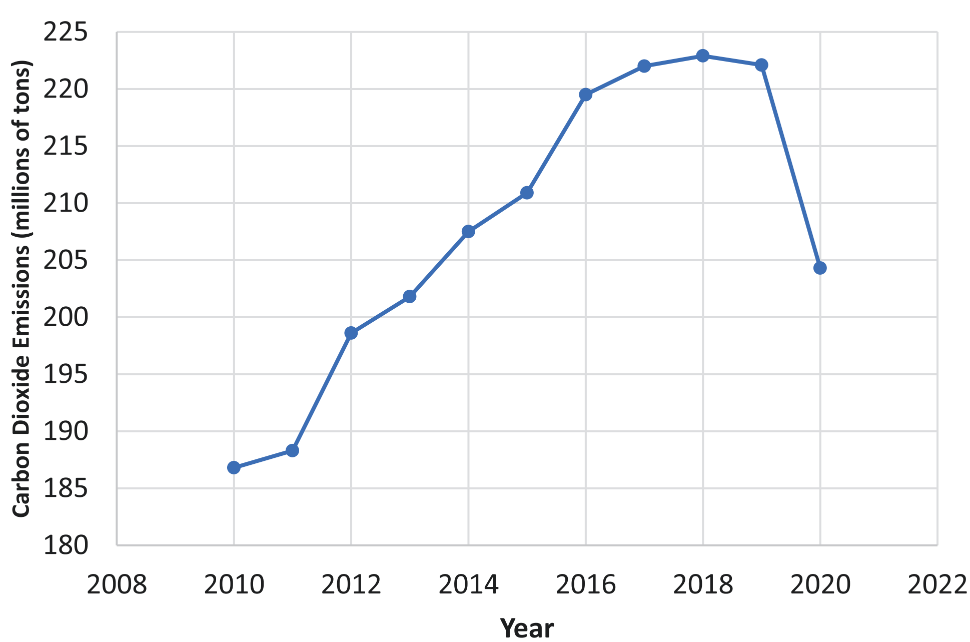

Fig. 12 Egypt's carbon dioxide emissions from 2010 to 2020. (Data from Ref. [14])

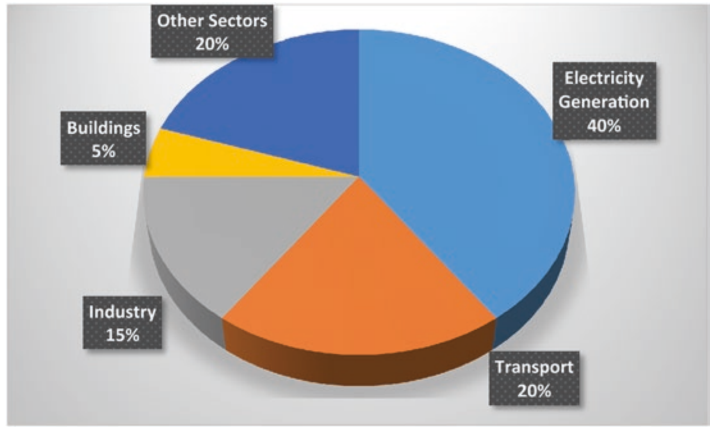

Fig. 13 Breakdown of Egypt's CO_2 emissions in 2018 [35]

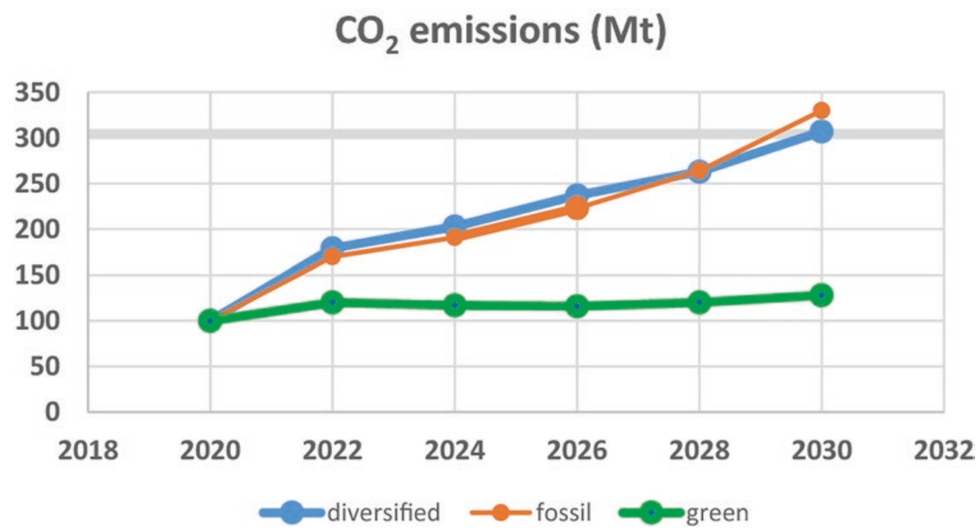

Fig. 14 Three power generation scenarios and their respective carbon emission outputs until 2030 [34]

Energy Resiliency

Electrical Grid

By mid-2020, Egypt's total grid length on the high-voltage and ultra-high-voltage levels was close to 52,000 kilometers, including overhead lines and underground cables [6]. Transmission lines at the 400–500 kV level increased from 3141 km in 2016 to 6185 km in 2020, about a 100% increase. The 400–500 kV lines account for 12% of total grid length, whereas 220 kV and 66 kV lines account for 80%. Total number of substations on the high-voltage and ultra-high-voltage levels by mid-2020 was 712, with total transformer capacity of about 158,000 MVA. About one-fifth of transformer capacity is in the 400–500 kV level, whereas 70% of transformer capacity is in the 220 kV and 66 kV levels [6].

In 2021, Egypt signed a $287.5-million contract to turn its grid into a smart grid. Four control centers utilizing Schneider Electric's latest smart-grid technology will be constructed to monitor and control the grid using big data and artificial intelligence [39].

Climate and Natural Disasters

Grid resilience has seldom been put to the test and therefore literature on energy and grid resilience in Egypt is limited. Fortunately, occurrences of natural disasters in Egypt are extremely rare. Parts of the country are occasionally hit by strong winds, but not strong enough to cause any major disruptions to electricity supply. Since 95% of the country area is desert, wildfires are not a threat to electricity supply. The occurrence of damaging earthquakes is extremely rare and, with the exception of the 1992 earthquake, the country has not experienced any major earthquakes in the last century.

Grid Resiliency

Although the country suffered from rolling blackouts due to insufficient generation capacity before 2016, the occurrence of major blackouts is very rare. In September 2014, Egypt suffered from a major outage that caused 50% of generation capacity to be lost due to a technical failure during a routine maintenance process, affecting basic services such as the greater Cairo underground train system and many hospitals. It was reported that 85% of lost generation capacity was restored 12 hours after the blackout occurred.

Power transmission towers were the target of terrorist bombings in the last 10 years, causing power supply disruptions in some areas. Damage from terrorist attacks was usually quickly fixed. In general, transmission tower bombings were often isolated events without major effects on the overall grid stability and as the security situation in the country improved, they no longer happen.

With new natural gas discoveries, a current capacity surplus of about 28 GW and an improving security situation, it is highly unlikely that energy supply could be disrupted due to fuel shortages or power plant damage or sabotage.

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

The 1973 war between Arab countries and Israel, which Egypt was part of, changed the global energy scene forever. After major Arab oil producers imposed an oil embargo that caused energy prices to soar to unprecedented levels in the United States and Europe, the West started to realize the importance of energy efficiency and the need to become more energy independent.

Egypt became a net oil importer in 2010, with most of foreign oil imports coming from Arab Gulf countries. After the military ousted the Muslim Brotherhood from power in 2013 and the chaos that ensued, Arab Gulf countries supported Egypt with enormous amounts of free fuel, reaching $6 billion in value in 2014, according to one report [40]. With the exception of Qatar, Egypt maintains strong political and economic ties with Arab Gulf countries. Egypt's imports of petroleum products in 2019 and 2020 amounted to $9.4 billion and $6.4 billion, respectively [41].

Relations with Global Community/ Socioeconomic Influence

Over the last decade, Egypt signed three maritime border demarcation agreements with its neighbors. In 2013, Egypt signed an agreement with Cyprus to demarcate their maritime border in the Mediterranean Sea, which helped Egypt discover the Zohr gas field. In 2016, the country signed an agreement with Saudi Arabia to demarcate their maritime border in the Red Sea. In 2020, Egypt signed an agreement with Greece to demarcate their maritime border in the Mediterranean Sea. These new agreements aim at enhancing Egypt's ability to explore oil and gas within its maritime borders without potential conflicts with neighbors.

The discovery of the Zohr natural gas field in Egyptian territorial waters in the Mediterranean Sea in 2015 has virtually eliminated reliance on foreign gas and turned Egypt into a gas exporter. It also prompted the political leadership to invest in two new French aircraft carriers and four German war submarines in order to secure economic interests in the country's territorial waters.

Egypt's national grid is connected to those of Libya, Jordan, and Sudan, with electricity exports to the three countries amounting to 885 GWh during the fiscal year 2019–2020. With about 28 GW of generation capacity above peak load in 2020, Egypt has been eyeing opportunities to increase electricity exports to its neighboring countries as well as Europe. There are plans to expand the Sudan interconnection capacity, and the Jordan interconnection capacity so that Egypt could export electricity to Syria and Lebanon via Jordan. There are also plans to build new interconnections with Arab Gulf countries, as well as Cyprus. The planned interconnection with Cyprus aims at making Egypt a gateway for energy transmission between Africa and Europe [6]. Figure 15 shows the status quo of Egypt's grid interconnections with its neighbors.

Egypt ratified the United Nations Framework Convention on Climate Change (UNFCCC) in 1994, the Kyoto Protocol in 2005, and the Paris Agreement in 2017 [42]. In November 2022, Egypt will host the 27th United Nations Climate Change Conference.

Summary

Current Energy Situation

Although Egypt announced ambitious plans for ramping up its renewable energy generation, the country still generates about 90% of its energy using fossil fuel. Over 90% of fossil-fuel-powered electricity generation comes from natural gas. The country's extensive use of natural gas is justified by its relatively vast natural gas resources. In 2015, the discovery of the giant Zohr natural gas field in the Egyptian Mediterranean territorial waters added about 30 trillion cubic feet to natural gas reserves, turning the country into a natural gas exporter, and prompted the political leadership to heavily invest in strengthening its military, as well as negotiate more maritime demarcation agreements with neighbors. In 2010, Egypt turned into a net oil importer due to increased consumption, maturing oil fields, and lack of new discoveries.

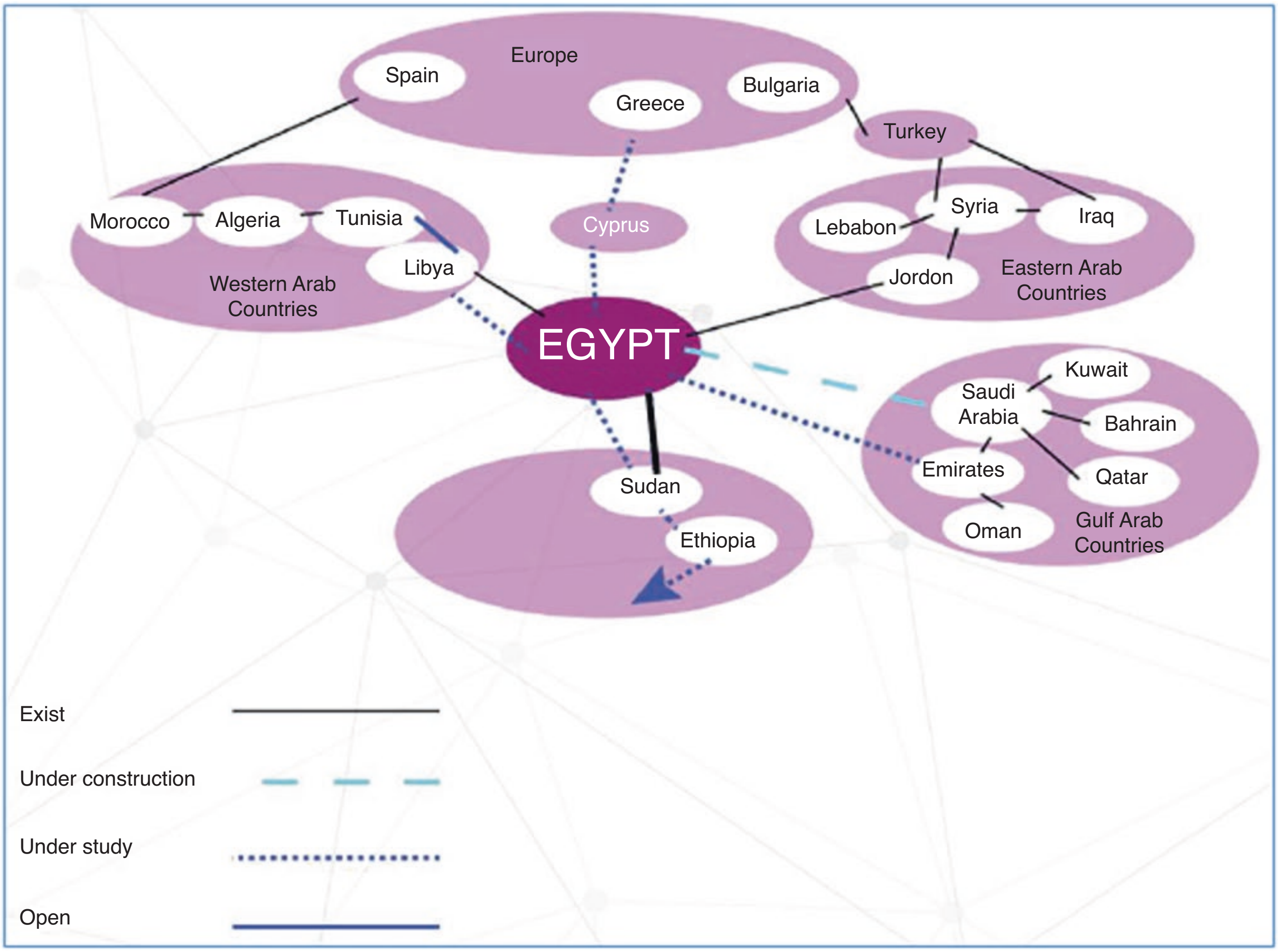

Fig. 15 Status quo of Egypt grid interconnections with neighbors [6]

Future Energy Situation

Egypt's announced renewable energy targets are 20% of electricity generation coming from renewables by 2022, and 42% by 2035. In order to meet these targets, the country made major legislative and policy changes, paving the way for local and foreign private parties to invest in renewable energy projects. The country also endorsed a Feed-In Tariff (FIT) scheme, allowing the purchase of electricity from private renewable energy projects under long-term Power Purchase Agreements (PPAs) at competitive rates. A decades-long electricity subsidy policy is being gradually eliminated, allowing the sale of electricity at fair market rates.

Between 2010 and 2020, solar PV generation capacity went from almost non-existent to 1.7 GW, and wind generation capacity went from 0.6 to 1.4 GW. In 2020, renewable generation capacity accounted for 10% of total capacity, and energy generated from renewables accounted for 12% of generated energy. Hence, it is improbable that the 20% renewable generation target will be met in 2022. Although Egypt significantly increased its renewable energy generation capacity in the last decade, that increase was overshadowed by tremendous parallel increases in fossil-fuel-based generation capacity, for example, more than 14 GW of combined-cycle power plant capacity was added to the grid between 2016 and 2018. Those major increases in both traditional and renewable energy capacity eliminated a rolling blackout problem due to insufficient capacity that persisted until 2015. However, Egypt is now faced with an electricity oversupply problem, which prompted the country to look for potential buyers overseas and put caps on power output from some renewable projects in 2020, although recent reports alleged that the government has rolled back those caps.

Egypt's renewable energy generation capacity is set to rise from about 6 GW in 2021 to 10 GW in 2026, a 68% increase [43]. The country will need to provide more incentives to renewable energy generation and increase the ratio of its renewable capacity increase relative to the overall capacity increase over the coming decade in order to be able to meet its announced target of 42% generation from renewables in 2035.

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Ethiopia

Slobodan Petrovic and Samuel Gaumer

National Energy Introduction

Energy Policies

Ethiopia's energy policy shows the effort taken to both increase the amount of energy that the country can produce, while also decreasing the harmful effects of those energy generation methods [1]. In Ethiopia's growth and transformation plan II, they stated they planned to increase their energy generation capacity to 8000 MW by 2025 compared to the around 4450 MW currently installed as of 2019 [1, 2]. Currently, in Ethiopia, hydroelectric dams are the primary electrical generation method and bioenergy is the largest primary energy source [2]. Most of the new development will be created by hydroelectric energy which is one of Ethiopia's largest domestic resource in terms of energy generation [3]. While not fully developed, there is an untapped potential of fossil fuels which can also act as a future domestic resource [4, 5].

Trends in Generation Technologies

The main trend in energy generation technology in Ethipia has been increase in the capacity of hydroelectric power for electricity generation and bioenergy for transportation and heat. Other renewable energy generation technologies such as solar, wind, and geothermal have also increased in capacity. An increase in fossil fuels energy generation capacity indicates that the country is working towards developing all forms of energy instead of attempting a transition from one energy generation method to another [6].

Domestic Resources

Most of the new development will be created by hydroelectric energy, which is one of Ethiopia's largest domestic resources in terms of energy generation [3]. While not fully developed, there is an untapped potential of fossil fuels which can also act as a future domestic resource [4, 5].

History of Energy

Ethiopia has control over their energy resource and manage their grid with state-owned companies such as Ethiopian Electric Power (EEP) and Ethiopian Electric Utility (EEU) [7]. They have always had control over their domestic resources, though they also receive help from multiple outside countries to help develop their grid. Two of these countries are Russia and China, which both have been taking steps to help develop different parts of Ethiopia's electrical grid [8, 9]. For deficiencies in the electrical grid, there is a large untapped geothermal potential as well as a lack of fallback measures to ensure that energy can continue to be provided even during periods of low generation [2].

Breakdown of Energy Generation "Mix"

Energy Generation Mix

Ethiopia's electricity capacity is dominated by hydroelectric power (Fig. 1).

Energy Consumption Mix

The overall energy consumption breakdown shows significant portion of bioenergy (Fig. 2).

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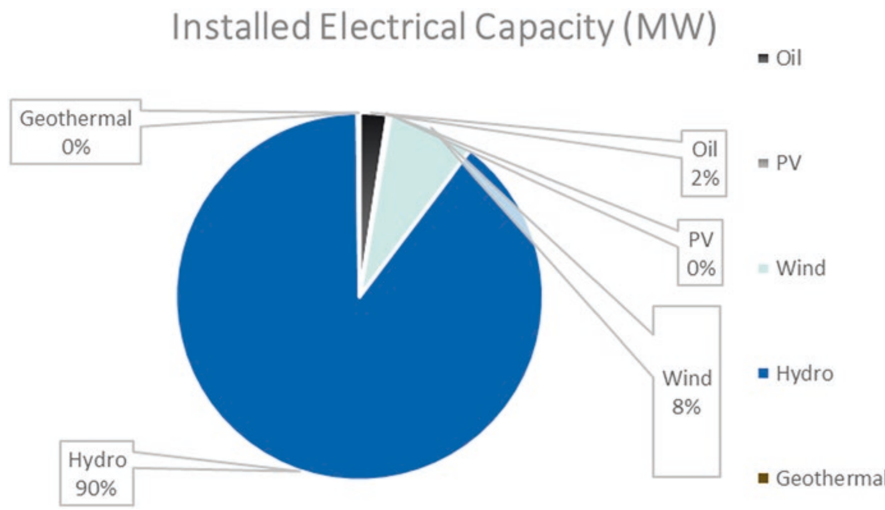

Fig. 1 Installed electrical capacity of Ethiopia

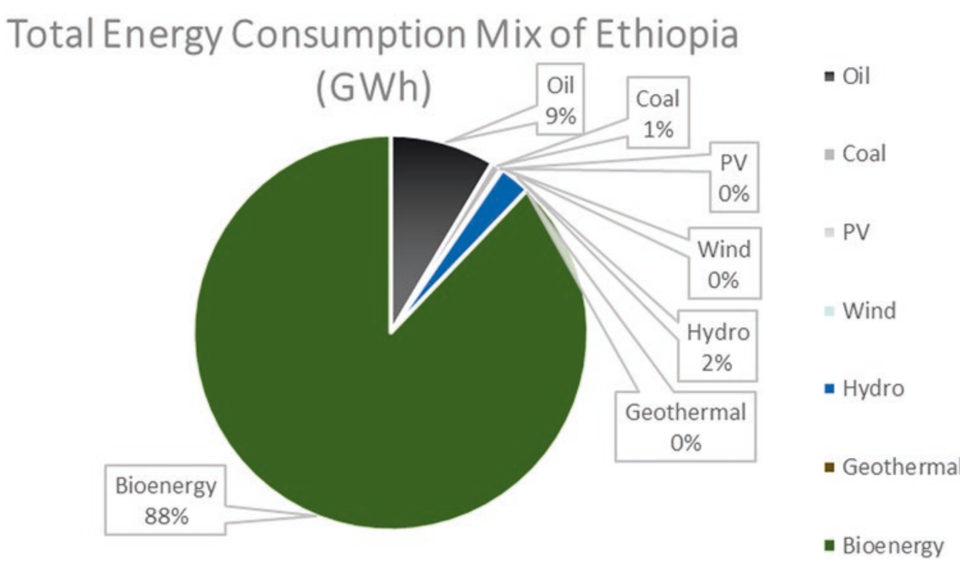

Fig. 2 Total energy consumption mix of Ethiopia

Fossil Fuels

Oil

Looking at the oil used in Ethiopia for electrical generation, there is only one plant in operation. This plant is a diesel generator that has an installed capacity of 104 MW [7]. While that is the installed capacity for electrical generation, around 43,356.6 GWh (3728 ktoe) was utilized in 2018 and the trend of consumption continues to increase [6]. Of the 43,356.6 GWh, around 60% of that is used in the transportation industry, the next highest consumer is industry, and the remaining oil is distributed among the remaining load types [6]. Currently, no oil is produced in Ethiopia, with all of it being imported. The oil that is imported is already refined, though there have been recent attempts to implement refineries in Ethiopia. An American investment firm, Fairfax Africa Fund, was planning on providing US$4 billion to help with implementing oil refineries in Ethiopia though the project was ended in 2018 [10]. Although oil is imported at the moment due to a lack of development in oil pumping, there is potential for future development. As of 2018, tests have been conducted showing the first successful production of crude oil within the country, which is leading to development to produce more crude oil in the coming years [4]. The region is predicted to have a reserve of around 6–8 trillion cubic meters of crude oil for the country [4].

Coal

Compared to oil, coal is used significantly less frequently with around 4454.3 GWh (383 ktoe) from coal being used in 2018 [6]. All of this coal is currently used in the industrial sector of Ethiopia [6]. With all of coal being used in the industrial sector for heating and for manufacturing, there is no installed capacity for electricity generated from coal. Even though around 2009, Ethiopia started to produce its own coal, the current amount that is being produced is around 31.5 kton, where the consumption at that time was 539.2 kton, so the vast majority of coal must be imported from other countries [11]. While hardly any coal is being produced in the country, there are predictions that there is a large supply of coal that could be exploited in the future. Around 600 million tons of coal is thought to be located under the ground and could be a source of revenue for future development [12].

Natural Gas

Natural gas within Ethiopia is a reserve that has not been utilized in any way at the current time though there is potential for future endeavors. Ethiopia does not consume any natural gas so the consumption would be 0 GWh [6]. While they do not use natural gas, this does not mean that they do not have access to natural gas within their borders. It is predicted that they have around 880,000 MMcf of gas reserves located in the country that has not been tapped into yet [13]. Though as of spring 2020, Ethiopia has signed a deal with GLC-Poly Energy Holdings Limited, a Chinese natural gas development company, to start to develop the natural gas industry in Ethiopia both for internal energy demands as well as a revenue stream from exports [5].

Nuclear Energy

Nuclear energy is one of the non-renewable forms of energy generation that has been seeing increased development from a number of different countries such as Ethiopia. At the moment, Ethiopia has no nuclear power plants though they have taken steps toward utilizing nuclear energy in the future. These steps have been working with Russia to develop nuclear power plants in Ethiopia as well as a center for nuclear science and technology [8]. This is a process that is still developing and is subject to new developments, as the department and the power plants continue in development. At its current stage, they are still developing the plans, meaning they have no nuclear energy policy in place [14]. Though this could be changing at any time, as these developments are very recent [14]. In terms of nuclear resources in the country, very little is actually known about how much is available for collection compared to how much would need to be imported to power the future projects. Only around US$22,000 has been spent for research into uranium within the country and much of that was done before 2012 [15]. Unless future explorations are conducted, it is unknown how much fuel would need to be imported compared to how much could be kept domestic.

Renewable Energy Generation

Photovoltaics (PV)

The horizontal solar irradiation within Ethiopia is on average 5–5.4 kWh/m^2 within most of the country though the region of Somali, located on the eastern side of the county, sees a much higher average of around 6.4 kWh/m^2 [16]. This shows that there is potential for a large number of solar devices for future projects.

Solar PV in Ethiopia is currently an underdeveloped field that shows potential for future development. As of 2019, only 11 MW of solar PV is installed within the country and mainly seen in the form of off grid systems meant to help areas with a lack of access to electricity [2]. With that installed capacity in 2018 around 20 GWh was generated and are mainly used for telecom systems for these smaller villages [6, 17]. While there is currently not a large amount of solar capacity utilized within the country, there is potential for a large amount of solar energy for future projects. Ethiopia has started work to implement around 800 MW of solar capacity to its electrical grid across six solar plants [18]. These future projects are designed to be managed and owned by Ethiopian Electric Power (EEP) [18]. The states that are expected to see this development are Oromia, Afar, Somali, and Tigray [18]. All four states have some portion of their borders within the north eastern border, showing that they all have a potential to have these plants utilize the high solar irradiation of that region [16]. Currently there has not been any updates on the progress of these plants. Though based on the region, it would be expected to be a great source of energy for the country.

Currently there is no solar thermal energy utilized in Ethiopia and there are no apparent steps taken to implement solar thermal energy within the country.

Wind

Wind energy is one of the more common types of electrical generation in Ethiopia. In 2019, there in a projected installed capacity of around 324 MW from three wind farms [7]. This has allowed for around 533 GWh to be generated from wind power in 2018 [6]. The wind speed in the area is relatively uniform 50 meters in the air. Most of the country has wind speeds at 50 meters of between 2.5 and 5.5 m/s [19]. Looking at 200 meters in the air, the eastern region of Somali sees wind speed increase to as high as 9.75 m/s [19]. The three plants that are currently finished are Adama 1 and 2 with a capacity of 51 and 153 MW, respectively, and Ashegoda with a capacity of 120 MW [7]. All three plants are owned and managed by EEP [7]. For projects that are currently underway, there is the Ashya and the Messabo projects which plan to produce 300 MW and 42 MW, respectively [20]. There are also three projects signed to add another 450 MW to the grid and 33 projects identified with a potential capacity of 5500 MW that can be added to the grid [20]. While this potential will probably not be reached in the foreseeable future, it is helpful to see the potential if more development is applied to this energy sector. All wind power is generated from onshore wind because Ethiopia has no ocean border.

Hydro

Hydroelectric power is the number one source of electrical energy generation within Ethiopia and accounts for around 90% of the renewable energy capacity within the country with a total capacity of around 3817 MW [2]. In 2018 alone, this hydroelectric energy was able to generate 13,018 GWh for the electrical grid [6]. This generation is being developed from 14 hydroelectric plants across the country [7]. The 14 power plants are as follows: Gilgel Gibe III (1870 MW), Beles (460 MW), Gilgel Gibe II (420 MW), Takeze (300 MW), Gilgel Gibe I (184 MW), Melka Wakena (153 MW), Fincha (134 MW), Amerti Neshi (95 MW), Tis Abay II (73 MW), Awash II (32 MW), Awash III (32 MW), Koka (43 MW), Tis Abay I (11.4 MW), and Aba Samuel (6.6 MW) [7]. All of these hydroelectric plants are owned and operated by Ethiopian Electric Power [7].

Ethiopia has additional hydroelectric resource potential and the work has been underway on the largest hydroelectric plants in all of Africa with the Grand Renaissance Hydroelectric Project (GRHEP) [21]. The GRHEP is a dam that will be built on the Blue Nile and have a projected installed capacity of 6450 MW, which is more than what the entire country's capacity is up to this point [21]. When completed, it would be a massive increase in energy capacity for Ethiopia and will be able to reach the 8000 MW goal [1].

Ocean

Ethiopia is a landlocked country with no access to the ocean.

Geothermal

Geothermal energy within Ethiopia is an industry that currently has limited usage though there is future development. The only geothermal plant within the country is the Aluto-Langano geothermal plant which was originally designed to have a capacity of 7.3 MW, though it is currently under construction to increase that capacity to 70 MW [7, 22]. The 8 GWh electricity generated by the plant was last observed in 2011 because the plant has been under repair ever since [6]. While that is the only geothermal plant currently operating, multiple projects have begun. One of the largest plans to bring geothermal energy to Ethiopia is from Reykjavik Geothermal, which, in 2019, planned to construct two geothermal plants in order to increase the geothermal energy in the country by 1000 MW [23]. This plan is estimated to cost $4.4 billion and would significantly increase the overall energy capacity of the country [23]. It is predicted that the total geothermal energy in Ethiopia is in the range of 4200–10,800 MW [24].

Biomass

Bioenergy is the most common form of primary energy within the country with 443,591 GWh (38,142 ktoe) being used in 2018 alone. This is broken up into biomass and biofuel, with most of the generation being from biomass sources [6].

Biomass in the form of burning wood, charcoal, residue, and dung is seen in most parts of Ethiopia. Biomass is the primary energy source in the residential (98.6%), service (94.3%), and industrial sectors (75.7%) in 2011 [25]. The biomass that is used in the country is used mostly for heating and cooking in areas that do not have access to large supplies of electricity [25]. As time passed, electricity has become more prominent and biomass use has decreased in some parts of the country, but with many areas with no access to the electrical grid, biomass is still the only source of energy for many people. The country has a large potential for biomass, 767 million tons of wood-based biomass and 38 million tons a year of crop and animal waste as of 2011 [25]. Even though there is a large amount of biomass used, there are currently no power plants operating in Ethiopia to turn this energy into electricity. All of the biomass is used in the form of creating heat and using the heat for a variety of daily tasks. While it could be possible to create power generation from the wide variety of biomass, no efforts are being made at the moment as the electricity generation is focusing on non-combustible renewable energy sources.

Biofuels

All of the biofuel generation in Ethiopia is done by collecting bioethanol from a number of different plants such as sugar cane, sugar beets, and sweet sorghum [26]. Biodiesel is also produced from plants like palm, castor beans, and jatropha. Biofuel is used for transportation, cooking, pharmaceuticals, and other applications [27]. Biofuels are currently not used for electricity generation.

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

There are currently no large-scale energy storage facilities in Ethiopia except 6.5 MWh battery capacity installed in 12 rural sectors of Ethiopia [28].

Country's Future Storage Direction

Additional battery storage facilities in areas distant from the electrical grid along with development of microgrids are planned to complement the Ethiopian electrical grid [28].

The other form of energy storage that could see development within Ethiopia is pumped hydro dams and pumped hydro storage. As stated earlier, Ethiopia's largest electricity generation method is from hydroelectric dams with an installed capacity of around 3817 MW currently [2]. With a large focus on hydroelectric energy, it means the main parts of technology are already in place to develop additional pumped hydro storage and utilize any excess energy created by the hydroelectric dam. As the country is subject to droughts, which can lead to times of low water levels in reservoirs, this form of storage could help provide some extra energy during these times [38].

While Ethiopia does not have any current pumped hydro systems, some of the neighboring countries do have this form of energy storage [28]. This means that there is a potential that this form of energy storage can work in this part of the world.

Carbon Footprint

Most Recent Carbon Output

Ethiopia, in 2018, produced 13.1 Mt of carbon dioxide emissions, which is around 0.037% of the global carbon emissions in 2018 [6, 29].

Historical Trends of Carbon Footprint

There has been an upward trend of carbon emissions in Ethiopia mainly caused by increased usage from the transportation and industrial sectors of the country [6]. Looking at the oil consumption during the same time frame, a similar upward trend is observed [6]. This correlation may explain why there is an increase in emissions for the transportation industry, as there is more oil consumption, there would be more CO_2 released from the vehicles.

Types and Main Sources of Pollutants

Most of the pollution that is prevalent in Ethiopia is caused by vehicles, with industry and residence following closely behind [30]. Along with carbon dioxide, there are also mixes of other pollutants in Ethiopia that affect the air quality. Nitrogen dioxide, carbon monoxide, fine particulate matter, and Poly Aromatic Hydrocarbons have also been found in larger quantities in the area [30].

Air Quality

According the IQAir, Ethiopia has moderate air quality with an average of AQI value of 56, ranking them 64th among the most polluted countries of 2020 [30].

Energy Resiliency

Electrical Grid

Ethiopia's electrical grid is a system giving 44.3% of the population access to electricity using 17,448 km of transmission lines [2, 31]. These transmission lines connect 163 substations across the country and range from 132 to 500 kV and operates at 50 Hz [31]. This is split between the rural and urban areas, with 29% of the rural and 85% of the urban areas having access to electricity [32]. Most of this grid was built in the early 2000s. With the National Electrification Program, Ethiopia plans to secure access to electricity for the entire country by 2025 [33].

The electrical grid is owned and operated by Ethiopian Electric Power, the same organization that runs most of the power plants in the country [31]. EEP is a state-owned company and has a near monopoly on the high voltage transmission lines in the country. The low voltage substations and transmission lines are managed by Ethiopian Electric Utility, another state-owned company that focuses on the low voltage power sector [31].

Like many power grids, Ethiopia's grid is not only connected to Ethiopia, but is a part of the East Africa Power Pool. EAPP is an organization that is working to connect the grids of ten different African countries: Burundi, Democratic Republic of Congo, Egypt, Kenya, Rwanda, Sudan, Tanzania, Libya, Uganda, and Ethiopia [34]. By having all of these electrical grids connected, it can allow for energy to be easily shared between the countries so that no energy goes to waste. If one country overproduces, it could sell power to countries that underproduce. In 2013, Ethiopia was connected to two countries, Sudan and Djibouti, and exported power to both countries at the time [34]. By 2023, a number of connections is planned as more lines are connected to Sudan and Kenya [34].

Climate and Natural Disasters

Ethiopia is a tropical country just north of the equator in Eastern Africa. There are three main climate zones within Ethiopia that vary depending on the altitude [35]. The first region is the Dega region, which is the coldest of the three areas. At an altitude of around 2400 m the average peak temperature is between 0 and 16 °C [35]. The Weina Dega is a bit lower ranging from 2400 to 1500 m. This area sees an increase in temperature with peaks between 16 and 30 °C [35]. The third, and the largest climate area, is the Kolla zone, encompassing all areas under 1500 m [35]. This zone has the widest variety of temperature fluctuations [35]. The average temperature for this area is 27 °C, while some parts closer to the sea experience temperature peaks as high as 50 °C [35]. There are two main rainfall regions with widely different average rainfalls, the highlands and the lowlands. The highland zones of dega and Weina Dega have a mean annual rainfall of roughly 2000 mm [36]. The lowlands of the Kolla zone receive 300 mm of rainfall in a year [36].

There are several types of natural disasters that occur in Ethiopia. This includes droughts, floods, earthquakes, pests, wildfires, and landslides [37]. Many of these disasters affect the water and the agriculture of the country, with impact on the energy industry. During the drought seasons, it becomes harder to produce hydroelectric energy, which provides most of the energy generation, and interruptions lead to blackouts [38]. The shortage of water creates problems for the agricultural region. During periods of long drought, rationing of power for both domestic use and exports leads to losses of around 25% of the GDP of Ethiopia [38].

Natural disasters can have a negative effect on the crop harvest needed to create bioenergy, which can lead to a lack of fuel for heating [38]. Floods are the most common type of disaster, followed by epidemics, and then droughts [37].

Grid Resiliency

Ethiopia experiences yearly on average 100 days of blackouts of about 4 h [39]. Between 2013 and 2016, there were 49 blackouts that affected the entire country [39]. With grid expansion, it is expected that the resiliency of the grid will be further affected and resolving peak demand fluctuations and restrictions due to droughts is the major concern for Ethiopia's energy, which uses a large amount of hydroelectric energy.

One method to increase grid stability is by having grid monitoring equipment in place by turning the grid into a smart grid with the use of sensors to help with the monitoring process. Currently, there are no smart grid technologies in place in Ethiopia's grid, though steps are starting to be taken to change that. Suggestions have been made for EEU to begin designing a smart grid layout for their electrification process as they continue to work on connecting Ethiopia's population to the grid [40].

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

Ethiopia only recently started crude oil production and most of its consumption is imported [4]. In 2019, Ethiopia imported around US$170 million worth of petroleum [41] from the United Arab Emirates (35.7%), China (26.7%) [41], Egypt (12.7%), India (8.61%), and Rwanda (5.71%) [41].

The coal imports are around US$37,000, mostly coming from South Africa [41].

Relations with Global Community/ Socioeconomic Influence

Ethiopia is involved in the Paris Climate Accord as well as the Climate Resilient Green Economy strategy. Ethiopia's pledge is to limit their 2030 emissions to 145 $MtCO_2e$, and in the long term reach a carbon neutral society [42]. This pledge was analyzed by Climate Action Tracker which found that the goal was compatible with the goal to decrease global warming by 2 °C [42]. Toward this goal, Ethiopia receives assistance from the United Nations to improve its agriculture and reduce emissions [43].

Ethiopia is involved in a project to create the Grand Renaissance Dam on the Blue Nile. While this project has the potential to produce a large amount of energy, there is also political opposition from Sudan and Egypt due to concerns of water flow disruption on the Nile [21].

Education

There are currently a number of programs available from different universities in Ethiopia that have a focus around both renewable energy as well as electrical engineering in general. One such school is Bahir Dar Institute of Technology, offering a Master of Science in Sustainable Energy Engineering [44]. Another university is Hawassa University which offers multiple electrical engineering programs that could build education into the electrical grid [45]. Arba Minch University offers a master's degree in dam engineering, which would be very beneficial based off the amount of hydroelectric energy seen in Ethiopia [46]. These are just a few examples of schools with programs that can affect the electrical grid, though there are many more schools in the country that offer programs that can help develop education in energy engineering.

Summary

Current Energy Situation

Ethiopia is a country with a massive energy generation resource from many different energy sources such as hydroelectric and wind power [2]. Other generation methods such as oil, geothermal, and solar are less developed [2].

While most of the electricity is produced by hydroelectric plants, most of the energy consumed in the country originates from bioenergy sources, as much of the country is still not connected to the electrical grid [2]. Ethiopia lacks diversity in energy generation needed to ensure system resiliency in case of natural disasters.

Ethiopia's solar, geothermal, and bioenergy generation are underdeveloped. The overall trend of the country is increasing the energy capacity of every type of energy source as they work to completely connect the country to the electrical grid and to increase export capacity [34].

Future Energy Situation

The future trends that will be expected are the creation of large-scale energy generation methods in almost every renewable energy field, either by private foreign companies or from the Ethiopian government [1]. Another future development would be the continued expansion of the electrical grid both within the country's borders as well as connecting to other countries. Finally, there is going to be future development in reducing carbon dioxide-producing energy method to decrease and 1 day reach a carbon neutral state.

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Morocco

Slobodan Petrovic and Andrew Reed

National Energy Introduction

Morocco, or the Kingdom of Morocco, is a country in the northwest corner of Africa in the historic Maghreb region. Spain lies directly north of Morocco across the strait of Gibraltar, connecting the Atlantic Ocean with the Mediterranean Sea, while Algeria is on Morocco's eastern border. Morocco has long been the location of great migrations and influence with Europe throughout history. Morocco is known for its northern port cities, including the city of Casablanca, and its connection to the Western Sahara region to the south, which is currently a disputed territory.

Morocco's terrain is mountainous and semi-arid. The country has two mountain ranges, with the Rif mountains along its northern area and the Atlas Mountains splitting down the middle of the country [1]. The climate is Mediterranean mostly, with hot and dry summers and a mild, rainy winter season. Often a hot and dusty wind will raise these temperatures and damage crops. Temperatures are typically 64–82 °F in the summer along the coastal cities and drop to 46–63 °F in the winter. Temperatures away from the coast will get much higher in the summer and colder in the winter [1].

Since 1963, a few years after its independence, Morocco's generation and transmission have been owned by the Office of National Electricity (ONE), which became ONEE in 2011 [2]. Having few fossil fuel resources to exploit, Morocco has relied upon imported energy resources for its generation. This meant Morocco has long been subject to global oil shocks and has had to explore ways to secure a more stable energy future. Morocco has since initiated expansive renewable energy policies and projects to exploit its substantial potential in solar and wind energy [3].

The year 2019 marks a big year for Morocco's energy history as the country became a net exporter of energy, primarily through its connection to Spain. From 2018 to 2019, Morocco's exports of electricity rose from 0.4 to 1.5 billion kWh, while imports of electricity dropped from 3.7 to 0.5 billion kWh. This is a drop from 3.4 billion kWh in net imports to – 0.9 billion kWh net imports [4] (Fig. 1).

Energy Policies

The overall objective of Morocco in terms of energy is to secure supply to reduce dependence on imports for energy, according to the International Trade Administration [5]. Morocco formed a new National Energy Strategy in 2009 with the goals of increasing renewable energy generation and improving energy efficiency [6]. The target was set to have 42% of installed electrical capacity being renewables, with installation of 2000 MW of solar energy, 2000 MW of wind energy, and 2000 MW of hydropower. After evaluating progress in 2015, Morocco updated the goal to have 52% renewable capacity by 2030 [6].

ONEE writes and implements the national policy for the grid with approval from the Ministry of Energy, Mining, and the Environment (MEME). Energy efficiency and conversation measures are key parts of the policy along with management of the grid itself. MEME is in charge of overall energy policy-making and managing the energy sector [7]. A new agency in the last decade is the Moroccan Agency for Sustainable Energy (MASEN), created as part of the National Energy Strategy. MASON and Research Institute for Solar Energy and New Energies are responsible for focusing on the research & development (R&D) for the major energy goals in Morocco (Table 1).

Morocco is leading the way for African countries by focusing on energy efficiency improvements. Morocco plans to utilize extensive energy efficiency changes to reduce electricity consumption by 15% by 2030 [8]. In 2011, Law 47-09 was enacted as a sweeping energy efficiency improvement act, focusing on energy studies, audits, and evaluations for different sectors. Initially, Morocco was aiming for a 12%

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Basic info about Morocco:

- Population: **36,471,769** (2019)
- GDP (USD): **$119.7 billion** (2019)
- CO^2 Emissions (metric tons per capita): **1.744** (2016)
- Population below national poverty line (%): **4.8** (2013)
- Life Expectancy at birth (years): **76.453** (2018)

Energy Statistics (IEA):

- Total Primary Energy Supply: 20.59 Mtoe (up 170 percent from 1990)
- Total Electricity Consumption: 33 TWh (up 270 percent from 1990)
- Total CO^2 Emissions: 59 Mt (up 200 percent from 1990)
- Electricity consumption per capita: 0.92 MWh/capita (up 156 percent from 1990)

Basic Facts about Morroco [10]

Fig. 1 Basic facts about Morocco [10]

Table 1 Morocco energy agencies

Some Moroccan government agencies involved with energy include the following:
Moroccan Ministry of Energy, Mining, and Sustainable Development http://www.mem.gov.ma/
National Office of Electricity and Water (ONEE) http://www.one.org.ma/
National Federation of Electricity and Renewable Energies (FENELEC) http://www.fenelec.com/
Research Institute for Solar Energy and New Energies (IRESEN) http://www.iresen.org/en/
Solar Cluster http://www.clustersolaire.ma/
Moroccan Agency for Solar Energy (MASON) E-Tenders https://masen.local-trust.com/index.php?page=entreprise.EntrepriseHome&goto=&lang=en
Company for Energy Investments (SIE) http://www.siem.ma/

Source: International Trade Administration [5]

Table 2 Morocco energy use per capita [9]

	1990	2000	2010
Energy use per capita	3570.41 kWh	4454.29 kWh	6140.64 kWh
Electric power consumption per capita	359 kWh	490 kWh	776 kWh

improvement by 2020, but this was adjusted to a more reasonable 5%.

The slow implementation and resource-gathering of the Moroccan Agency for Energy Efficiency (AMEE) is the reason for this adjustment, with more human and financial resources needed. The national energy efficiency goal is still to improve this number to 20% by 2030. Thermal building regulations were written in 2014 and an energy audit of industries in Morocco was mandated in 2019 [5]. Morocco is aiming to improve energy efficiency in the agricultural sector particularly, as agriculture is a major part of Morocco's economy at 13% of its GDP and around one third of the Moroccan workforce. According to a report by Boulakhbar et al., the overall energy improvement policies at a national level in Morocco can only be fully realized by counting on local authorities to apply the standards in their municipalities [8].

Total installed electricity capacity is expected to reach 25,000 MW by 2030 [8]. Primary energy demand in Morocco is expected to rise from 26 million TEP in 2020 to 43 million TEP by 2030. Electricity consumption is expected to rise form 52 TWh in 2020 to 95 TWh in 2030 [8].

Total energy consumption in Morocco has increased by about 5% per year since 2004, according to ONEE [5]. Electricity demand consumption has gone up at an average of 7% every year for the last two decades [8] (Table 2).

Morocco submitted its Voluntary National Review of progress toward the 17 UN Sustainable Development Goals (SDGs) in 2020. The review highlights Morocco's investments framework, including SDGs, since the early 2000s. Morocco has seen progress in reducing national poverty, social inequalities, hunger, and drought vulnerability, as well as improve electrification, drinking water quality, and waste management [33]. Morocco used one third of its GDP in the last 20 years to improve social programs, reduce poverty, and combat climate change [34]. The National Commission for Sustainable Development was created to implement plans and respond to recommendations on development, consisting of members of all departments of the Kingdom [35]. Morocco first adopted SDGs in 2015 and had the first national review a year later [34]. An example of Morocco's commitment is the country's improvement in the methods of waste collection compared with other Mediterranean countries. Municipal solid waste treatment efforts have sped up over the last decade, with less waste dumped into open dump sites. While 93% of waste was dumped into open dump sites in the 2006–2010 period, this share decreased to 31% in 2010–2014 and to 19% in 2014–2018. Water pollution is part of national policy, with the Wastewater Treatment and Purification Program being launched in 2016. Morocco treats water that it eventually dumps into the Mediterranean Sea at a rate of 73 million m3 annually [36]. Morocco has also focused on increasing water reuse, primarily for agriculture. This is essential for the volatility of water resources for the country.

Breakdown of Energy Generation "Mix"

Energy Generation Mix (Fig. 2)

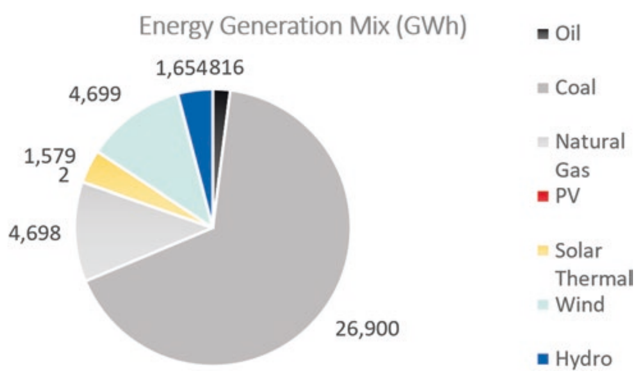

Fig. 2 Energy generation mix for 2019. (Source: IEA Data [10])

Energy Consumption Mix (Fig. 3; Table 3)

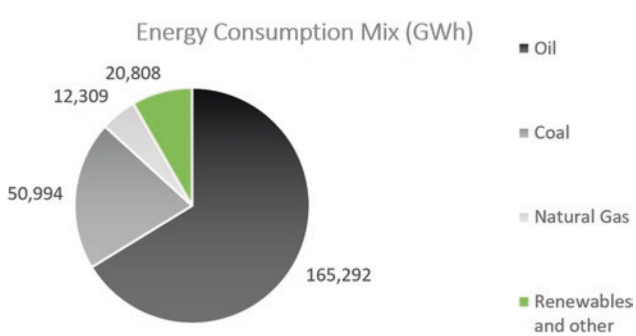

Fig. 3 Energy consumption mix for 2019. (Source: EIA Data [4])

Table 3 Installed capacity of electricity in Morocco [8]

Installed capacity of electricity in Morocco:
2015 – 66% fossil fuels, 22% hydro, 10% wind, 2% solar
2020 – 58% fossil fuels, 14% hydro, 14% wind, 14% solar
2030 (predicted) – 48% fossil fuels, 12% hydro, 20% wind, 20% solar

Fossil Fuels

Studies in the last few decades have shown Morocco has potential for non-conventional hydrocarbon reserves, with 57 billion barrels potential in the mountainous regions and in the southern Sahara regions, including significant shale oil potential [12]. Feasibility studies have thus far shown that these reserves are not presently able to compete for energy use if recovered [11]. Despite this, Morocco has developed a network of interested parties and has seen great expenditure on exploration for hydrocarbons. In 2018, $197.8 million was invested in exploration and production for hydrocarbons according to the National Office of Hydrocarbons and Mines (ONHYM) [12]. This funding is primarily from interested international investors, who are attracted to the unexplored regions, fair regulations, and tax exemptions of the country.

Oil

Morocco has never become an oil-rich country like many of its North African neighbors. The disappointing lack of oil discoveries in Morocco factors into the versatility of the energy infrastructure, partnerships, and regulatory frameworks that Morocco has developed. Morocco has looked to develop its own domestic oil resources to try to reduce its reliance on imports. Petroleum is consumed much more than produced in Morocco, with production never over 5000 barrels a day in Morocco, according to EIA, while total consumption of petroleum and other liquids was over 286,000 barrels/day [4]. Oil production has seen a decline from just 15 kilotons a year in 1990 to just 4 kilotons in 2019. Consumption of oil products has seen a rise from 3582 kilotons a year in 1990 to 12,124 kilotons in 2018, with total energy supply of oil being roughly the same as the total consumption [11]. Crude oil has been imported from other countries at a rate between 4200 and 7300 kilotons per year since the 1990s. This rate dipped to 2690 kilotons in 2015, which is the last available data from IEA [10]. In general, Morocco is thought to have potential hydrocarbon shale that is yet to be tapped [4]. Exploratory efforts include Chariot Oil and Gas from the UK, which owns a concession of 4600 sq. km in plots near the city of Muhammedia. Another example is Italian subsidiary company Eni Morocco, who has a concession for 45% of a 23,900 sq. km offshore area near Tarfaya, with Qatar Petroleum owning 45% and 25% owned by ONHYM [12].

Coal

Coal has historically been a major part of Morocco's energy plans, in particular for coal-powered energy generation. The low cost of international coal imports has long been part of the government's plan for increasing access to electricity across the country. Coal represented 16% of the country's primary energy needs in 2012. Coal-fired powered plants produced 43% of total electricity generation in that year [13]. This increased to 58% in 2016 [17]. Electricity generated from coal rose from 2938 GWh in 1994 to 8783 GWh in 2000, 12,141 GWh in 2013, 17,545 GWh in 2017, and 26,900 GWh in 2019. Total energy supply of coal resource rose from 1134 ktoe in 1990 to 3025 ktoe in 2011 and 4939 ktoe in 2018 [10]; 5584 ktoe of coal was imported into Morocco in 2018 [10]. Despite having impressive mining industry, including being the producer of 75% of the world's phosphate, domestic resources of coal in Morocco are practically nonexistent. Morocco had production of anthracite coal at the Jerada mine until the mine closed in 2000. Since then, all coal for power usage in thermal power plants is imported into Morocco [11]. Morocco uses imported coal to produce half of its power generation. This huge energy need requires large-scale imports. For example, 7 million tons of coal were consumed in 2017 for power generation [4]. The enormity of this coal import process can be seen at Jorf Lasfar. Taqa Morocco is an independent power producer that runs a coal-fired power plant at Jorf Lasfar. This plant was first built in 1994, with capacity doubling from 2000 to 2001 [18]. Jorf Lasfar is an important site for Morocco's energy profile. Around 85% of all imported coal into Morocco pass though Jorf Lasfar's port. More than 5.4 million tons of coal are imported to the power plant itself [19].The large plant produced 42.8% of Morocco's total output in 2018 with 14,772 GWh of electricity produced [7]. Jorf Lasfar has 2056 MW of total capacity, with a storage park capable of holding 1 million tons of coal. Morocco completed a 700 MW extension of the plant in 2016, bringing the total capacity to 2056 MW. The PPA with Taqa Morocco was extended another 17 years in early 2020 [18].

Recent projects include Safi Coal power plant, which is actually two 693 MW plants. Located on Morocco's west coast, this addition of 1386 MW of capacity boosted overall coal capacity by nearly 50% [4]. Coal generation in 2019 was from the following plants: Jorf Lasfar (1–6) at 15,125.7 GWh, SAFIEC at 8082.7 GWh, Jerada 350 at 2396.8 GWH, and Muhammedia at 1292.6 GWh [15].

Natural Gas

As part of its drive to reduce dependency on energy imports and meet its carbon footprint goals, Morocco has been increasing its own natural gas domestic production. Although imported energy has primarily been in the form of oil, Natural gas potential in Morocco is high and can contribute to meeting the rising energy demand in Morocco. Liquid natural gas is expected to be 14% of Moroccan energy mix by 2025 [11]. Morocco's consumption of natural gas is still much higher than its production: in 2018, consumption was at 44 billion cubic feet of natural gas, while production was at 3.1 billion cubic feet [4]. Natural gas was only in the picture for Morocco since 2005, when Morocco began receiving some of the natural gas from neighboring Algeria. The Gas Maghreb Europe pipeline runs through Morocco as it flows from Algeria to Spain. Rather than any transit fees, Morocco receives natural gas from this pipeline. This section of the pipeline in Morocco will see its ownership pass to Morocco in 2021 [4]. Since 2011, Morocco has increased its purchase of this natural gas substantially [13]. Morocco also has an agreement with Nigeria called the Nigeria–Morocco Pipeline Project. The aim of this agreement is to supply natural gas via pipeline to countries in West Africa. This agreement was signed in 2017 [4]. Morocco imported 37,214 TJ-gross natural gas in 2019, and generated 4663 GWh from natural gas in 2019 [14, 15]. This energy is produced at two plants: Tahaddart Natural Gas plant and Ain Beni Mathar Combined Cycle plant [15].

Morocco is also planning a large liquefied natural gas and combined-cycle gas project on the Atlantic coast at Jorf Lasfar, south of Casablanca. This is considered a "Gas to Power" project, with main objectives of Gas to Power projects being to meet electrical demand in the country and reduce dependence on energy imports [11]. This project was still in the tenders stage as of 2021, with implementation of the project at Jorf Lasfar planned to take place between 2021 and 2025. The plant will be of 2.4 GW capacity [4]. This $4.6 billion project is hoped to produce 7 billion cubic meters of natural gas by 2025 [16]. Small volumes of natural gas are produced in the Essaouria Basin and the Gharb Basin [11]. UK company SDX Energy owned five concessions in the Gharb region, where it has been producing natural gas and plans to drill more wells [12]. SDX plans to eventually produce 75,000 ktoe of natural gas per day in Morocco [16]. Tendrara natural gas field, near the border with Algeria, is being developed by Sound Energy from the UK. Sound Energy signed a deal in late 2019 to sell gas output from its Tendrara project to ONEE that will be used for ONEE thermal power plants. This will replace natural gas being supplied from Algeria at these plants. Natural gas will begin production in 2021 at the Tendrara location [4]. Sound Energy also plans to build a 120-km pipeline from Algeria to Spain, running through Morocco, as part of the deal [12].

Nuclear Energy

Morocco produces no nuclear power and imports no electricity generated from nuclear sources. Morocco does, however, have exploratory interest and legislative frameworks in place for nuclear resource. Morocco's Ministry of Energy, Mines, and Environment (MEME) discusses nuclear techniques could be applied in the energy sector as part of the Nuclear Power Program (NPP) [20]. Morocco first installed nuclear at a research center called Triga Mark II. This center is run by the National Center for Energy, Science, and Nuclear Techniques [20]. The only nuclear power plant currently planned is called the Sidi Boulbra nuclear power plant. This is planned for beyond 2030 [11]. Thus, it remains in an early planning stage. With the large phosphate industry, it has been found that phosphates from Morocco have large amounts of uranium. Recent studies by the IAEA show that phosphates in Morocco have close to 7 million tons of potential uranium [11].

Renewable Energy Generation

Photovoltaics (PV)

The solar irradiation in Morocco is significant and yet varies also significantly from one region to another. Northern Morocco sees around 2700 hours of sunshine per year while 3500 hours per year of sunshine are seen in the southern regions of the country [8]. Average solar irradiation in Morocco is 5 kWh/m^2 every day and 2300 kWh/m^2 annually [13, 21]. This is on top of the large potential from the open, unoccupied stretches of land in Morocco. Morocco has been moving to capitalize on this immense potential through healthy relationships with world bank institutions, private investments, and cooperation with independent power producers (IPPs).

November of 2009 saw the initiation of the Morocco Solar Plan and the beginning of the Moroccan Agency for Solar Energy (MASEN). This agency was established to oversee the solar power plant installations in the country. Along with its 2000 MW goals for wind and hydro, Moroccan Agency for Sustainable Energy (MASEN) plans to have installed solar capacity to at least 2000 MW by 2020 [5]. This plan was initiated in November 2009, with estimates of $9 billion investment in total for the "NOOR" solar program [13].

The installed capacity of solar was 180 MW in 2017, according to MASEN. This number soared to 705 MW in 2018 with the opening of new PV plants [14]. The first solar farm constructed was a 160 MW farm called Noor 1, which was connected to the grid in early 2016 by MASON [11]. Noor 1 is part of the larger 580 MW Noor Ouarzazate Solar Complex, one of the largest solar sites in the world, takes advantage of large desert land and intense solar irradiation and heat southeast of Marrakech. includes both standard Photovoltaic (PV) generation as well as a large Concentrated Solar Power (CSP) complex [4]. Noor Ouarzazate includes the following individual plants (Table 4):

Table 4 Solar capacities and technologies of the Ouarzazate site

Name of Ouarzazate plant	Capacity	Technology
Noor I	160 MW	CSP
Noor II	200 MW	Parabolic mirror
Noor III	100 MW	Solar tower
Noor IV	72 MW	PV

Source: Boulakhbar et al. [8]

Shandong Electric Power Construction Co., Ltd. from China constructed the large solar tower of Noor III, which towers 248 meters in the air [22].

Morocco is in prime position for continuing its growth of large-scale solar installations moving forward. Electricity production from solar was 1616.2 GWh in 2019 [15]. Future projects include a new PV plant planned to be constructed in the Atlas Mountains, generating 800 MW. This plant will also include standard solar generation as well as concentrating solar power [4]. The cost is estimated at US$781 million. The first section was awarded to Masdar, a firm out of Abu Dhabi, and Green Energy of Africa [7]. In January of 2021, Morocco put out a call for projects to add 400 MW of capacity [23].

Wind

Average wind potential has been shown to be at 5290 TWh/yr with a technical potential of 3264 TWh/yr [13]. Similar to the outstanding potential of solar in Morocco, some of the best potential wind generation sites in the world exist in Morocco. This can be attributed to Morocco's 3500 km of coastline, with wind speed at 80 meters up reaching 11.5 m/s. The installed capacity of wind was 1015 MW in 2017, according to MASEN. Notable windy regions in Morocco include the following:

- Strait of Gibraltar region
- Essaouira region
- Taza corridor between the mountain ranges of Atlas and Rif
- Tarfaya to Lagouira regions along the Atlantic

In June of 2010, Morocco's wind energy program was launched with a plan to increase wind capacity to 2000 MW by 2020 [11]. This goal matching the 2000 MW goal of the solar energy program and the hydroelectric goal of 2000 MW. The estimated cost of investment to achieve this aim was US$3.5 billion [24]. The goals of this program also include increase annual production capacity to 6600 GWh along with 26% of electricity generation mix, saving an estimated 5.6 million tons of CO_2 [24]. Morocco's installation target for 2030 is 2200 MW of wind [25].

In Morocco, private companies are allowed to develop projects under the Law 13-09. These private developers have sped up the renewable energy goals of Morocco. In fact, Morocco has updated the 2000 MW by 2020 goal to raise wind energy capacity to 2600 MW by the year 2030. This ambitious plan for wind has led to Morocco now holding the title of the largest wind energy plant in Africa: The Tarfaya wind farm, with a capacity of 300 MW [8]. This project was led by Nareva Holding, a Moroccan company owned by SNI, holding company of Morocco's king Mohammed VI [26]. The farm is run by Tarfaya Energy Company TAREC. The farm produced 1207.6 GWh and 1268.4 GWh in 2018 and 2019, respectively.

Five other wind power projects planned by ONEE, with development from a consortium of developers, were scheduled to come online in 2020:

- Tiskrad in south Morocco, 300 MW.
- Jbel Lahdid in northern Morocco, 200 MW.
- Midelt in northern Morocco, 150 MW.
- Tanger in north Morocco, 100 MW.
- Boujdour in northern Morocco, 100 MW.

Companies involved with these projects include Enel Green Power from Italy and Siemens Wind Power from Germany [4].

Electricity generation from wind started at 64 GWh in the year 2000. This rapidly grew to an annual wind generation of 728 GWh in 2012, 2519 GWh in 2015, and 4699 GWh in 2019 [10]. Despite the large energy output from wind in Morocco, most wind farms are not interconnected with the electrical grid or are not designed to efficiently integrate with the grid. This is largely due to the great distances between plants and consumers and the lack of upgraded, smart-grid infrastructure. This represents a major challenge for Morocco's grid infrastructure renovations being undertaken by ONEE [8].

Hydro

Hydropower in Morocco began to develop in the 1960s. The installed capacity of hydropower in Morocco has been steady over the last few decades at 1770 MW. Morocco is keen to improve the availability of water to its consumers, meaning that the contribution of hydroelectric will continue to be uncertain. Most of Morocco's new dam installations over the next two decades – around 60 dams – will be for irrigation and management of water resource rather than for power generation [8]. Overall, variability in water supply has been an issue and will continue to be with the variability associated with rising global temperatures. Variability in water resource has led to a variability of actual output from the hydro capacity. For example, the late 1990s saw hydroelectric output of below 1000 GWh annually, while output from the same dams was over 2000 GWh annually between 2013 and 2016. Hydropower sources in Morocco produced 1653.8 GWh for the grid in 2019 [15]. Morocco's goal of 2000 MW of new hydro capacity is being attained through construction of new hydroelectric dams and through Pumped Energy Transfer Stations (PETS). These are the integration of energy storage into existing hydroelectric dams. Future projects lined up include a total of 1652 MW of capacity as of 2019 [8]. An example is the PETS capacity at the Abdelmoumen project in the Agafir region, with capacity of 350 MW. This site will raise the hydropower capacity of Morocco to 2120 MW by the end of 2020 [8].

Ocean

Morocco currently has no wave energy research development or programs to develop wave energy. However, it has been found in numerous studies that wave potential off the coast of Morocco is significant. With more than 3500 km of coastline, this can contribute to Morocco's energy goals. Wave energy is still in a research and development stage globally. Many assessments of Morocco's coast display a wide variation of results for potential, with some focusing on average potential across the coast, finding wave energy potential between 2 and 6 kW/m, and others focusing on areas with high energy, finding a potential of 30 kW/m [27]. Another study attempts to analyze the effect of climate change on the wave energy resource along Morocco's coast [28].

Geothermal

Morocco has no current utilization of geothermal energy. However, there are hot springs in the northeast of the country and other indicators of potential geothermal use [29]. It is estimated that Morocco has 5.02 MW thermal and 22 GWh per year of potential geothermal energy [25].

Biomass

Morocco has significant biomass resources within its borders with 5,350,000 hectares of forest and 3,300,000 hectares of halfa. Morocco has over 9,000,000 hectares of agricultural land with 7,000,000 livestock animals [8]. The large agricultural nature of Morocco creates many organic components that can be utilized. Meanwhile, transitions from using wood for cooking have been rapidly occurring. The use of butane in residences has seen a growth of 67% in this period, while electricity consumption has grown by 50%. This has contributed to the decrease in biomass usage for cooking: Between 2007 and 2017, biomass usage for cooking dropped by 43%. Despite these trends, Biomass and waste still make up a larger part of the total primary energy supply in Morocco [14]. Both MASEN and IRESEN are involved with looking into the potential of using biomass as an energy resource. A biomass recovery strategy was initiated by the Department of Energy and Mines, financed by the EU. This strategy is currently involved in evaluating agricultural regions for the potential of biomass recovery with focus on agricultural waste [8]. The two regions studied show that recovery of agricultural waste could yield substantial energy potential if techniques exist for exploiting the resource [8]. The lack of water and inadequacy of incentives are a few major hurdles for biomass utilization [8].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

With a growth in renewable energies and a need to upgrade the energy infrastructure to integrate the renewables, there is an increasing need for energy storage technologies in Morocco. Present energy storage technology is lacking in the country. In 2004, the first big energy storage project in Morocco was commissioned – the 460 MW Afourer PETS station, a hydraulic system with two large reservoirs and hydroelectric production units.

Country's Future Storage Direction

Pumped hydro potential is high in Morocco, with the government developing these technologies. Morocco has high potential for Power to X technologies, integrating electricity with industrial chemical processes. Morocco is one of the best countries globally for Power to X technologies according to a study by World Energy Council Germany [8]. Total pumped hydro potential is thought to be 6000 MW [14]. In 2018, the government began studies into using pumping stations powered by PV as well as using solar water heating [14]. In the Taroudant province, a hydraulic storage system has been under construction since 2019 – The Abdelmoumen Wastewater Treatment Plant. This station was commissioned by ONEE with a construction contract of €284 million awarded to French company Vinci Construction in a consortium with Andritz Hydro. In this system, two water basins are connected via transfer line to a central hydroelectric plant [8]. This plant, composed of two stations, has a capacity to generate 175 MW from each [14].

Carbon Footprint

Most Recent Carbon Output

Currently, Climate Action Tracker predicts that the total greenhouse gas emissions in Morocco reduced by as much as 10% in 2020 due to the global pandemic [30]. They predict that total greenhouse gas emissions will be in the 80–120 MT of CO_2 equivalent in 2030. This would put Morocco on track to achieving its goal of being a 1.5 °C compatible country by 2030, despite the installation of coal-fired power plants and rise in emissions by then. (This goal is discussed in the section Geopolitical Circumstances) [30]. Morocco's government estimates that US$50 billion is needed in funding to reach its ambitious emissions targets [14].

Historical Trends of Carbon Footprint (Fig. 4)

Between 2006 and 2016, Morocco's use of CO_2 increased by 55 MT of CO_2 [14].

Types and Main Sources of Pollutants

Being so widespread, Morocco has over 5 million vehicles and a road network of over 62,000 km. Transportation in Morocco accounts for 50% of the national petroleum consumption and 35% of overall energy consumption. Pollution from transportation covers 15% of the total pollution in Morocco [8]. IRESEN is taking up the task of improving the electric vehicle integration into Morocco through major initiatives. This includes the Green Miles project: installing over 70 charging stations at various points throughout Morocco. However, 0.02% integration has been accomplished as of 2019, according to IRESEN [8].

Energy Resiliency

Electrical Grid

The grid in Morocco is dense and widespread throughout the country after construction began over five decades ago. Morocco began a rural electrification program in 1995, given that 48% of its population lived in rural areas [31]. The rural electrification program called PERG successfully raised electrification from only 14% in 1990 to over 99% in 2016. This rate was for nearly 350 rural villages in Morocco [11]. The grid now consists of 11,780 km of 60 kV lines, 9000 km of 225 kV lines, 3000 km of 400 kV lines, and 147 km of 150 kV lines. The grid is aging and weathering, with many old components combined with updated compo-

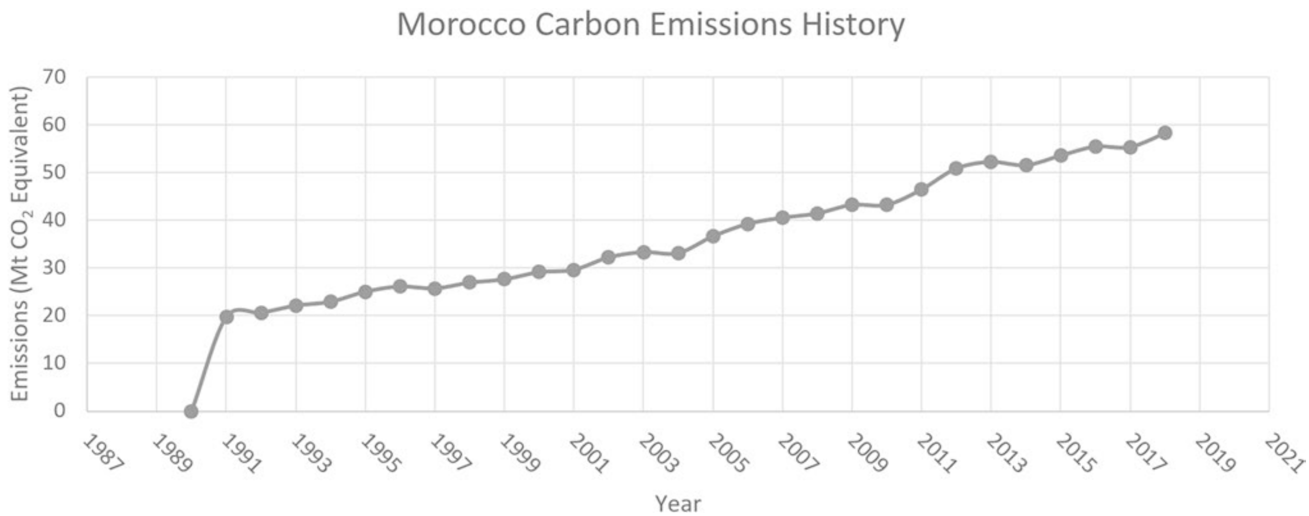

Fig. 4 CO_2 emissions over time. (Source: IEA data [10])

nents. The National Agency for Electricity and Water (ONEE) is working to expand and reinforce the grid [8]. These reinforcements include adding new transformers, new three-phase lines, and hundreds of additional 400 kV line installations. One of the first steps toward smart grid for renewables integration was a new control center created in Casablanca in 2008, simply called "Dispatching." This control center was a step toward technologies attempting to reduce electricity production losses. This is especially important in the context of Morocco's grid infrastructure issues: long distances, a high number of lines, and very cold winters [8]. The maximum energy demand for 2019 was 125.8 GWh seen on July 25, 2019, while the maximum demand reached 6.54 GW [15]. Currently ONEE is the only purchaser of electricity within the country. This includes power from renewable energy projects and independent power producers. Put into law 38-16 is the delegation that ONEE will give control of all renewable energy assets except pumped hydro plants to MASEN in a five-year period [8].In 2016, ONEE provided energy from its own plants (29.2%), through independent power products (52.9%), from imports (14.6%), and private commercial production (3.3%) [8].

Climate and Natural Disasters

Natural disasters that affected Morocco include exposure to droughts, flooding, and earthquakes. The country's location leaves Morocco vulnerable to increasing impacts of these as well as rising sea levels. Morocco has created a resilience partnership with the World Bank, including a $200 million Integrated Risk Management and Resilience Program [32].

Grid Resiliency

Morocco has made strides to improve its energy resiliency by way of renewable energy integration as well as interconnections with neighboring countries. Morocco has 1400 MW of capacity shared with Spain – the only electricity connection between North Africa and Europe. This capacity is planned to be raised by 700 MW via a new line. Morocco also has a shared capacity with Algeria of 1200 MW and is planning to connect lines to the country of Mauritania. Morocco also has a project lined up to connect a line with Portugal with a 1000 MW capacity [8]. Also under consideration is a massive project of connecting to the UK directly which would 1 day offer a 3 GW shared capacity [8]. These interconnections help bring Morocco into a position as the major player of regulating energy markets between the continents of Europe and Africa. Morocco has continued to show improvement and modernization of its electrical grid. For a better design of the energy sector, more renewable energy options should be explored, such as using more renewable power in agricultural management and using EVs to help stabilize the grid. The heating and cooling sectors can be utilizing more carbon-free options as well. The electrical grid can use more private investment from outside the country to continue to capitalize on Morocco's renewable energy potential. There is opportunity now, as the reduction of fossil fuels has been aided by the removal of many fossil fuel subsidies by the government. Medium and low voltage projects should be offered on the open market. European regulators can aid the process for establishing the necessary frameworks for these transitions.

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

Morocco has a high reliance on other countries to fulfill its fossil fuel needs. In fact, over 96% of Morocco's energy needs are supplied from imports. Gas is primarily imported from Algeria, oil from Saudi Arabia, and coal from South Africa and Russia [25]. Total energy imports were 525.8 GWh in 2019, making up 1.3% of the total 40,348 GWh requirement for the year [15].

Relations with Global Community/ Socioeconomic Influence

Morocco is investing in Africa to strengthen its partnerships across the continent. This is a major goal of King Muhammed VI. Some ONEE projects for the betterment of Africa's electrification include construction of a rural power plant in The Gambia, rural electrification concessions in Senegal, Mali, Chad, Niger, and The Gambia. Morocco is also an active member and contributor for the Mediterranean Energy Observatory (OME), The Association of African Electricity Companies (ASEA), the Maghreb Electricity Committee (COMELEC), the Arab Electricity Union (UAE), and the Global Sustainable Electricity Partnership (GSEP) [15]. Overall, Morocco enjoys good relations with its import and export partners as well as financing countries. Morocco's location and potential for renewable energy are playing a major role in connections made with other countries' grids, including interconnection deals with European countries. Morocco has also made significant promises at COP events, ensuring its place in the climate action environment. Morocco has been a host to many climate summits and is involved in open discussions of climate change efforts. The government has a National Committee for Climate Change, along with many other committees devoted to the topic. Morocco has made a commitment to reduce greenhouse gas emissions by 32% by 2030 [8]. This plan is included in Morocco's Intended Nationally Determined Contribution (INDC), which is further backed by Morocco's National Climate Plan enacted in 2019 [30]. The INDC focuses on the energy sector as well as industrial processes and agriculture, ensuring an economy-wide plan [33].

Key areas for focus listed in the INDC include the following:

- Reducing fossil fuel subsidies
- Increasing natural gas projects
- Renewable energy generation mix increase
- Reducing energy consumption in industry, transportation, and building by 15% by 2030
  Source: United Nations Environment Programme [29]

Morocco's main conflict is over the disputed Western Sahara territory. For decades, Morocco has been in conflict with the Algeria-backed Polisario Front, a liberation movement of the Sahrawi people, over the territory. There has been a ceasefire since 1991, with UN peacekeepers monitoring the situation. Morocco considers 85% of the territory to be its southern provinces, having constructed a berm that runs north to south separating the region. Neither side has compromised on the issue, with Morocco submitting multiple efforts for international recognition of the region [37]. Occasionally violence has occurred during the ceasefire. Notable was US President Trump acknowledging Morocco's sovereignty over the region in December of 2020 [38]. Morocco's relations with Spain were tested when the leader of the Polisario Front, Brahim Ghali, received hospital treatment for COVID-19 in 2021. Morocco's foreign ministry called the action "inconsistent with the spirit of partnership and good neighborliness" [39].

Education

Morocco has many free public universities. Universities throughout Morocco offer energy programs. Some examples include Abdelmalek Essaâdi University in North Morocco offering an Energy & Technology degree with specialization in Renewable Energy [40]. A Bachelor of Science in Renewable Energy Systems is offered at Al Akhawayn University in Ifrane, Morocco [41]. A private university, Université Internationale de Rabat (UIR), offers a master's in Engineering and Renewable Energy [42].

Summary

Current Energy Situation

Morocco has limited local energy resources being exploited [11]. Morocco is developing renewable energy domestically to supply electricity without relying on imports from other countries. However, fossil fuels are still more than 80% of total generation mix as recently as 2017 [4]. Morocco imports more hydrocarbons than it produces [4]. MIEM has stated that 90% of energy needs are still acquired from imports [5]. Overall Greenhouse Gas use is expected to nearly triple between 2010 numbers and 2040. Effective policies for increasing renewables and energy efficiency across all sectors are crucial for mitigating these emission counts. By 2020, renewable energy is planned to be 42% of installed capacity for generation. This amounts to 6 GW [3]. In 2018 alone, Morocco installed 3700 MW of renewable energy. This consisted of 711 MW of solar, 1220 MW of wind, and 1770 MW of hydro [5].

Renewable plants under development between the years 2018 and 2021:

- Taza wind farm, 150 MW, (IPP)
- 5 wind farm projects, 850 MW (IPP)
- Upping power at Abdelkhalek Torres wind park from 50 to 100 MW, extension of 200 MW added.
- Pumped Storage power plants: Akdelmoumen 350 MW, Ifahsa 300 MW, and El Menzel 300 MW.
- Photovoltaic plants: 570 MW total from Noor Tafilalt, Noor Atlas, and Noor Argana. (ONEE-managed)
- PV and CSP: 1320 MW total from Noor Ouarzazate, Noor Layoune, Noor Boujdour, and Noor Madelt (MASON-managed)
- Private companies: solar 740 MW, wind 220 MW, microhydraulic 126 MW. These projects are under framework of Law 13-09.

Renewable Plants Under Development [11]

Fig. 5 Renewable plants under development [11]

Future Energy Situation

Although fossil fuels still dominate the electricity generation in the country, Morocco has great renewable energy resource potentially from solar and wind. The Moroccan government has put great focus into developing these resources for electricity generation. MASON has an approach to this growth that is integrated and based on major pillars: electricity generation, R&D, local development, industrial development, training, and capacity building. Renewable capacity increased to 711 MW in 2018 [7]. Despite setbacks created by the coronavirus epidemic (estimated to set projects back by at least 2 years), Morocco will continue to be a leader in North Africa for transitions into renewable electricity generation [43] (Fig. 5).

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Nigeria

Slobodan Petrovic and Kaleb Edmunds

National Energy Introduction

Energy Policies

As Nigeria's energy needs continue to grow, production of energy sources must additionally increase. The Nigerian government has begun implementing policy to increase domestic consumption of natural gas and renewable energy sources. This would allow Nigeria to then continue to maintain production of fossil fuels such as crude oil for export to improve annual GDP.

For electrical energy policies, Nigeria has anticipated the implementation of several renewable energy technologies, primarily solar, hydroelectric, and nuclear. By 2030, Nigeria anticipates solar capacity to be upwards of 13 GW per year; for hydroelectric, although there is no hard numeric mile marker for generation or capacity, it is desired to increase power plants to provide power to rural communities and stabilize grid capacity during load shedding periods. Finally, although it will take several years to begin implementation, Nigeria is working with the International Atomic Energy Agency to begin design and implementation of nuclear power plants to provide continual power to the citizens of Nigeria.

Trends in Generation Technologies

Since the introduction of electricity generation in the nineteenth century, most of the electricity generation has been done via thermal and hydroelectric plants. The first thermal plants operated on coal and as time progressed, thermal plants that operated on natural gas were primarily utilized. As an alternative to thermal power plants, hydroelectric power has been slowly integrated into the Nigerian electrical grid. With the continual improvement on renewable energy technologies, Nigeria has begun implementing and organizing the development of solar and wind-generating stations throughout the country.

Domestic Resources

Primary energy resources in Nigeria are biomass, coal, oil, natural gas, hydroelectric, solar, and wind generation. The bulk of electricity generation stems from natural gas with an estimated total generating capacity of 8457.6 MW. Hydroelectric is the next most utilized electricity-generating resource with an estimated total capacity of 1938.4 MW [1]. Nigeria is one of the world's largest oil exporters with exports roughly 2096 million barrels per day (estimate from 2015) and relies heavily on this resource for national income [2, 3].

History of Energy

Coal had been the primary energy source for Nigeria from 1902 up until the 1960s for electricity generation [4]. Before this, biomass was the common fuel source for small heating and cooking needs. Like many developing countries, introduction of electricity into Nigeria did not occur until the late nineteenth century. The first electrical generating plant was introduced in 1896. Thirty years later, the Nigerian Electricity Supply Company was established as the first Nigerian utility company which had a capacity of 6200 MW output from a combination of hydroelectric and thermal electrical generation plants [5]. With only four generating plants, the Nigerian electrical grid was continuously unstable, resulting in the electricity sector requiring reform in 2001. This resulted in the privatization of electricity generation, and in 2005, the Electric Power Sector Reform Act allowed independent regulatory committee to oversee the development and growth of the Nigerian electricity markets [5].

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Breakdown of Energy Generation "Mix"

Energy Generation Mix (Fig. 1)

Energy Consumption Mix (Fig. 2)

Fossil Fuels

Oil

Nigeria is Africa's largest oil producer [6]. In 2018, there for four separate refineries capable of producing 445,000 barrels of crude per day [7]. Nigeria has very large oil reserves with an estimated 37.41 billion barrels empirically found, making it the sixth largest oil producer globally [2]. Oil and its derivatives accounted for 280,562 GWh (24,124 ktoe) of energy consumption by the year 2018 [8]. Oil is the largest energy source exported in the nation and has been the primary source of national GDP increase.

Coal

As of 2018, there remains an estimated maximum coal reserve of 2.75 billion tonnes with an empirical reserve of 650 million tons available for extraction [7]. With these potentials, it has been predicted that Nigeria can supply up to 53,900 MW capacity from coal thermal plants by the year 2030 [9].

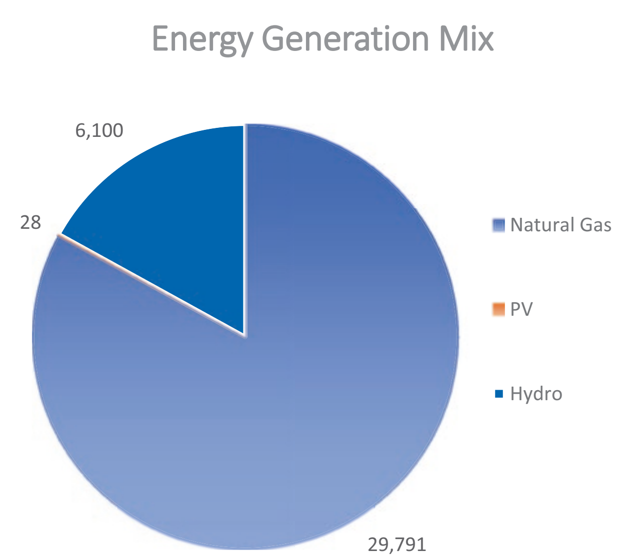

Fig. 1 Nigerian energy generation

Despite these large reserves and potential for usage in electrical generation, as of 2011, coal was only used for 0.4% of total grid electrification [10]. Most of the coal that is extracted and refined is used for export and non-electricity generation usage. An additional reason as to why coal is not commonly used for large-scale electricity generation is the general environmental concerns encompassed with using coal thermal plants [9].

Natural Gas

Natural gas is the primary source of electricity generation throughout Nigeria. Currently, Nigeria is the 41st ranked Natural Gas consumer and the 13th largest Natural Gas exporter globally [2]. With that level of natural gas extraction and production, Nigeria consumed roughly 29,791 GWh of electricity generated from natural gas [11].

Currently, Nigeria extracts and produces an estimated 44.48 billion cubic meters, with a remaining 34.69 billion cubic meters of estimated reserve per year [2, 12]. There is a total estimated volumetric reserve of 187.44 trillion cubic feet of natural gas reserves in Nigeria [10]. Despite producing large amounts of natural gas, there is only 17.24 billion cubic meters of domestic consumption [2].

There are currently four federally invested natural gas operating thermal plants. The plants generating installed capacity and names can be seen below [1] (Table 1).

Nigeria currently has an installed generation capacity of roughly 12 GW per year, but only can utilize 5 GW for grid integration. This is caused by issues with supply and demand of Natural Gas [7] in conjunction with other issues pertaining to grid capacity and transmission capabilities.

Nuclear Energy

Nuclear power generation does not currently exist in Nigeria. This partially is a result of the financial requirements to build and operate a nuclear plant, including the procurement of non-weapons grade reactive material for fuel. The additional complication is that with an already unstable grid, integration of nuclear may not be a wise decision.

As time progresses, Nigeria is hopeful that grid stability and population electrification will improve, at which point nuclear power integration may be a feasible option. In order to implement a Nuclear Power program by the year 2030 [10], the Nigerian government and Nigerian Atomic Energy Commission has been in communication with the International Atomic Energy Agency to generate an effective plan and integration program [7, 13].

Fig. 2 Nigerian energy consumption

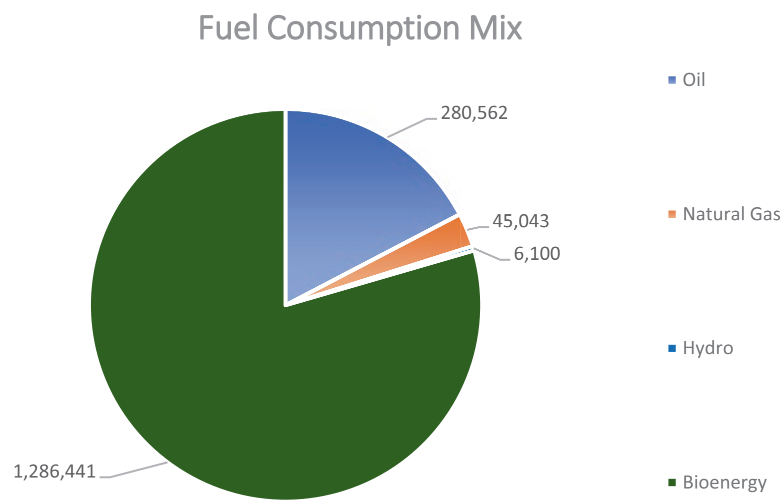

Table 1 Example of Nigerian thermal generators

Afam Power	776 MW
Sapele Power	414 MW
Egbin Power	1020 MW
Ughelli Power	900 MW

Renewable Energy Generation

Photovoltaics (PV)

In 2018, solar electricity generation equated to roughly 28 GWh according to the International Energy Agency [14]. The Nigerian government has plans on increasing solar electricity generation to 5 TWh by the year 2040 to help supply power to the grid [11], likely to prevent the necessity of fuels like oil which are in high export demand.

The Nigerian national irradiance average is 5.25 kWh/m^2/day. Values dependent on region vary between 3.5 and 7 kWh/m^2/day of irradiance. With the highest irradiation being in the North-North-East, the average solar intensity approximates to 2100–2200 kWh/m^2/year [15]. This is indicative that Nigeria is capable of meeting high energy demand that can be supplied from photovoltaic generation. In addition to PV power generation, as of 2019–2020, there is no solar thermal electricity generation in Nigeria and there is no known usage of solar thermal heating [16], but with high solar irradiance, there is potential for future installation.

Wind

Wind energy is not currently being used for electricity generation in Nigeria [7]. Previous predictive models indicated a hope for generation of 30 MW in 2015, but this has not been achieved yet [15]. Although not currently in use, Nigeria has hopes to be able to implement growth of up to 1 TWh by the year 2040 [17] with an installed capacity not fully utilized of 10 MW [18].

Hydro

During 2020, hydroelectricity generation was the third largest electricity production method utilized in Nigeria [11]. In 2019, Nigerian hydroelectric power plants generated roughly 6100 GWh of energy [19].

Hydroelectric is not utilized as largely as it should be. Most of the hydroelectric potential for Nigeria is derived from the Niger, Benue, Cross River, and Kano River systems. These large river systems unfortunately only account for 1930–2110 MW, or 13–15% of the total potential accessible within Nigeria [7, 20, 17]; as of 2018, hydroelectric power generation accounts for 19% of total grid electrification [7].

The Nigerian Ministry of Power and Ministry of Water Resources have been working together to boost the hydroelectric generation for the country. The Nigerian government is currently working on improving current medium hydroelectric plants such as the 30 MW Gurara 1 and 10 MW Tiga, while also currently constructing a massive 700 MW plant named Zungeru. The two largest hydroelectric plants, the Kainji Power Plant and Mambilla Power Plant, currently generate an estimated 760 MW and 3500 MW, respectively [5, 7, 19].

Increase of hydroelectric potential could be done by creating large hydroelectric power plants in the Jos, Bauchi, and Mambilla Plateaus for a cumulative 14,750 MW increase [20]. The downside to implementation of large hydroelectric plants is the sheer costs of design, construction, and operation and maintenance, in addition to a small workforce that has proper technical training on hydroelectric power plant operations. This issue has been a major hurdle in the implementation of small hydroelectric plants for usage in

Nigeria [21], so logic would dictate that it must be more difficult for projects that are significantly scaled up.

Although cost for implementation is a deciding factor in low implementation, higher hydroelectric generation could be done by implementing small hydroelectric power on the 278 rivers throughout the country; if implemented, hydroelectric generation could increase by up to 734 MW [20]. As many of the rural Nigerian communities are far from large rivers like the Niger, distribution to these communities from large hydroelectric power plants is not efficient. As an alternative, these are the locations in which small hydro would not only generate power for those who cannot be reached but would potentially add stability to the grid [21].

Biomass

As with many African countries, especially those with regional biomes that are not predominantly arid and desert like, agriculture has been a staple practice in many of the indigenous cultures. Biomass is largely used for individual usage in homes or communities. Biomass can be used for heating or cooling purposes which is typical for communities where electrification is poor. Biomass is additionally used for cooking purposes, and total energy consumption equates to 1,286,440 GWh for the entire nation.

Although not used, biomass can be an effective tool in steam-powered electricity generation systems. With the level of plant-based agriculture, Nigeria has a maximum energy potential of 1.011×10^6 GWh (3.64 Exajoules) of energy [22]. In addition to the plant-based biomass, Nigeria, on average, has a potential of 602,780 GWh per year (2.17 Exajoules) [22] of energy that could be produced from animal waste. Additionally, biomass, especially human and animal waste, has the potential to be converted into biogas. This can then be used as a combustible fuel for transportation, cooking, and electrical generation [23].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

There have been no known sources indicating that Nigeria currently utilizes energy storage techniques.

Country's Future Storage Direction

There has also been no indication of future for energy storage, which is a likely result as a need to improve the electrical grid before storage methods can be implemented. A potential option for storage would be the implementation of pumped hydroelectric systems. Specific potentials are unknown, but it would be logical to assume that pumped hydro could be used in conjunction with small hydroelectric plants in regions prone to load shedding. Large battery backup could be another option considered, but due to costs of installation, maintenance, and grid instability for recharging purposes, it would be recommended that battery backup be used for more isolated locations that have independent electricity generation, or for regions that utilize stand-alone renewable energy generation systems like solar.

Carbon Footprint

Most Recent Carbon Output

In 2018, Nigeria produced 104.3 megatons of CO_2. Most of these emissions are produced from oil (73 megatons) and natural gas (29 megatons), with the remaining 2.3 megatons coming from a combination of other electricity generation and energy consumption sources [8]. Breaking this down further, the Nigerian transportation sector (67 megatons) is the primary contributor of CO_2 emissions, followed by electricity/heat production (15 megatons). Industrial and residential only account for 9 megatons of CO_2 output [8]. If general carbon emissions are to be reduced, the transportation industry will likely need to be the primary focus.

Historical Trends of Carbon Footprint (Fig. 3)

Energy Resiliency

Electrical Grid

Nigeria's electric grid has a total installed capacity of 16,384 MW [18]. Only 60–62% of the population of Nigeria has simple and easy access to electricity supplied from the grid [2, 18]. Not only is this an undesirable percentage for the Nigerian government, as of 2012, an estimated 40% of total capacity can only be supplied from all generating locations [12]. This is a result of poor infrastructure related to the electrical generation, transmission, and distribution to the population. In addition to poor electrical infrastructure planning, there is very little redundancy due to transmission configuration, which causes larger geographical blackouts [24].

Plans to improve the electrical systems throughout Nigeria are currently taking place, but hurdles such as capital to conduct upgrades has been difficult to overcome. As a result, the Nigerian Electricity Regulatory Commission is

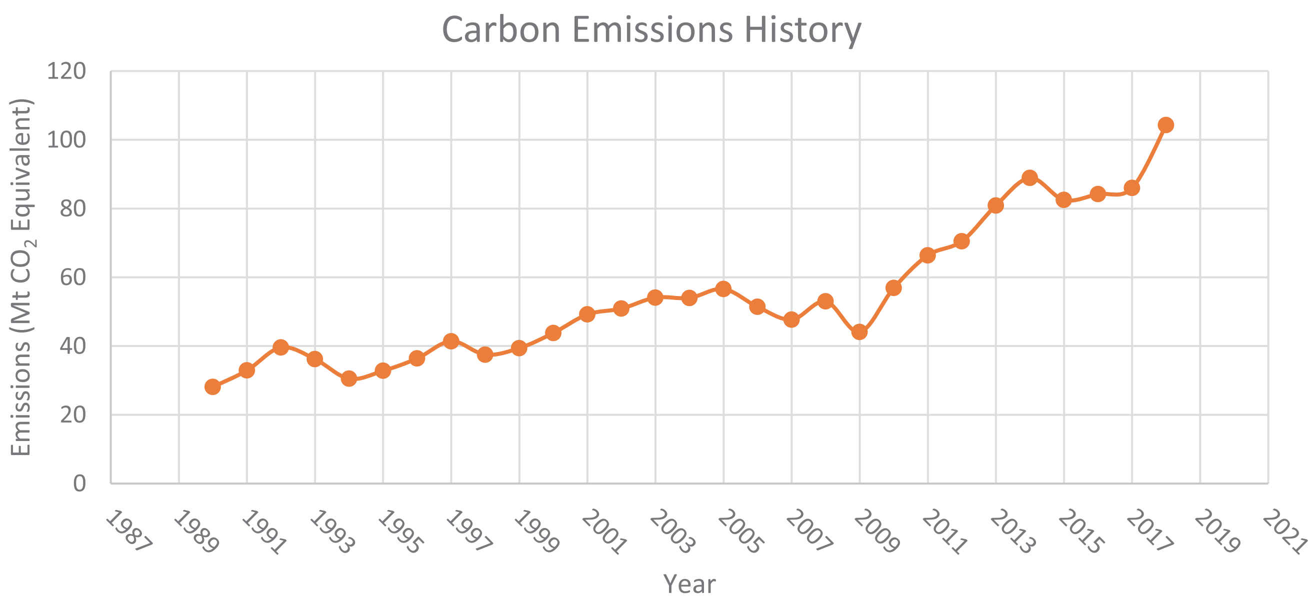

Fig. 3 Nigerian carbon emission history [8]

working on the privatization of generation plants in hopes that it will encourage investment opportunities that will benefit the Nigerian people and economy.

Climate and Natural Disasters

Climate change poses a major risk to Nigeria. As a sub-Saharan country, it is anticipated that climate change would increase average annual temperatures, and with a reduction in annual precipitation, parts of Nigeria would run the risk of severe and potentially long-term droughts [25]. Long-term droughts would result in a severe reduction of hydroelectric power generation, thereby worsening the national electrical grid more than its current state. This would additionally reduce the amount of water for individual consumption, which has its own humanitarian conflicts and issues.

An additional concern over climate change for Nigeria is the sea level rise. A study in 1994 predicted that if the coastal sea-levels were to increase by just 1 m, 3.2 million people will be displaced, and the Nigerian oil economy will take a major hit [26]. This would potentially decimate the local economy if oil production were severely affected. This would consequently have global impacts with potentially cascading effects, with other climate change concerns that would further harm the global economic and political atmospheres.

Grid Resiliency

Currently, the Nigerian electrical grid is already susceptible to blackouts and brownouts resulting from poor distribution capacity and grid overloading. This is indicative that if a natural disaster were to strike, the electrical grid could potentially collapse leaving millions without power. Rural communities have had to rely on private on-site generation to supply adequately the electrical demands of the area [24]. Although private generation for constant supply is a result of a poor electrical distribution from the national grid, this does show that rural communities may have localized electrical resiliency in the effects of natural disasters. Depending on the size of the generating devices (i.e., industrial sized generators for village electrification), additional power could potentially be added to the grid, therefore adding a small facet of resiliency.

Geopolitical Circumstances

Nigerian politics continues to be a complicated affair which creates national and international tensions. A report from the International Crisis Group identified six states within Nigeria that pose a high probability for social issues and potentially social conflicts [27]. With a diverse ethnic and religious population, future conflicts as results of these characteristics are anticipated to occur. In addition to civilian conflicts, Nigeria is home to the Boko Haram [27], a large terrorist organization.

With Nigerian government intervention, radicalization to join Boko Haram has increased and poses future security issues domestically. This also poses concerns over international relations as the Nigerian government may not be able to adequately confront the Boko Haram. In addition to the ethnic/religious issues in conjunction with Boko Haram, there has been an increase in domestic tensions because of Nigerian oil wealth not being distributed to the population. This may cause more tensions between the population, the Nigerian government, and international oil companies as it may be less desirable to potentially continue operation in the region; an alternative would be an increase in oil security which may cause future outrage among the local population and spark violent actions between the two.

Despite these conflicts, there has been international investments targeted toward Nigeria's energy sector. The United States, under both the Obama and Trump administrations, has worked to help to privatize the Nigerian energy sectors, with the addition of China investing in energy projects throughout the nation [27]. As a result, there may be an increased competition between American companies and foreign companies for land and resource rights.

Education

With a large renewable energy potential in Nigeria, it is important to educate those who may require the usage of these resources. There has been an increase in renewable energy training institutes for technician positions. An example of this is the Wavetra Energy Academy which has established solar energy training locations throughout Nigeria [28].

In addition to education increase because of market need, there have been international agencies helping with increased education. The United Nations Human Settlements Programme has been working with the Nigerian government to increase youth education in renewable energy topics [29].

The University of Nigeria has developed a research group combining multiple university faculty. This program is the Renewable and Alternative Energy Research Group and utilizes grant funding to further research into renewable generation technologies [30]. It is possible that this research group program may expand into renewable and alternative energy science and engineering programs at the University of Nigeria and other institutions.

Summary

Current Energy Situation

Despite having a large energy-based GDP, Nigeria remains poorly electrified. Much of the energy resources of the nation (i.e., oil and coal) are used for export rather than domestic energy consumption. With only 62% of the population able to receive electricity, the distribution of power is very poor. The nation also experiences rolling blackouts and load shedding, which further makes distribution difficult. Much of the energy consumption stems from bioenergy in the forms of biomass. This not only affects the nation's carbon footprint greatly but has the potential for decreasing local air quality [31].

Future Energy Situation

It is important that Nigeria seek investments to improve the national electrical grid to improve quality of life for the population. Current projects such as hydroelectric installation are a prime example of the methods the Nigerian government is taking to improve the nation's grid and equalize distribution of power to the people of Nigeria [32].

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Rwanda

Slobodan Petrovic and Jacob Ewing

National Energy Introduction

Rwanda is a landlocked country in the Great Rift Valley in Central Africa and is home to around 12,943,132 people. Initially under German colonial rule in 1898, Belgian forces captured Rwanda in 1916 during World War I; Rwanda established its independence in 1962 [1]. Historically, Rwanda is fairly unique in the energy sector; until 2004, Rwanda relied solely on hydropower for electricity, and heavily used, and still uses, primarily biomass for heating and cooking. In late 2004, the Rwandan government made the choice of renting diesel generators from private companies at high cost to provide more energy to the country [2]. The Rwanda Energy Group (REG) was established in 2014 and is a government-owned holding company that is responsible for all import, export, generation, and transmission of electricity in Rwanda [3]. Though historically Rwanda was primarily powered by hydropower, still to this day hydropower contributes to over half of the country's electricity generation and has various new projects in the works.

Energy Policies

Energy policies in Rwanda were not very prevalent over the last decade as the country is still forming a grid and energy generation. There are several important newer policies to note, such as the 2019 National Environment and Climate Change policy, 2019 National Cooling Strategy, 2015 Rwanda Energy policy, and an Extended Producer Responsibility (EPR) [4]. The National Environment policy sets forth to promote a green efficient economy that is low-carbon and advances sustainable consumption and production patterns [5]. The 2019 National Cooling Strategy provides context and regulations for space conditioning and refrigeration by using better insulation, natural ventilation and more to reduce the amount of electricity wasted [5]. The 2015 Rwanda Energy Policy revised from the original NEP promotes energy efficiency through a combination of approaches such as regulations, new codes and standards, introduction of economic incentives [6]. A notable mention is that the Rwanda government is working with Kenya on an Extended Producer Responsibility to pass legislation to promote recycling and e-waste management.

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Domestic Resources

The main domestic fossil fuel resource in Rwanda is methane gas; there is an estimated 50 billion cubic meters of methane lying at the bottom of Lake Kivu, and much more already on reserve. There are also abundant peat and wood resources throughout the country that are used for cooking and heating. As mentioned previously, Rwanda is also well off in the world of hydropower, though landlocked Rwanda has various water resources, including rivers and streams to be used for power. Additionally, Rwanda has a high solar radiation which could be promising for future solar power growth. There are some areas that may be promising for wind power, but they have not been fully exploited for the country [7].

Breakdown of Energy Generation "Mix"

Energy Generation Mix

Rwanda has excellent potential when it comes to natural energy resources with hydro, solar, and methane gas. Though the country is only about 65% electrified (12% in rural areas, 72% in urban areas), it has a total of 235 MW of generating capacity installed [8]. While less than half of the population has access to electricity, Rwanda only imports 11% of their electricity that is consumed.

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Hydropower and methane gas make up most of the electricity consumed within the country, backed by smaller amounts produced by thermal, peat, and solar power. Out of the total 235 MW of installed capacity, 50% of the capacity is produced by hydropower. Additionally, there are various off-grid and micro hydropower plants across the country that may not be accounted for. The rest of Rwanda's generating capacity is produced by methane (20%), peat (17%), solar (8%), and finally diesel (5%) [8, 9]. Biomass is not included in capacity or consumption charts as they are largely used for residential heating and cooking in homes (Fig. 1).

Energy Consumption Mix (Fig. 2)

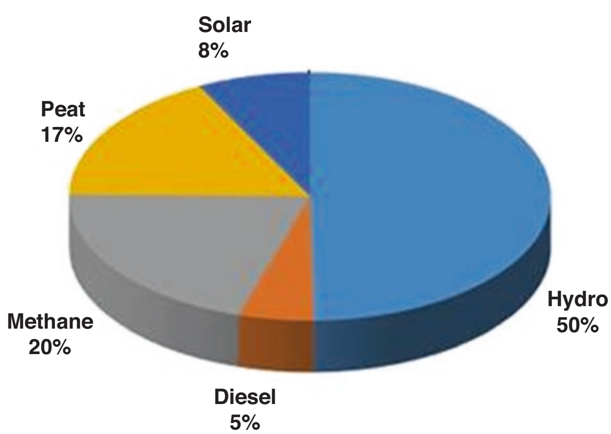

Fig. 1 Breakdown of the energy generation mix for Rwanda provided by the Rwanda Energy Group [9]

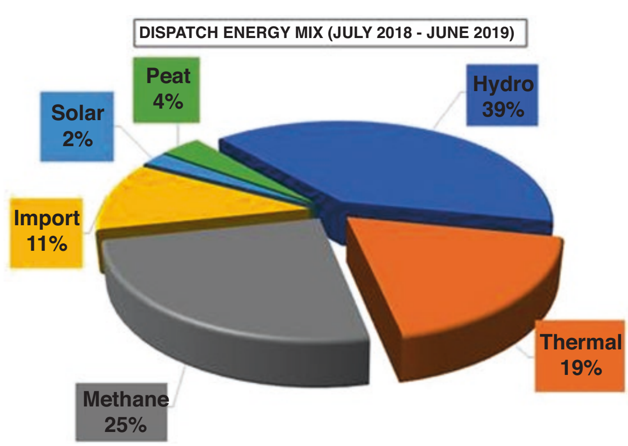

Fig. 2 Breakdown of the energy consumption mix for Rwanda from 2018 to 2019 provided by the Rwanda Energy Group [9]

Fossil Fuels

Oil

Rwanda does not currently produce or extract any crude oil domestically and does not have an oil refinery. However, the country does operate five diesel thermal power plants that account for 26% of the total electricity [9]. All crude oil and petroleum products must be imported. The total imported and consumed refined petroleum products for the country is estimated in 2016 at 6700 bbl/day [10]. In 2019, Rwanda imported $411 M in Refined Petroleum, being the first most imported product of the country. Refined petroleum is primarily imported from the United Arab Emirates, Saudi Arabia, Switzerland, and India [11]. There is not a large potential of crude oil or petroleum for the country as there is estimated to be no oil reserves in the country [10].

Coal

Rwanda does not have any means of producing or consuming coal in any manner. As of 2016, the country does not import nor export any coal. There are estimated to be no coal mines or reserves throughout the country [12].

Natural Gas

Current natural gas usage in Rwanda is limited to the usage of methane. There are currently two methane power projects producing around 50 MW of methane to be used [13]. As of now, it is not reported that Rwanda imports or exports any natural gasses. Proven gas reserves are estimated around 56 billion m^3, primarily methane gas located in Lake Kivu. In 2019, a $400 million deal was signed to extract and process methane from Lake Kivu and was expected to be ready to use within 2 years. This will not only serve various households that rely solely on wood for cooking but will likely also increase Rwanda's export of natural gasses [14].

Nuclear Energy

Currently, there are no active nuclear energy policies or generating power plants in Rwanda. In 2018, Rwanda and Russia agreed on a roadmap for an inter-governmental agreement on the use of nuclear energy [15]. The Rwandan cabinet approved the establishment of the Rwanda Atomic Energy Board – an institution to coordinate nuclear science and technology activities in the country [15]. This will build a nuclear research center and a reactor in the capital of Rwanda, Kigali. The Center of Nuclear Science and Technologies and a research reactor with a 10 MW capacity are planned for completion by 2024. There are no other future plans for the country, and it does not have known sources of nuclear fuel.

Renewable Energy Generation

Photovoltaics (PV)

Solar irradiation throughout Rwanda is quite high, between 4 and 6 kWh/m^2 per day, making for excellent PV potential. PV growth and install rate is largely reduced due to high initial costs and load limitations. The cumulative power generated by solar plants in the country is just over 12 MW from five large solar power plants installed on-grid [16]. Surprisingly, just under half of the total capacity is estimated to be dispatched or used by the country.

In 2014, the largest power plant in Rwanda, the Rwamagana Solar Power Station was installed and had a capacity of 8.5 MW. Gigawatt Global was the organization who financed and installed this solar plant, and it was later taken over by the Rwanda Energy Group [16]. The Government of Rwanda has plans to and intends to increase solar power plants throughout the country to take advantage of the available resources. In 2018, a Memorandum was signed to develop a 30 MW solar power plant with an energy storage facility in Rwanda [16].

Wind

Wind potential has not been fully explored for Rwanda, with only one study from 1985 to 1993 on wind speed. This study summarized the wind direction and average wind speeds from three different cities' weather stations. These weather stations used anemometers installed 10 m above ground level. The results revealed that wind direction varies from 11 to 16 degrees, and wind speed varies from 2.5 to 5 m/s [17].

The wind speeds extracted from the results are high enough to be used for water pumping or windmills. In 2010, a wind system was constructed to serve the Rwanda office of information on Mount Jali, which overlooks the country's capital, Kigali. It is not a large system to provide any notable power to the grid, but it serves the office alongside the same site of the 250 KW solar system connected to the grid on Mount Jali [17].

Hydro

Throughout the history of Rwanda, there has been a high use of hydropower, and this has increased evermore over the last decade. There are 37 grid connected hydropower plants in Rwanda that account for nearly 120 MW of installed capacity, which is over 50% of the country's total capacity [18]. Hydropower usage accounts for 39% of Rwanda's total energy usage, which is a total of 527 m kWh [19]. The largest current operating power plant in Rwanda is the Rusizi II Hydroelectric Power Station, with a total capacity of 44 MW. This power plant was installed in 1989 and is operated by the SNEL [20].

Historically, there has always been great potential for hydro in Rwanda, and continues to be the case; feasibility studies are under implementation for large dams with a 400 MW capacity. Among those dams are current projects Rusizi III 48 MW and Rusumo Falls 26 MW that are planned to be completed within the next few years [9]. In an attempt to address the low rural electricity access of the country, the government has begun a sizable micro hydro development program to provide power to rural villages. In total, there are 23 government-initiated projects that will deliver an additional 14 MW of power to rural areas [21].

Ocean

As Rwanda is landlocked there is no ocean power generated or used throughout the country. Without any generating plants or ocean, there is not any ocean energy potential nor future plans. The only access to ocean energy would come from imported energy from the nearest coastline countries of Kenya and Tanzania.

Geothermal

Rwanda currently does not have any geothermal plants producing power, though the country is thought to have good geothermal potential in the form of hot springs. Geothermal energy is a main energy policy priority for Rwanda's electricity strategy. Serious investigations for geothermal production began in 2006 at four potential sites; the studies concluded a geothermal energy potential of around 100 MW for the country. Two of the four sites we found to be risky areas for geothermal production, and the others are now being explored via drilling and well testing to further the investigation [22].

Biomass

Due to the energy crisis of Rwanda and having only 65% of the country electrified, there has been an extremely large use of biomass within households to heat and cook in homes. The current national energy statistics show that biomass, primarily wood, accounts for around 85% of total energy consumption [2].

The large demand for wood throughout the country has increased the price of wood and is posing a problem for the population. The Rwandan government plans to cut biomass use by 50% by 2024 and is actively setting strict tree-cutting laws alongside implementing forestry programs. This is largely because the country operates at a deficit with biomass usage and it is not sustainable for the country [2]. Additionally, there are projects to improve charcoal stoves, and implement electric and gas stoves for cooking.

Peat is also a widely used form of power generation within Rwanda with large reserves and a few peat to power plants. The country has a 15 MW peat-powered plant and has another 80 MW peat-fired plant as a current project in the Gisagara district [9].

Biofuels

To reduce biomass usage, in 2007, the National Domestic Biogas Program focused on capacity development in Rwanda. The market for biogas is estimated at around 150,000 households, being primarily rural customers. In 2008, the government announced and implemented biogas digesters in all schools and over 10,000 have been installed into households to reduce firewood usage. Since Rwanda has no domestic gas production, it relies on importing LPG and Kerosene as alternatives, though the two have not made a notable impact in reducing biomass usage yet [23].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

There are no large-scale energy storage systems currently in place within Rwanda. Battery storage technology does exist throughout the country in small forms, in rural villages that have small-scale solar and hydropower off grid.

Country's Future Storage Direction

In 2018, the government signed a plan to produce a 30 MW solar plant with a power storage facility, which could very well push the country into investing more into on- and off-grid storage technologies [24].

Carbon Footprint

Most Recent Carbon Output

Total annual CO_2 emission for Rwanda was 1.08 million tons in 2018. This is the most CO_2 emission produced in the history of Rwanda, as CO_2 emission has been greatly increasing over the last 8 years.

Historical Trends of Carbon Footprint

Previously, in the 1980s, the country's CO_2 emission peaked at around 0.7 million tons of CO_2, but in the 1990s, the emission dropped to around 0.5 million tons and stayed there until the late 2000s [25] (Fig. 3).

Types and Main Sources of Pollutants

As over 40% of Rwanda's energy production comes from fossil fuels, and the need for electricity is growing, increasing CO2 emission will only continue year by year, especially since Rwanda is a developing country [25]. However, Rwanda contributes to less than 0.004% of the world's total CO_2 emission annually. If the country continues to utilize hydropower and focus heavily on installing PV systems, then it is possible the emission can remain relatively low.

Energy Resiliency

Electrical Grid

The Rwandan national grid is managed and operated by the government entity Rwanda Energy Group (REG), which was incorporated to expand, operate, and maintain the energy grid. Over the last 7 years, a total of over 16,000 km of distribution voltage lines have been constructed to provide electricity, including low voltage and 30 kV, 15 kV, 17 kV, and 5.5 kV high voltage lines [27]. By 2019, REG has laid nearly 1300 high voltage transmission lines between the country's various peat, hydropower plants and substations. As of June 2021, 65% of households were connected to the national grid, though primarily urban [28].

Improvement projects are actively being performed on the nation's electrical grid. These maintenance and improvements are largely funded by the Kingdom of Belgium and the Government of Rwanda. To improve access and grid reliabil-

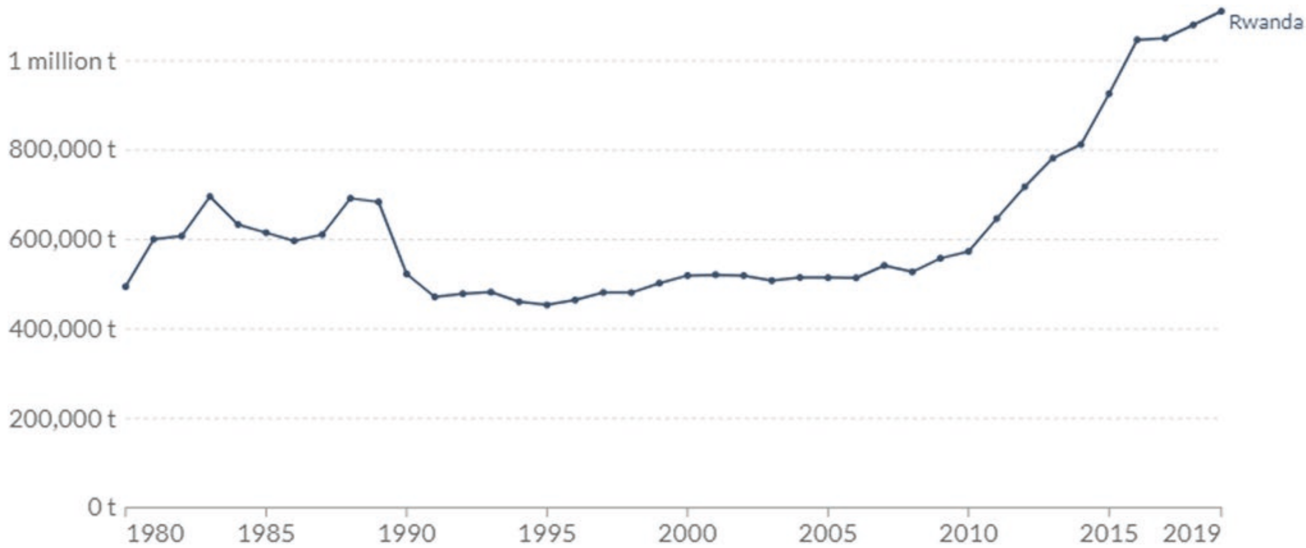

Fig. 3 Rwanda's annual CO_2 emissions [26]

ity, REG is making single to three phase upgrades, upgrading MV and LV lines, extending the grid, and adding protection systems [29].

Climate and Natural Disasters

Rwanda, like any other country, is still prone to natural disasters and have experienced a growing number of them over the last decade. Droughts and floods are common disasters that affect the population, increasingly so with climate change. These disasters are particularly dangerous as the country relies heavily on hydropower as a resource and these climate-related disasters can decrease power output from that. Rwanda is also prone to earthquakes and landslides. Forty percent of the country's population has a moderate to high level of susceptibility to landslides [30].

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

Rwanda is dependent on other countries to meet their energy demand by having to import refined petroleum and diesel to power the country. This is due to Rwanda not producing any crude oil or having the means to refine it. In 2019, $411 M of refined petroleum was imported into the country, primarily by China, Kenya, and the United Arab Emirates. Aside from using the petroleum for fuel, in 2019 $137 M of refined petroleum was exported [31].

Relations with Global Community/ Socioeconomic Influence

Rwanda is a party to the Paris Climate Accord, and among other recent energy policies has a vision and goals to become climate-resilient. To achieve the Vision 2050 target and meet commitments, Rwanda has prepared an ambitious climate plan to reduce greenhouse gas emissions by 38% by 2030. In addition to having 100% of households have electricity by 2024, Rwandans will also plant more than 25 million trees to contribute to global climate action [32].

Summary

Current Energy Situation

Rwanda, as a developing country may be struggling to meet power and electricity demands without importing for the entire country, but is proactively trying to increase sustainable energy production and improve the grid. Historically, and to this day, Rwanda relies on the 50% installed capacity of hydropower and intends to continue to build hydro and improve on current systems. Solar accounts for a small amount of energy production, with high energy potential, Rwanda plans to utilize this by increasing solar installations. With large amounts of biomass and diesel thermal power production, the Rwandan government intends to reduce biomass and fossil fuel usage to be more carbon neutral. The implementation of new methane gas plants, and larger hydro plant expansions may assist by increasing total production capacity to meet the increasing energy demands as the rest of the country becomes electrified.

Future Energy Situation

The Rwandan government is starting to become quite proactive by implementing new energy policies, taking climate initiatives to increase sustainable energy production and reduce impact on the climate. There may be some private investment into the energy sector, but energy improvements will largely be funded by government and international organizations. The country may face natural disasters, such as floods and droughts, in the future. However, expending solar photovoltaic capacities and introducing more green energy practices will improve Rwand's energy system.

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South Africa

Slobodan Petrovic and Nathan Margoshes

National Energy Introduction

Energy Policies

South Africa has a few key policies directing their energy sector. The White Paper on Energy Policy and The White Paper on the Renewable Energy Policy are both overall policies directing the importance of energy, and how South Africa should approach energy. The White Paper on Energy Policy lays down key objectives such as increasing access to affordable energy services, improving energy governance, stimulating economic development, managing energy related environmental and health impacts, and securing supply through diversity [1]. The White Paper on the Renewable Energy Policy, enacted in 2003, directs the long-term goal of renewable energy, calling for 10,000 GWh to be achieved over 10 years. The current guiding policies are The Integrated Resource Plan 2010–2030 and The Integrated Resource Plan 2019. The IRP 2010–2030 pushes for doubling the existing energy capacity, and increasing the diversity of energy sources. The IRP 2019 calls for 2500 MW of nuclear power to be part of the energy mix, and calls for the extension of the life cycle of the Koeberg Nuclear Power Station by 20 years [1].

Trends in Generation Technologies

Since 2010, South Africa has had a very consistent energy generation mix, characterized by a high reliance on coal. There has been a very slow increase in the rate of renewable energy penetration; however, coal is still the dominating generations source [2] (Fig. 1).

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Domestic Resources

South Africa has a large amount of coal reserves, estimated at 53 billion tonnes, but very little oil and natural gas. South Africa was under Dutch colonization in the seventeenth century, and under British colonization in the eighteenth and nineteenth centuries. South Africa acquired nominal independence in 1909, and complete independence in 1931 with the passage of the Statute of Westminster.

Breakdown of Energy Generation "Mix"

Energy Generation Mix

South Africa's energy sector is dominated by coal. Coal accounts for over 85% of the electricity generation. The remaining 15% is split between oil, natural gas, nuclear, solar, wind, and hydro [2] (Fig. 2).

Energy Consumption Mix

Due to the prevalence of coal as a generation fuel, coal dominates the energy consumption mix as well. Oil accounts for 21.9%, coal 70.6%, natural gas 2.8%, nuclear 2.3%, solar 0.8%, wind 1.1%, and hydro 0.1% [2] (Fig. 3).

Fossil Fuels

Oil

As of 2018, South Africa consumed 674,000 bbl/day of petroleum products for both transportation and electricity generation, and generated 5340 GWh from oil [2, 3]. As of 2018, South Africa did not have a large oil production industry. South Africa produced an estimated 1600 bbl/day, exported an estimated 0 bbl/day, and imported and estimated

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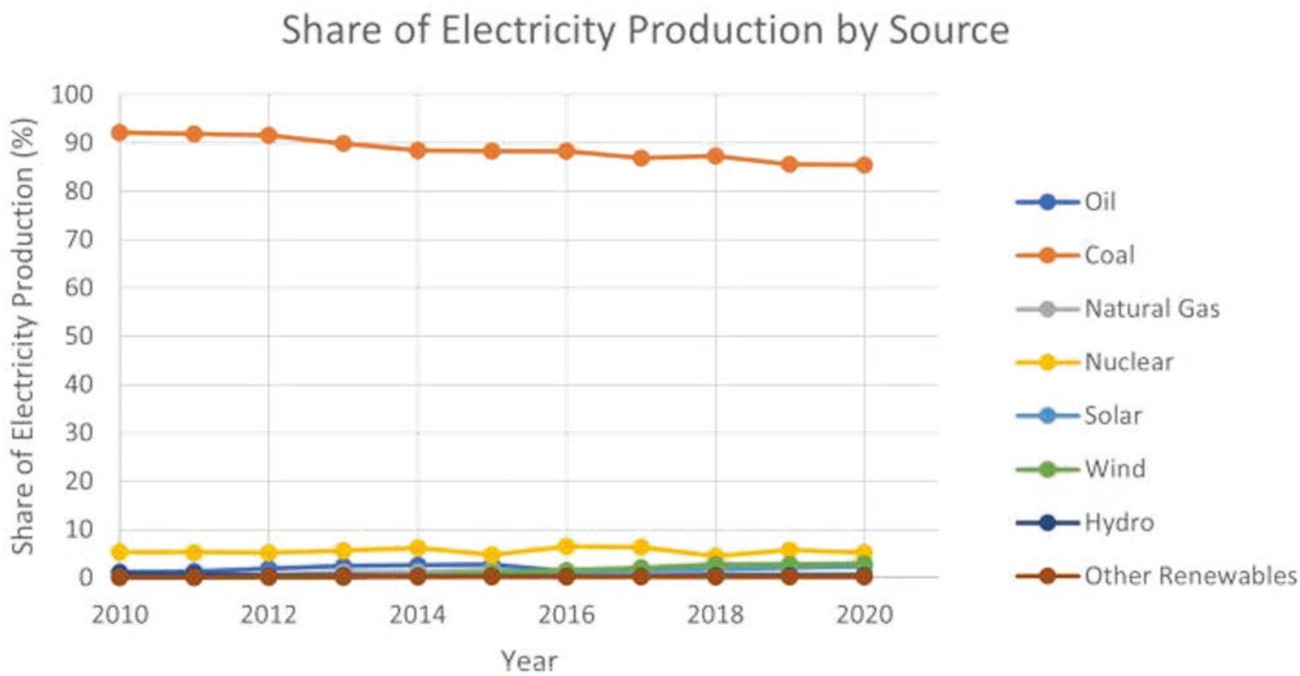

Fig. 1 Historical trends of electricity generation by source for South Africa

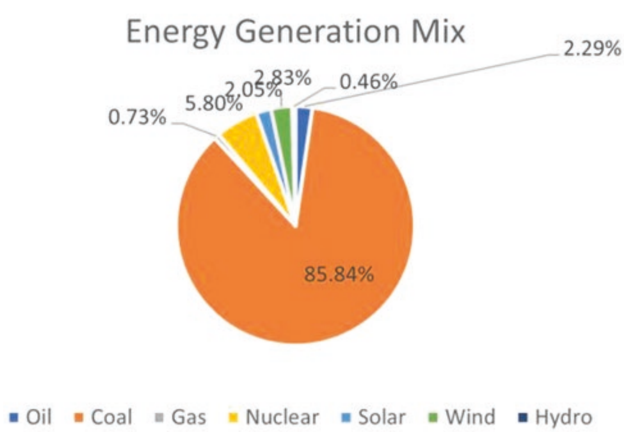

Fig. 2 The energy generation mix of South Africa [1]

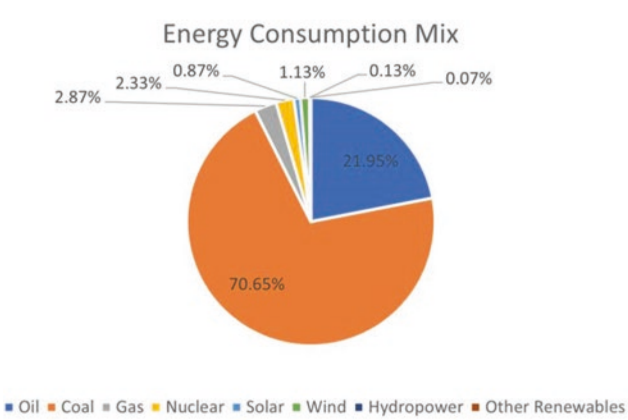

Fig. 3 The energy consumption mix of South Africa [2]

404,000 bbl/day of crude oil. South Africa produced an estimated 487,100 bbl/day, exported an estimated 105,600 bbl/day, and imported an estimated 195,200 bbl/day of refined petroleum products [4]. Due to South Africa's minimal oil production, almost all of their crude oil is imported. Over 90% of the imported oil comes from Saudi Arabia, Nigeria, and Angola. Specifically, 51% comes from Africa, 45% from the Middle East, 2% from Europe, 1% from Asia, and 1% from America. The Middle East supplies 51% of their refined petroleum products, Asia 38%, Europe 5%, Africa 4%, and others 2% [5]. South Africa has 15 million barrels of proven oil reserves, all of which are on shore in the Bredasdorp basin of southern South Africa, and near the maritime border of Namibia on the western coast [3].

Coal

As of 2018, South Africa had 39,000 MW of coal generation capacity, consumed 177,641 million metric tons of coal, and generated 206,940 GWh from coal [2, 3]. In 2018, South Africa produced 258,666 million metric tons of coal, exported 80,190 million metric tons, and imported 3008 million metric tons. South Africa uses 75% of the coal produced for domestic usage, and exports 24%. Only 1% of the countries coal is from imports [5]. South Africa has an estimated 53 billion tonnes of coal reserves [6].

Natural Gas

In 2018, South Africa consumed 4.8 billion cubic meters of natural gas and generated 1700 GWh from natural gas [2, 3]. In 2018, South Africa produced 1.1 billion cubic meters, exported 0 cubic meters, and imported 3.7 billion cubic meters of natural gas [3]. Due to South Africa's minimal natural gas reserves, most of their natural gas must be imported, which is supplied entirely by Mozambique [3]. While South Africa does not have any known reserves of natural gas, a study has shown that South Africa is home to the eighth largest shale gas reserves in the world, at an estimated 11.04 trillion cubic meters [3].

Nuclear Energy

South Africa takes an optimistic approach to nuclear energy. The Government's intent is to promote nuclear energy, and create a safe and secure framework that will allow nuclear to thrive with minimal environmental impact [1]. South Africa has one nuclear power plant, which consists of two reactors, Koeberg 1 and Koeberg 2. These reactors have a combined capacity of 1860 MW. From this 13,600 GWh of electricity were produced. In 2019, plans were outlined with the intent to build an additional 1000 MW of nuclear energy by 2030 [2, 7]. Currently, South Africa receives half of its fuel from Russia; however, South Africa is hoping to be self- sufficient with its uranium needs. Currently uranium production within South Africa is a result of gold and copper mining, uranium is found as a by-product [7].

Renewable Energy Generation

Photovoltaics (PV)

As of 2020 South Africa had 2320 MW of solar capacity installed and generated 5690 GWh from solar [2, 8]. The largest solar farm in South Africa is the De Aar solar plant. This 175 MW plant began operation in 2016 and was built by Solar Capital, a subsidiary of the Phelan Energy Group [9]. South Africa has a high solar potential. South Africa receives over 2500 h of sunshine each year, and the average irradiation ranges from 4.5 to 6.5 kWh/m^2/day [10, 11].

The future of solar power in South Africa comes from both the city level and the government level. Recently, the energy ministry approved the request from cities to allow them to source their own electricity, rather than be forced to buy from Eksom, the state utility company. Following this, major cities such as Johannesburg and Cape Town have plans to diversify their energy sources and use more renewables [12]. Additionally, in the 2010 Integrated Resource Plan, it is stated that the intent is to increase the solar capacity to 9.6 GW by 2030 [10] (Fig. 4).

Wind

As of 2019, South Africa had 2100 MW of wind power capacity and generated 6620 GWh from wind [2, 3]. The largest wind farm in South Africa is the Kangnas wind farm. This 140 MW wind farm was constructed by Concor and Conco Consortium and Siemens Gamesa Renewable Energy, and began operation in November 2020 [13]. It is estimated that South Africa has 6700 GW of wind potential [14]. Most of South Africa has sufficient wind speeds for wind power, with average speeds ranging from around 4–9 m/s [15]. Currently 3366 MW of wind capacity has been contracted for completion by 2022. Additionally, the 2016 Integrated Resource Plan calls for 37,400 GW of wind power to be added by 2050 [10].

Hydro

As of 2020, South Africa had 3596 MW of conventional hydro power and pumped hydro storage capacity and generated 5670 GWh of electricity from these sources [16]. The largest conventional hydroelectric power plant is the Gariep Dam, a 360 MW dam that began operation in 1971 and is owned by Eskom [17]. The largest pumped hydro plant is the Ingula Pumped Storage Scheme, a 1330 MW storage facility which began operation in 2016 and is owned by Eskom [18]. It is estimated that there are 247 MW of micro hydro power potential in South Africa.

Ocean

As of 2020, South Africa does not have any ocean energy generation capacity. As of 2013, the tidal currents around South Africa were not sufficient for tidal power, with velocities of 1.5 m/s [19]. From wave energy, the coastal waves around South Africa have energy potentials between 25 and 50 MW/km, which means there is an estimated total wave power of 56,800 MW along the South African coast [20]. Currently Eskom is investigating the potential of wave energy in South Africa, though there are no concrete plans at this time [21].

Geothermal

As of 2019, South Africa does not have any geothermal energy generation capacity. While more studies will need to

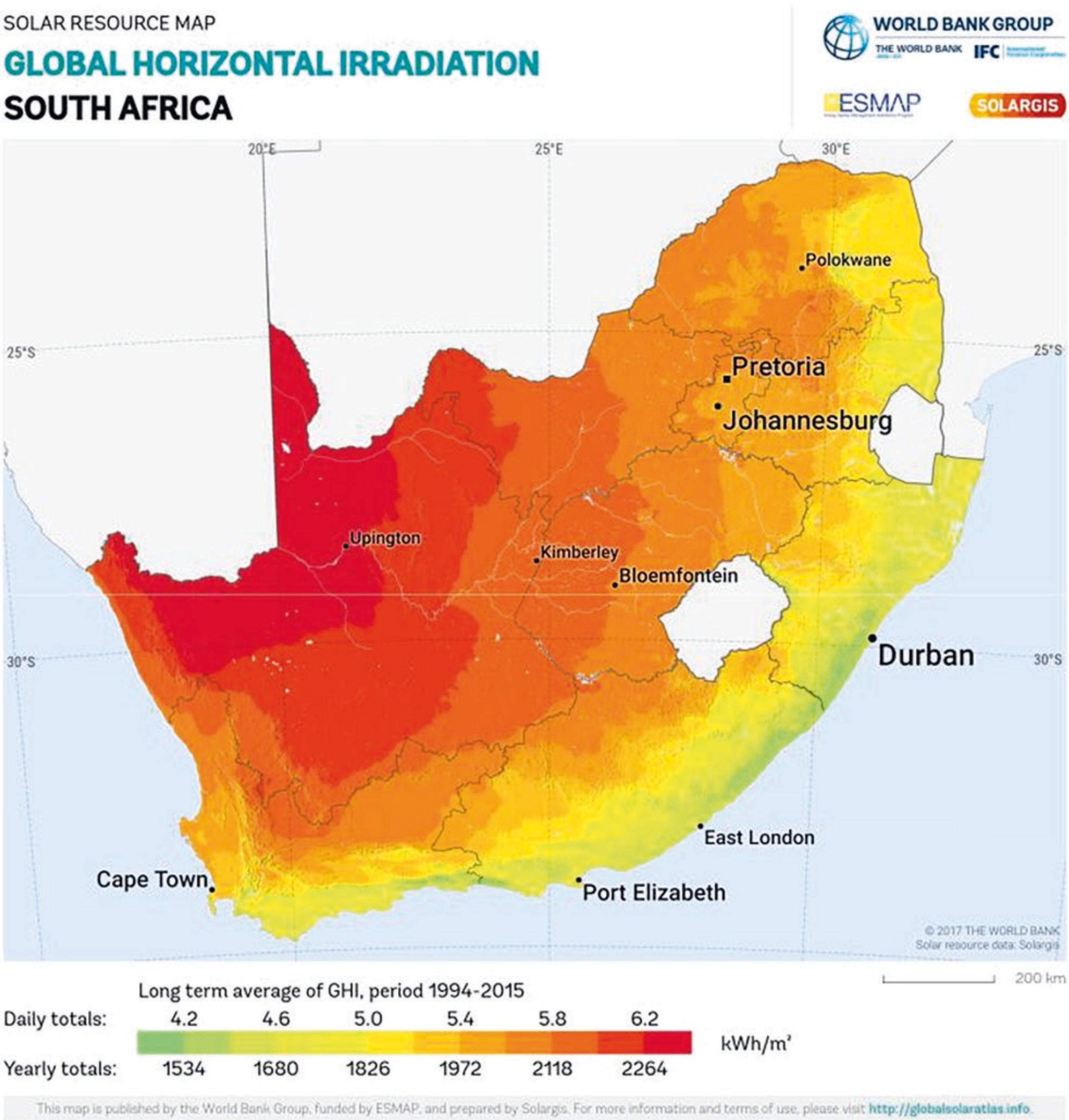

Fig. 4 The average global horizontal irradiance of South Africa

be done to achieve an exact number, there is theoretical geothermal potential in South Africa. Studies have shown that there is geothermal potential in Namaqualand, south and west Upington, and the northern part of Kwazulu-Natal [22]. As of 2019, there are no notable plans for geothermal implementation in South Africa.

Biomass

Bioenergy is still immature in South Africa. While biomass is used across the country at residences for traditional uses such as cooking, it does not have much use as a generation fuel [23].

Biofuels

South Africa does not have any notable biofuel usage or production currently. A biofuel strategy was approved in 2007; however, it has had difficulties coming into effect due to financing and framework issues. The goal of the strategy is to have biofuels make up 2% of the annual fuel consumption [24, 25].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

Currently, South Africa's energy storage sector is dominated by pumped hydro storage. As of 2019, South Africa has 2910 MW of pumped hydro storage. The pumped hydro facilities consist of the Steenbras Dam (180 MW), the Drakensberg Pumped Storage Scheme (1000 MW), the Palmiet Pumped Storage Scheme (400 MW), and the Ingula Pumped Storage Scheme (1330 MW) [26].

Country's Future Storage Direction

A recent tender process performed through the Risk Mitigation Independent Power Producer Programme in 2021 has resulted in a planned 1300 MWh of utility energy storage [27]. While there have been a few sites identified for new pumped hydro storage, development of future facilities has been postponed until 2030 by Eskom [26].

Carbon Footprint

Most Recent Carbon Output

In 2019, South Africa had annual CO2 emission of 478.61 million tonnes [28].

Historical Trends of Carbon Footprint

South Africa has seen a steady rise in CO2 emissions over the past 100 years. In particular, 2009 saw the highest level of emissions at 502.26 million tonnes. Since then, emissions have risen and fallen (Fig. 5).

Types and Main Sources of Pollutants

The primary pollutant, and source of pollution is the CO2 coming from the power industry. This is due to South Africa's large reliance on coal as a generation fuel. The rest of the CO2 is distributed among transportation, industry, and buildings. Outside of CO2, there are minor levels of methane, nitrous oxide, and fluorinated gases [29].

Air Quality

South Africa has a moderate air quality. Cape Town, Western Cape is considered the cleanest city, with and average PM 2.5 concentration of 3.8 μg/m^3, and Sebokeng, Gauteng is the most polluted with an average PM 2.5 concentration of 20.1 μg/m^3 [30].

Energy Resiliency

Electrical Grid

As of 2020, South Africa had 33,027 km of transmission lines, 351,023 km of distribution lines, and 7734 km of underground lines. These are owned by Eskom, who has a monopoly over the transmission, distribution, and trade of electricity [31]. Stability has been an issue Africa has dealt with for years. As of 2012, on average, the coal power plants providing South Africa with the large majority of their electricity had already reached three times their designed life span [32]. This, combined with the financial problems Eskom deals with, has led to an often-unreliable system. The aging generation facilities have been the primary cause of service interruptions, with frequent load shedding being required when the grid is overloaded. This load shedding has resulted in residents going without power for two to four hours a day, for 40–50 days a year [33]. Eskom has stated that this will likely continue for as many as 5 years.

Climate and Natural Disasters

South Africa is subject to floods, wildfires, sinkholes, droughts, and earthquakes. Notable natural disasters include the 2016 Johannesburg floods, the 2019 Cape Town floods, and the 2018–2021 drought [34]. The primary cause of pollution is the power industry. More than half of South Africa's carbon emis-

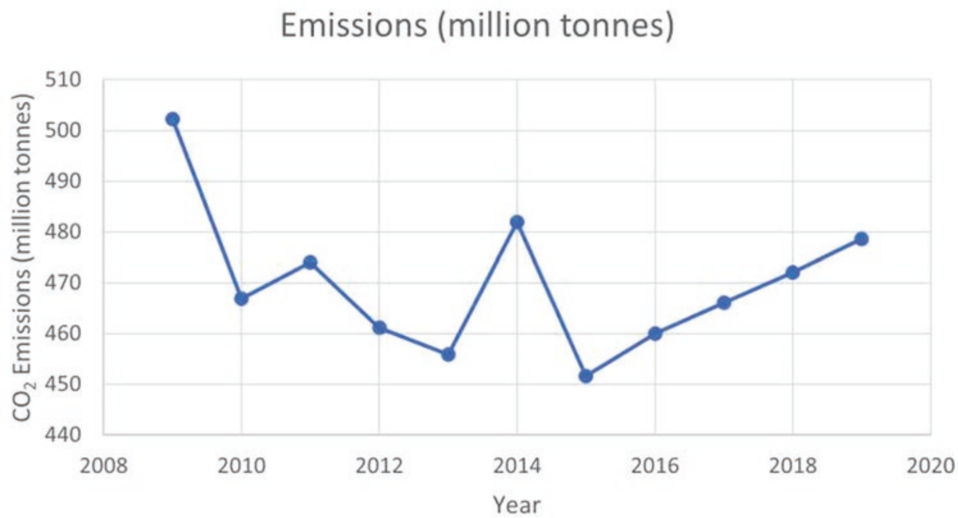

Fig. 5 Annual emissions of South Africa over the last 10 years

sions are due to coal power plants. It has been found that South Africa has warmed at twice the rate of the global average. So far, this has led to worse and more frequent droughts [35]. Additionally, climate change has a large impact on the water cycle, this could affect any hydro power. In the case of pumped hydro storage, which makes up the majority of South Africa's hydro power, a reduction in available water would affect the total capacity of the storage scheme.

Grid Resiliency

South Africa's resiliency issues stem from the aging coal power plants, which are responsible for the large majority of their electricity generation. Eskom's Energy Availability Factor (EAF), which is a measure of the availability of generation facilities, reached 65% in 2020. This means that 35% of Eskom's power plants were consistently down for maintenance. The EAF has been decreasing each year. In 2018, the EAF was 71.9%, then in 2019, 66.9%. Outside of the load shedding, breakdowns were responsible for 21% of all outages [36–38].

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

While the majority of South Africa's electricity is generated from coal, which South Africa sources locally, there is still a reliance on imports for oil and natural gas. The majority of South Africa's oil comes from Saudi Arabia, while their natural gas comes entirely from Mozambique. South Africa exports 24% of their coal, which mostly goes to Asia, India receiving the majority [3].

Relations with Global Community/ Socioeconomic Influence

South Africa's pledge in the Paris Agreement is to keep emissions between 398 and 614 Mt CO2 equivalent over 2025–2030. Then to stabilize emissions between 2025 and 2030, and decrease emissions to between 212 and 428 MT CO2 equivalent by 2050 [39]. As of 2020, South Africa is in good standing with the United Nations. South Africa served as a non-permanent member of the United Nations Security council in 2007–2008, 2011–2012, and finished their third term in 2019– 2020 [39, 40]. South Africa currently does not have any notable political conflicts that affect their energy system. In South Africa's Integrated Resource Plan, South Africa is hoping to increase their renewable energy penetration from 11% to around 41% by 2030, while also hoping to reduce fossil fuel reliance from 80% to around 51% [41].

Education

South Africa has a few notable higher education options that deal with energy, along with a renewable energy technology center. The University of Johannesburg has a masters of Sustainability Energy, while Cape Peninsula University of Technology has education in both Smart Grid Electrical engineering and Mechanical Engineering in Renewable Energy [42, 43]. South Africa is also home to the South African Renewable Energy Technology Centre (SARETEC). SARETEC is a renewable energy facility that specializes in accredited training for the entirety of the renewable energy industry [44].

Summary

Current Energy Situation

South Africa has a fossil fuel dominant energy system. While there has been an increase in renewable penetration over the past few years, it has been slow and inconsistent.

Future Energy Situation

With the recent deregulation of the energy market, cities are now able to purchase electricity from other sources than just Eskom, which opens the door for more private investment. Due to the financial troubles Eskom has experienced in the past, improving the energy system will likely require some level of outside investment.

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Tanzania

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National Energy Introduction

Tanzania is an East African country located in the African Great Lakes region. Tanzania has an electrification rate of around 40%. Urban areas have around 71% electrification, and rural areas have around 23%. Due to the remoteness of these rural areas, Tanzania has been an ideal location for small residential solar arrays. Among the rural households with electricity access, 65% of the households get their electricity from solar energy. To improve the electrification, Tanzania is implementing their National Rural Electrification Program, with the goal of increasing the electrification to 50% by 2024, and a further 75% by 2033 [17].

Breakdown of Energy Generation "Mix"

Energy Generation Mix

There are two statistics to look at when examining Tanzania's energy situation. These are the electricity generation mix, and the total energy breakdown. The electricity generation mix looks at all the electricity generation methods and how they compare to each other in usage (Fig. 1).

Energy Consumption Mix

The total energy breakdown looks at total energy consumption. This takes into account all the different ways energy is consumed by the people such as electricity, motor fuels, and biomass for cooking (Fig. 2).

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Fossil Fuels

Oil

Tanzania has an installed generating capacity of 1.457 million kW. Of this, 55% comes from fossil fuels. As Tanzania does not have any crude oil producing capabilities, all of their refined petroleum must be imported. Tanzania imports 67,830 bbl/day of refined petroleum products. Despite this number 72,000 bbl/day of refined petroleum products are consumed [1, 2].

Coal

The majority of the coal produced in Tanzania is used domestically. They produce 304,238 tons/year and consume 327,861 tons/year. Additionally, Tanzania exports 53,522 tons/year and imports 84,992 tons/year. The coal industry is fairly undeveloped, especially considering that Tanzania has 297 million tons of confirmed reserves, one of the largest reserves in East Africa [3].

Natural Gas

Tanzania is a small producer of natural gas, producing 3.115 billion m^3/year, all of which is currently used domestically. Tanzania holds 6.513 billion m^3 of proven natural gas reserves. Additionally, there is potential for Tanzania to become an LNG exporter. Though so far, this plan has run into trouble, preventing it from taking off. The most recent estimates are for the LNG project to begin construction in 2022 [4, 5].

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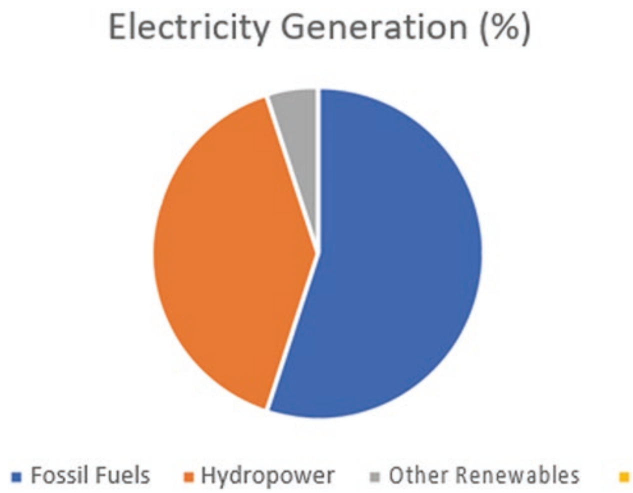

Fig. 1 Electricity generation breakdown [1, 2]

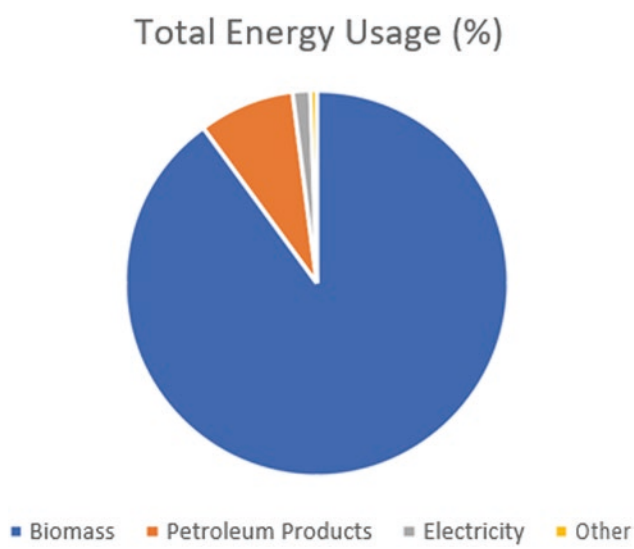

Fig. 2 Total energy breakdown [12]

Nuclear Energy

Currently, Tanzania does not have any nuclear energy generating capacities. Despite this, they are open to nuclear. In 2003, a law was enacted that allows for the use of uranium to produce energy [6]. Tanzania has begun uranium mining though, with the Mkuju River mine receiving the first uranium mining license in 2013 [7]. The Mkuju River mine and the Manyoni mine are the most notable uranium mines in Tanzania, as they hold the largest uranium reserves.

Renewable Energy Generation

Tanzania has fairly large renewable usage energy usage. Forty percent of their electricity generation comes from hydropower, and 5% through other renewables.

Photovoltaics (PV)

While solar power only makes up a small part of Tanzania's electricity generation as a whole, it is significant for its usage in rural areas. Only around 23% of rural household have electricity access, but among those that do, solar power accounts for 65% [1, 8]. Currently, most of Tanzania's solar power is in off-grid photovoltaics, with about 6 MW installed countrywide, there is only one grid connected PV plant with a capacity of 1 MW [9, 10]. There is large potential for utility scale solar power. Tanzania receives between 2800 and 3500 h of sunshine every year, and has an average global horizontal radiation of 4–7 kWh/m^2/day [10].

Solar thermal has been used for drying crops, wood, and salt for ages, and currently solar dryers are used in agriculture for drying farm products. While there is some usage of solar water heating among hotels, hospitals, and health centers, the adoption of the technology is fairly low [9].

Wind

Currently Tanzania does not have any wind power generation, though there is potential. There are two areas with potential for grid-scale wind power generation. Those are Kititimo and Makambako. Kititimo has an average wind speed of 9.9 m/s and Makambako has an average wind speed of 8.9 m/s [9, 10]. Currently, the Ministry of Energy and Minerals (MEM) is working with TANESCO to assess sites for possible wind farms.

Hydro

As mentioned, hydropower makes up 40% of Tanzania's electricity generation. Tanzania has 562 MW of installed capacity [9]. Tanzania has suffered intermittent river flows which result in droughts which have decreased the reliability of hydropower though. Another issue is the geographical location of the hydropower facilities compared to where the major demand is. The facilities are mostly located in the southwest, while the demand centers are in the north, northwest, and east [9]. It is estimated that Tanzania still has some 4000 MW of hydropower potential, which the country intends to exploit.

Ocean

Ocean energy has only recently been explored off the coast of Tanzania. There is potential for tidal power off the coast of Dar es Salaam in the submerged channels [11]. Though further research is needed to figure if tidal energy would be reasonable.

Table 1 Transmission line breakdown [14]

Line voltage (kV)	Length (km)
400 and 230	71,629
220	3340
132	2063
66	668
33	24,165
11	6006

Geothermal

Tanzania is not currently exploiting its geothermal potential, which is fairly significant. It is estimated that Tanzania has over 650 MW of usable geothermal, most of which is located in the East African Rift System. Due to this potential, the government formed a National Task Force on Geothermal Development, whose main goal is to advise the government on geothermal resources [9, 10].

Biomass

Biomass is a complex topic. For electricity generation, there are around 18 MW of power plants running off of biomass for grid use, and around 58 MW for agro-industry electricity. However, the primary use comes from domestic usage. Biomass is used around the country in unsustainable ways for charcoal production, cooking, and heating. Due to weak enforcement and a lack of awareness, it is estimated that 100,000–125,000 hectares of forests are lost each year [9].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

Energy storage is incredibly important, despite being small in scale, for Tanzania. Due to the low electrification of the country, especially in rural areas, solar-battery systems are integral to off-grid electricity generation. Outside of batteries, there is not much energy storage currently being utilized. As the economy advances though, expanding storage capabilities could be necessary.

Energy Resiliency

Electrical Grid

Tanzania's electrical grid consists of more than 100 thousand km. The breakdown of grid parts and line voltages can be seen in Table 1. The grid faces a variety of problems, which end up causing frequent blackouts. In Dar es Salaam, depending on the district, monthly blackout hours can range from 10 to 120 hours/month. These issues are caused by aging cabling, unreliable transformers, fluctuation in electricity generation, and old and overloaded transmission and distribution systems [12–14].

Climate and Natural Disasters

Tanzania has struggled with droughts throughout its history. Severe droughts have been seen from 1999 to 2005, and more recently, in 2010/11 [15]. These droughts have resulted in water and food shortages, while also having an effect on hydropower facilities. In 2015, Tanzania's main hydropower facility had to be shut down for months due to low water levels. Additionally, in December, the hydropower plant, which had a combined capacity of 561 MW, only generated 110 MW [16]. Droughts influenced by climate change have a large influence on Tanzania, which have caused the country to look more toward fossil fuels in the past.

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

There are currently no outstanding geopolitical issues affecting Tanzania's fuel supply.

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Uganda

Slobodan Petrovic and Niels Williams

National Energy Introduction

Uganda holds considerable potential for renewable energy, which has only been partially represented in the current energy framework. With the demand for clean, cheap, and easily accessible energy continuing to rise, the participation of both the public and private sectors is critical in meeting this demand. Uganda has a relatively well-structured and unbundled electrical sector that is characterized by the input from different components, particularly the Independent Power Producers (IPP). The exploitation of solar, wind, hydro, biomass, and biofuels potential requires significant capital and a stable regulatory regime. There are different frameworks under which investors can develop projects in Uganda, and the most important one is the private-public partnerships (PPP). The 250 MW Bujagali hydropower plant was developed in this manner. The enforcement of such agreements is subject to legal rigor, which reduces the investment risk for anyone looking to generate renewable power in Uganda.

However, the power demand is significant in the rural areas which are not covered by the national grid. The role of microgrids in such regions is crucial. The electricity access rates in Uganda are still relatively low, and the power demand domestically and within the East African Power pool continues to rise. These factors secure for investors a feasible opportunity to support Uganda in developing a sustainable and resilient energy network.

Energy Policies (Key Internal Policies the Country Has)

Uganda's energy policies are centered around two key areas – increasing access and consumption of clean energy and development of energy infrastructure (National Planning Authority 2020, pg. 144). The availability of reliable and affordable energy services has been identified by the planning authority as the key policy that will drive the countries' socioeconomic development to a stronger economy. Efficient energy transmission and distribution system promote access to electric power and mitigate against excessive power losses on the grid. These policies are articulated in Uganda's strategic national policy and vision document, the Third National Development Plan (NDPIII) 2020/21–2024/25.

Trends in Generation Technologies

Uganda has a liberalized energy market with generation, transmission, and supply segments. They are regulated by an Independent Electricity Regulator. There are three categories of ownership structures – Public-Private Partnerships (PPPs), Independent Power Producers (IPPs), and government-owned power plants. Generation plants are steadily being built, from just 3 in 2001 to more than 40 in 2019 (ERA 2021). Generation capacity increased from 60 MW in 1954, to 400 MW by the year 2000, and more than tripled to 1238 MW as of October 2020. While new power plants are being commissioned in a quest of diversifying the energy mix, the installed capacity is projected to increase to 18,378 MW by 2022. The energy generation trends in contributions by technology from 2015 to 2019 are shown in Table 1.

Domestic Resources (Oil, Possible Renewables)

Uganda has extensive energy resources with an empirical generation potential close to 5300 MW (UNREEEA 2020). This includes an energy potential of up to 1650 MW of biomass cogeneration, 450 MW of geothermal, and 2000 MW of hydropower (UNREEEA 2020). The country has the potential of 50 million tons of biomass yield annually. The

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Table 1 Energy generation by technology in GWh

Technology	2015	2016	2017	2018	2019
Large hydro	2745	2967	3183	3157	3506
Small hydro	307	294	264	444	480
Bagasse	174	178	150	206	197
Thermal	73	66	231	199	103
Solar	/	4	25	32	78
Imports	48	41	13	39	21
Total	3348	3549	3867	4079	3384

Adapted from Electricity Regulatory Authority (ERA)

solar energy averages 5.1 kWh/m^2. There is close to 250 million tons of peat.

Uganda has no domestic production of oil and so must import all petroleum products and imports most of its petroleum through Kenya with approximately 5% being routed through Tanzania (Aryanpur et al. 2019, p. 70).

History of Energy (Colonialization, Who Controlled Their Domestic Resources)

Since the early 1960s, the Government of Uganda engaged various bilateral and multilateral agencies and lenders in a bid to develop the financial and human capital necessary to develop the energy sector. The World Bank was involved in this effort, funding the first project in 1961 (Gore 2008, pg. 362). By the 1990s, the problems of the power sector necessitated the reforms to privatize the electricity sector. The passing of the Electricity Act of 1999 enabled the liberalization of Uganda's energy sector (ERA 2020). The Act led to separation of electricity generation, transmission, and distribution functions from the Uganda Electricity Board (UEB). In its place, new entities for the generation, transmission, and distribution sectors were formed.

Breakdown of Energy Generation Mix

Uganda has a total installed generation capacity of 1252 MW (ERA 2020, pg. 1). Of this total, 1246 MW is part of the grid supply, and 6 MW is off grid. The energy generation is dominated by hydropower and breaks down as follows: hydro 1004 MW, cogeneration – 96 MW, grid-connected solar – 50.8 MW, and thermal power – 100 MW (ERA 2020, pg. 8).

Fossil Fuels

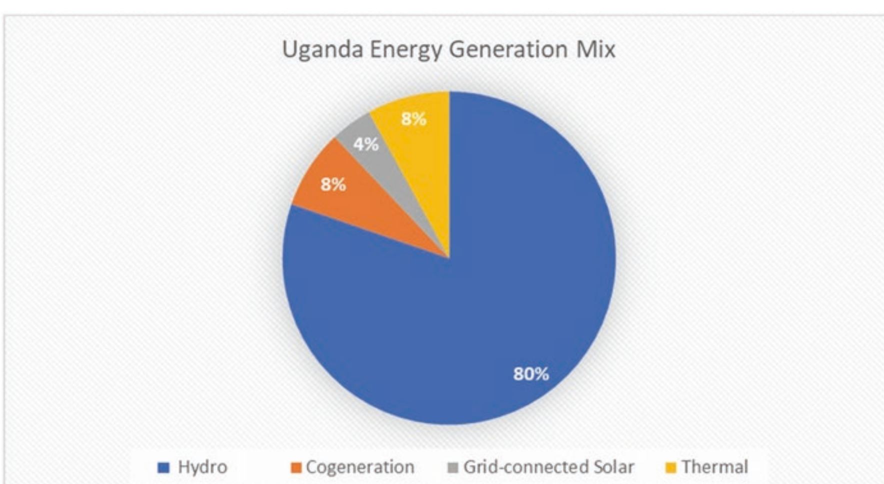
Oil

Uganda had an annual consumption of 1,443,505 cubic meters of oil (Department of State U.S. Embassy in Uganda 2020). There are two thermal plants, Jacobsen (U) Limited and Electromaxx (U) Limited, each with an installed capacity of 50 MW. The category of oil is Heavy Fuel Oil (HFO). Uganda's oil import in 2021 was worth US $1.3 billion (WITS 2021). Uganda imports its fuel and petroleum products from the UAE ($700 M per year) and Saudi Arabia ($600 M) (WITS 2021).

The first commercial deposits in Uganda were discovered in 2006 in Albertine Graben area. The Ministry of Energy and Mineral Development estimates that Uganda has 1.4 billion barrels of recoverable oil (2021, pg. 102) and 2.5 billion barrels of appraised total reserves (Energy Information Administration 2021).

Coal

While Uganda does not have its own coal reserves, the country plans to import a significant amount of coal from Tanzania



to support the development of energy demanding iron and steel production industry (IEA-CCC 2020).

Natural Gas

The estimates for the proven natural gas reserves were roughly 500 billion cubic feet as of the end of 2015 (Energy Information Administration 2021).

Renewable Energy Generation

Solar Photovoltaics

There are four solar plants with a cumulative capacity of 50.8 MW, generating 78.1 GWh which is 1.8% of total power (ERA 2020, pg. 14). The largest solar plant in Uganda is the 20 MW Kabulasoke Pilot Solar Park. It is in the central Ugandan district of Gomba and was commissioned in 2019 (Xinhua 2019). The project was installed by The Xsabo Group, a private company. According to the Uganda National Renewable Energy & Energy Efficiency Alliance, Uganda has an average solar insolation of 5.1 kWh/m^2 (2020).

There is a plan for a 10 MW solar photovoltaic power plant to be located in the West Nile region. The construction is set to begin in 2021 (Construction Review Online 2020). Additionally, a UAE-based IPP, AMEA Power, is set to construct an 80 MW solar plant in the Karamoja region. Overall, Uganda's Vision 2040 sets out a target of 5000 MW of solar power (Lane et al. 2018, pg. 19).

Wind

There is an average wind speed of 3.7 m/s, indicating that the Uganda wind energy resource is insufficient for electricity generation (Construction Review Online 2020).

A 10 MW wind farm is set to be constructed in the West Nile region of northwestern Uganda where feasibility studies have confirmed wind speeds to be above average (Construction Review Online 2020).

Hydropower

149.2 MW of power is drawn from Small Hydropower Plants that have less than 20 MW capacity, while 855.0 MW is drawn from Large Hydropower Plants (ERA 2020, pg. 10). Out of the 4383.9 GWh total energy transmitted by UETCL in 2019, large hydro plants accounted for 3506 GWh while small hydro plant provided 479.9 GWh, cumulatively accounting for 91% of the total power (ERA 2020, pg. 14).

The 600 MW Karuma Hydro Power Station is the largest hydro plant in Uganda (UEGCL 2021). The plant was installed by Sinohydro Corporation Limited.

Uganda has considerable hydro potential due to the presence of the Nile River. The potential power is estimated at over 2200 MW (Hydropower 2021).

Geothermal

Uganda's Vision 2040 hydropower sets out a target of 4500 MW in the next 20 years (Lane et al. 2018, pg. 19). The reserves of extractable geothermal power especially along the East African Rift Valley are estimated at 450 MW (Construction Review Online 2020), and the target is to extract up to 1500 MW of geothermal power (Lane et al. 2018, pg. 19).

Biomass

Currently, Uganda has close to 93% usage of biomass fuel (firewood, charcoal, and crop residues) to meet the national energy demand (Lane et al. 2018, pg. 11); 85% of the residents use firewood and 13% use charcoal in urban and suburban areas, with the total charcoal demand of 2.09 million tons (National Planning Authority 2020, pg. 145).

Still under construction is the 20 MW Earth Energy Limited biomass power plant in northern Uganda (Bungane 2017). In 2019, 196.8 GWh of power was produced from biomass (bagasse) (ERA 2020, pg. 14). There is a considerable potential of up to 1650 MW of biomass cogeneration. There is also an estimated 460 million tons of biomass stock available in Uganda (Construction Review Online 2020).

Biofuels

In 2015, the total biofuels output was 276 ktoe, with a significant amount of the input being molasses generated by sugar companies (Agunyo et al. 2020, p. 279). Because of its low cost, ethanol is the most commonly used, but methanol can achieve higher biodiesel conversions. With current fossil fuel imports of 70 million liters per month, the annual biofuel demand is 176 million liters with a 20% blend (Grida 2021 p. 5). Kakira Sugar Ltd, a US$36.6 million ethanol plant, is the largest plant, and was installed by India-based Praj Industries (Agunyo et al. 2020, p. 276). The plant was commissioned in 2017. The most notable production of biofuels in Uganda is close to 20 million liters of fuel grade anhydrous ethanol (Agunyo et al. 2020, p. 276). The production is drawn from 74,000 metric tons of molasses generated by sugar companies.

Uganda has had an industry-wide target of bioenergy contributing 4–16% of the renewable energy mix. Sugarcane, corn, oil palm, and jatropha are among the biofuel crops that had been found (Grida 2021, p. 1). A suitability analysis of these crops reveals that certain biofuel feedstocks had a high potential output.

Energy Storage Technologies

Uganda is currently using mechanical, electrical, biological, electrochemical, and thermal energy storage techniques. These techniques have been in place for many years (Amiryar 2017, p. 4). Battery storage, pumped hydro energy storage, and thermal storage are also techniques used in Uganda to store energy.

Examples of energy storage facilities include a 100 MW solar thermal plant with molten salt storage (built by SENER and ACCIONA), which uses parabolic trough technology to produce electricity (Amiryar 2017, p. 6). The project is expected to save approximately six million tons of CO_2 over the next 20 years.

Carbon Footprint

In 2019, Uganda's total carbon dioxide (CO_2) emissions from the burning of fossil fuels for energy and cement production totaled 5.53 mil tons (Ritchie and Roser 2020). At 0.125 t, Uganda's carbon footprint is still relatively low (Ritchie and Roser 2020). Over the last decade, the footprint has been rising, but with 1.39 tons carbon dioxide equivalent in 2011 the country still had well below the global average of approximately 7.99 tons carbon dioxide (INDC 2015, pg. 13).

The notable pollutants include fumes from automobiles, bush and charcoal burning, domestic burning of rubbish, road dust, and industries (NEMA 2019, pg. 2).

Air Quality

The air quality of Uganda is poor in urban areas. The annual mean concentration of PM2.5 being 50 μg/m^3 exceeds the World Health Organization's recommended maximum of 10 μg/m^3 (IAMAT 2021).

Energy Resiliency

Electrical Grid

Uganda has a relatively efficient grid system that has managed to keep power losses under control, but its limited geographical size has hampered access to power, particularly in Northern Uganda. The energy losses have come down to 16% in 2020 compared to 30% when the liberalization started (UETCL 2021). Overall, the customer base has grown steadily to 1,643,288 in 2020, from roughly 180,000 customers in 2001.

The grid has been continually developed and expanded in the last two decades. There has been a notable investment in grid infrastructure as captured by UEDCL; the amount has increased from Ush 5456.6 million in 2016 to Ush 5917 million in 2017 (ERA 2018, pg. 3). The main priorities have been in the distribution infrastructure to deliver the power from the main generation centers to the load centers.

The power transmission network (heavy voltage) has a total length of 2898.2 km as of 2020, while the distribution network had a 45,423.1 km total length (ERA 2020, pg. 17).

The main power distributor holding multiyear concessions, Umeme Limited, saw the gross capital investments increased by US$72.5 million in the 2017 period (ERA 2018, pg. 3).

By the end of 2019, the Transmission Segment operated 22 substations with a total transformer capacity rating of 1738.5 MVA. These included fault transformers and voltage boosters, which protected the grid from power imbalances (ERA 2020, pg. 17).

The grid network only connects to 33 of the 54 districts in the country (Energypedia 2018). This access is mainly limited to the south of the country especially in the region of Kampala, with the grid being correlated more to the population density (Lane et al. 2018, pg. 23).

Climate and Natural Disasters

Climate change is having a major effect on Uganda, including changing weather patterns, a drop in water levels, and an increase in the frequency of extreme weather events such as floods and drought. Energy production is vulnerable to these weather events (Boyd et al. 2015, p. 8).

Other natural disasters, such as wildfires and floods, can affect forests and cause structural changes to ecosystems (Boyd et al. 2015, p. 8). Wildlife may be affected either directly or indirectly by changes in habitat and energy supply.

The extensive use of biomass for energy and cooking adds to the local pollution and the greenhouse gasses. The presence of these greenhouse gasses in the atmosphere raises the earth's temperature (Boyd et al. 2015, p. 10). The harvesting of the local biomass also destroys the local ecological system that relied on it.

Climate change is expected to positively affect development of renewable energy sources and potential energy networks under a baseline warming scenario (Boyd et al. 2015, p. 12). Several hundred additional renewable energy projects are planned over time that would lower CO_2 emissions.

Annual emissions in 2030 are expected to be 77.3 million tons of carbon dioxide. The projected cumulative effect of the policies and initiatives could result in a 22% reduction in national greenhouse gas emissions. The protection of vulnerable groups, including women, is a top priority across the board. The full implementation of these actions is contingent on the international community's support, which will come from both climate finance instruments and international market mechanisms (Amiryar 2017, p. 6). The Ugandan government will continue to devote resources to climate-change-related strategies, and it has UN's support in this endeavor (Jackson et al. 2018, p. 216).

Summary

Uganda is a country with considerable energy generation potential, but the full potential of all resources is yet to be realized. There are specific policies that have been enacted to facilitate Foreign Direct Investment (FDI) and reduce government red tape. Investors have taken advantage of these developments to deploy capital into the country.

The country has a self-mandated obligation to reduce carbon emissions. The exploitation of renewable energy resources will play a vital role in achieving this goal. The administration of feed-in tariffs has proceeded without many challenges. By having a receptive energy sector regulator, any potential challenges can be reviewed and resolved. Among the most impactful forms of renewable energy development in the country are solar PV microgrids. They have supported the government's quest to accomplish rural electrification.

Most importantly, more than 90% of Uganda's energy generation comes from renewable energy sources, dominated by hydropower, solar PV, and cogeneration. The energy demand continues to grow with peak system demand currently at 723.8 MW as of December 2019 (ERA 2020, pg. 12). The total electrical power generated is 4383.9 GWh before factoring in 3.6% transmission losses. At the same time, the development of the fossil fuel industry is likely to play a more significant role with the Albertine oil deposit reserves that the country seeks to exploit.

With a total energy potential of more than 5000 MW, the country can meet its demand and furthermore play a crucial role in energy supply within East Africa. While the access to electricity is currently hampered by the limited size of the electrical grid, efforts have been made to liberalize the power subsector to allow the development of mini grids. This will in time see a reduction in the proportion if biomass used to generate energy.

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Zambia

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National Energy Introduction

The country of Zambia, home to over 19 million people, is a landlocked nation in southern Africa [1]. Previously known as Northern Rhodesia, a protectorate of the United Kingdom during the period of European colonization on Africa, Zambia has existed as an independent country since 1964 [1].

Energy Policies

The Zambian government has set forth its goals for the future development of its energy sector in its 2019 National Energy Policy. Using this policy, Zambia intends to update and improve its institutional capacity and regulatory framework including decentralizing some of the energy sector to allow for independently owned participants in the energy sector, establishing regulation for off-grid energy systems, and coordination between institutions within the industry [4]. The policy also involves attempts to improve energy efficiency, promote, and effectively use biomass and biofuels, and diversify the energy generation portfolio through utilizing nonlarge-scale hydro sources [4]. Additional measures of the National Energy Policy include increasing electrification of Zambian households, improving the petroleum sector, and increasing the "systematic mainstreaming" of gender, climate change, health, and safety consciousness within the energy sector [4].

Trends in Generation Technologies

Electricity generation in Zambia has historically been reliant upon hydroelectric power, with a smaller amount of coal and oil-fueled thermal plants being the only other significant generation sources. Hydroelectric power currently constitutes 2399 MW out of the country's total installed capacity of 3051.08 MW [2]. Although hydroelectricity is the primary source of electricity generation, it is only responsible for a fraction of total energy consumption in Zambia. Biomass, mostly wood and charcoal, makes up 70% of total energy consumption [3, 4]. This is largely due to a deficiency in the electrification of Zambian households, and the majority of households rely on biomass for heating and cooking. Currently, only 31.4% of Zambian households have access to electricity; 67.3% of urban households are electrified while only 4.4% of rural households are electrified [4].

Rural electrification, difficulties in meeting energy demands, and climate change are pressing issues that Zambia's energy sector must face [5]. Although the country is a net exporter of electricity, importation still does occur [2]. This importation will be critical as long Zambia remains reliant on hydroelectricity, and this is because increased temperatures and drought frequency related to climate change will reduce hydroelectric dam output. Zambia observed this in 2016, when water levels reached near-record lows for one of its largest dams. Total electrical energy produced decreased because of the low water levels, and Zambia needed to become a net importer of energy [2, 5]. Increased annual demand and further electrification of the country will make meeting peak demand more difficult; a task already challenging for the country as load shedding is a common occurrence [4, 6]. Importation of petroleum will also be a concern for Zambia for the foreseeable future, as the country has no crude oil domestically, and its only refinery produces insufficient refined petroleum products to meet total national demand for those goods [1, 2].

Domestic Resources

Zambia possesses several renewable and nonrenewable energy resources domestically. There are known, exploitable deposits of coal, uranium, and cobalt in the country

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[1]. Geothermal, oil, and natural gas reservoirs are speculated to exist, but there are not any proven deposits or domestic exploitation of these resources, presently [1, 7, 8]. There is significant hydroelectric, solar, and wind energy potential, and most of this potential has yet to be utilized for electricity generation [3, 5]. Although there are small levels of biomass and biofuel sourced energy usage in the country, there is potential for growth in the cultivation of feedstocks such as jatropha, sugarcane, sweet sorghum, and palm oil [3, 4, 9, 10].

Breakdown of Energy Generation "Mix"

Energy Generation Mix

Renewable energy sources constitute the majority of total energy consumption in Zambia. This is mostly due to much of the population relying on traditional biomass means for heating and cooking. Renewables also make up the majority of installed electricity generation capacity and electrical energy generation in the country. Although solar PV technology is present in the country, electrical energy generated via PV is not officially reported and thus not included in the energy mix breakdown charts below. Figures below represent energy consumption, generation, and installed capacity as reported by official sources (Figs. 1 and 2).

Energy Consumption Mix (Fig. 3)

Fossil Fuels

Oil

Zambia does not extract any oil domestically. Instead, the country relies entirely on the importation of crude oil or finished petroleum products [2]. Importation of crude oil is done through the TAZAMA pipeline beginning in Tanzania and ending at the Indeni Petroleum Refinery in Ndola in Copperbelt Province [2]. The pipeline is one-third owned by Tanzania and two-thirds owned by Zambia [2]. The TAZAMA pipeline is capable of sending 0.8 Mt (800,000 metric tons) of crude oil per year to Zambia, and as of 2018 the actual amount of imported crude oil was 0.629 Mt (629,394 metric tons) [2].

All crude oil refining in Zambia is conducted by the Indeni Petroleum Refinery Company Ltd., a Zambian government owned firm. When the refinery began production in 1973, the capacity of the facility was 1.1 Mt per year (8.063 million barrels per year) [2]. However, that number has decreased to 0.85 Mt (850,000 metric tons) per year in 2018 [2]. Of the 0.647 Mt (646,907 metric tons) of petroleum products produced at Indeni in 2018, the primary products manufactured were 135,733 metric tons of petrol, 274,292 metric tons of diesel, and 118,751 metric tons of heavy fuel oil (HFO) [2]. Indeni also produces small amounts of kerosene, liquefied petroleum gas (LPG), and the aviation fuel Jet A-1. The Indeni production accounted for only 48.1% of the national petroleum fuel requirements in 2018 [2].

A majority of finished petroleum products imported into Zambia are imported by the government, and the remainder is imported by Oil Marketing Companies (OMC) [2]. The Zambian government imported a total of 0.547 Mt (546,717 metric tons) of finished oil products in 2018, of this, 184,971 metric tons was petroleum products and 361,746 Mt was low sulfur gasoline (LSG) [2]. In 2018, OMCs imported a total of 145,461 metric tons of finished oil products, consisting of 121,938 metric tons of LSG, 22,458 metric tons of Jet A-1, and 1065 metric tons of LPG [2]. This is much less than in previous years because in June 2018, the government revoked the licenses for OMCs to import LSG. For reference, 2017 LSG importation by OMCs was 232,277 metric tons [2].

Total petroleum consumption in Zambia in 2018 was 1.345 Mt (1,344,908 metric tons), an increase of 1.2% from the 2017 consumption [2]. Of this, the primary products consumed were 823,822 metric tons of diesel, 327,029 metric tons of petrol, and 144,610 metric tons of HFO [2]. The majority of petroleum products are consumed in the provinces of Lusaka, Copperbelt, and North Western [2].

In 2018, petroleum-sourced facilities represented 6.86% of Zambia's electricity generation installed capacity [2]. The largest of these is a 110 MW HFO generation plant owned by Ndola Energy Company Limited [2]. In 2018, this site provided 451 GWh of electricity to the national grid [2]. The state-owned Zambia Electricity Supply Corporation (ZESCO) owns the remainder of the diesel-sourced electricity generating facilities. These seven facilities have a combined capacity of 8.88 MW, and in 2018, supplied 4.5 GWh of electricity [2]. An additional 80 MW of capacity is owned by Copperbelt Energy Corporation (CEC), but that is reserve capacity designed to supply mining operations [2].

Exploitable oil deposits have yet to be identified in Zambia. However, regions of Zambia fall within the East African Rift Province classified by the US Geological Survey. The US Geological survey has assessed that undiscovered oil deposits likely exist in the region including a mean assessed value of 3218 million barrels of oil in the Tanganyika-Rukwa area [7]. Part of this area is in Tanzania near the Zambian border. In 2018, Zambia granted a 10-year license to the UK firm Tullow oil to perform exploration including in the Tanganyika basin in the Northern Province [12].

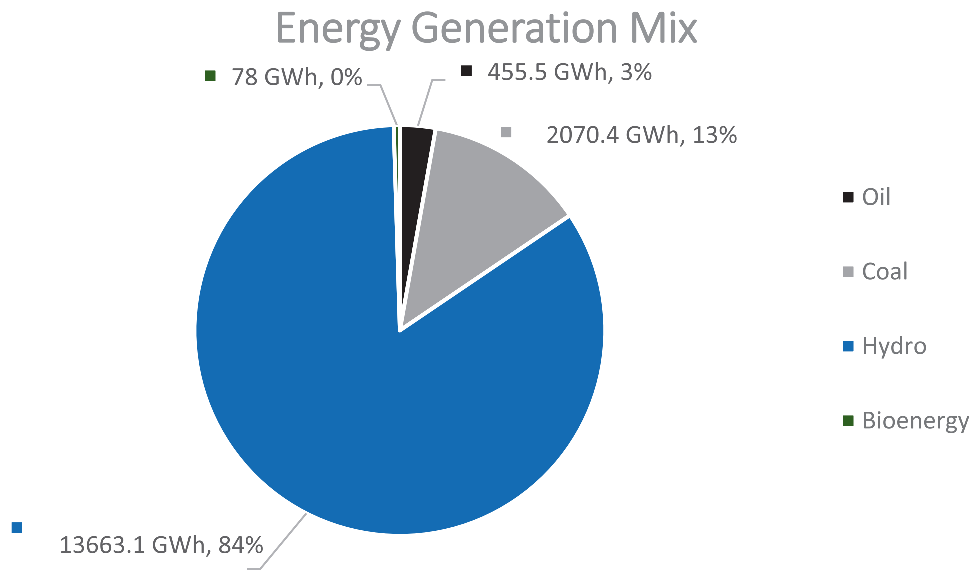

Fig. 1 Breakdown of electrical energy generated from all officially reported facilities in Zambia as of 2018. Zimbabwe has historically been reliant upon hydroelectricity to meet electricity needs, and this source makes up most of its installed capacity

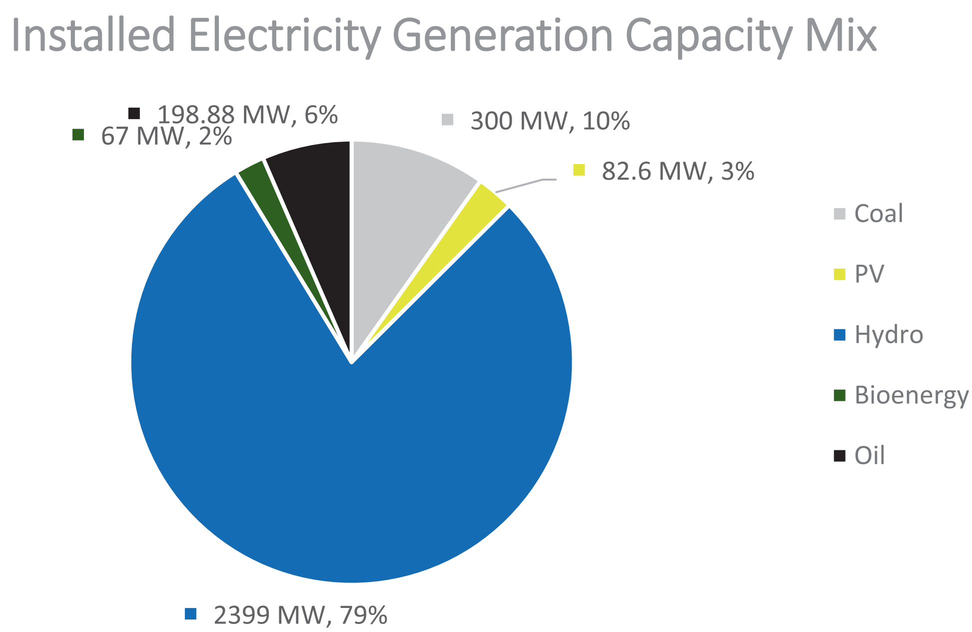

Fig. 2 Breakdown of the installed capacity for electricity generation from all reported facilities in Zambia as of 2018. Zambia has historically had most of installed capacity in the form of hydroelectric dams. Although there will be future capacity expansion from other sources, such as solar, this trend will continue for the foreseeable future

Coal

In 2018, domestic coal production was approximately 1.174 Mt (1.294 million short tons) of coal [13]. This represents a significant increase over the last several years as there was only 0.159 Mt (0.175 million short tons) of coal production in 2014 [13]. Coal consumption has historically been greater than coal production. In 2018, 1.259 Mt (1.388 million short tons) of coal were consumed domestically [13]. However, there has been a sharp rise in coal consumption in recent years as consumption in 2014 was only 0.159 Mt (0.175 million short tons) [13]. In 2018, coal imports 0.088 Mt (0.097 million short tons) were greater than coal exports 0.0027 Mt (0.003 million short tons) [13].

Presently, Zambia only possesses one coal-fueled electricity generating thermal plant. This is the 300 MW Maamba Power Plant owned by Maamba Collieries Ltd [2, 14]. The facilities first began generation in 2015, and by 2018 it produced more electricity than any other Zambian facility outside of ZESCO ownership with 2070.4 GWh of power produced that year [2].

Zambia is estimated to have 50 million short tons of coal reserves. There are several projects aiming to exploit the nation's coal reserves for additional electricity generation installed capacity. Maamba Collieries has a planned expansion of an additional 300 MW of capacity. An additional 300 MW was planned for a coal-fired thermal plant in Sinazongwe [15]. ZESCO initiated the

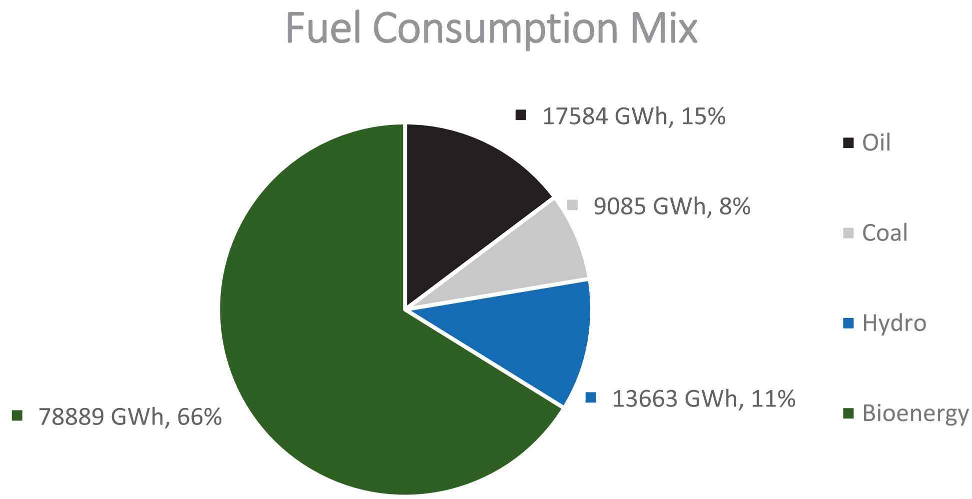

Fig. 3 Breakdown of total energy consumption in Zambia during 2018 from all sources including electricity, transportation, cooking, and heating. Biomass makes up the greatest energy consumption due to its heavy use for heating and cooking

project in 2014 [15]. However, the project has not been completed and the Maamba site is the only coal-fired, installed capacity in Zambia [2, 14]. Zambia's SEforALL Action Agenda envisions a total of at least 1000 MW of coal thermal plant capacity to eventually be installed [14].

Natural Gas

As of 2019, there was no natural gas production or consumption in Zambia [13]. Also, there was no importation or exportation of natural gas into or out of Zambia [13]. There currently is not any installed capacity generating electricity in country, nor any planned projects for installing natural gas-fired thermal plants [2, 14]. As there is no current production of natural gas domestically, if any future natural gas-fired facilities are installed, the fuel for these facilities will have to be imported, and pipelines for this importation will need to be constructed [13].

Presently there are no identified deposits of natural gas to exploit in Zambia. Natural gas deposit exploration studies were previously conducted in the 1980s [16]. The exploratory drill wells were unsuccessful in discovering natural gas potential [16]. Renewed exploratory efforts in the 2000s discovered hydrocarbon oxidizing bacteria possibly suggesting the presence of natural gas or oil which emit hydrocarbons [16]. As of 2016, exploratory efforts had not progressed beyond this point, and natural gas deposits have yet to be discovered [16]. Assessments by the US Geological Survey provided a mean assessment value of 880 billion cubic feet of natural gas which could possibly exist in undiscovered deposits within the Tanganyika-Rukwa geological region, primarily in Tanzania near the Zambian border, but no deposits have been discovered as of yet in Zambia [7].

Nuclear Energy

As of 2020, there were no nuclear power plants or nuclear energy generation in Zambia [4]. Zambia began exploring the possibility of establishing a nuclear energy program with the intent of constructing its first nuclear power plant. In 2018, The Zambia Atomic Energy Agency (ZAMATOM) signed a contract with the Russian State Atomic Energy Corporation (Rosatom) to construct the Zambia Center for Nuclear Science and Technology, a nuclear research center with a 10 MW research reactor [17–19]. The completion of this this would be the first of two phases as part of their Nuclear Science and Technology Programme. The second phase would be the completion of a 2000 MW nuclear power plant [17].

An agreement with Russia for the construction of this plant was reached in 2016 with an anticipated cost of US$10 billion [20]. As of 2020, the design and approval phases for the construction of the power plant and research facilities were concluded [20]. However, physical construction of the facilities has stalled because the Russian Federation has not yet committed to funding, and Zambia is unable to self-finance the construction. Officials from both governments are in talks for continuing the nuclear energy project despite this [20].

Although Zambia presently does not generate nuclear power, it still has access to electricity generated from nuclear sources because it is a member of the Southern African Power Pool (SAPP). SAPP is an organization of 12 countries in southern Africa developed to import/export electricity among member states [3, 21]. In 2008, 1% of electricity usage in SAPP came from nuclear sources [3]. This increased to 3% by 2016, all of which was generated in South Arica, the only nation in Africa currently possessing operational nuclear power plants [21]. Four percent of SAPP's installed capacity is nuclear power plants [3].

Although Zambia currently does generate nuclear energy, it does have potential for nuclear fuel extraction. Zambia mined uranium from 1957 to 1959 after it was discovered at the Mindola copper mine [22]. Eighty-six tonnes of uranium (tU) were produced as a result of this mining [22]. Although no uranium mining has occurred in the country since then, Zambia has taken steps to renew its uranium mining efforts. In accordance with guidance from the International Atomic Energy Agency (IAEA), Zambia has updated its regulations to allow for uranium mining, and it began issuing licenses for such mining [22]. There exist two future sites for planned uranium extraction. A site at Lumwana has been identified to possess 6967 tU of recoverable deposits, and a site at Mutanga has been identified to possess 20,311 tU of recoverable deposits [22]. Canadian firm GoviEx Uranium plans on investing US$123 million into the Mutanga site where an estimated 920 tU can be produced annually [22].

Renewable Energy Generation

Photovoltaics (PV)

As of 2019, 3% of the installed electricity generation capacity in Zambia came from solar PV facilities (82.6 MW) [2, 4, 24, 25]. This an increase from the 2018 portion of 0.04% of the total installed capacity (1.1 MW), as well as a significant increase from 0.002% of the total installed capacity in 2017 (0.1 MW) [2]. This increase was a result of the completion on the country's first two large-scale solar projects in 2019. The first of these projects was the US$70 million Bangweulu Solar Project in Lusaka Province [24, 25]. This site added 47.5 MW of capacity to the grid [24]. The project was undertaken by American firm First Solar, French firm Neoen S.A.S., and the Zambian Industrial Development Corporation (IDC) [24, 25]. Foreign funding for the project came from a combined $15 million in loans and grants from the US Agency for International Development (USAID), World Bank Group's Scaling Solar Program, and the US Overseas Private Investment Corporation [24, 25].

Zambia's only other large-scale solar PV facility is the Ngonye solar power plant in Lusaka province [2, 25]. This US$49 million, 34 MW facility was also completed in 2019 [2, 25]. The site was developed by Italian firm Enel Green Power and the IDC [2, 25]. This project benefitted from foreign funding from Power Africa and the Scaling Solar Program, as well as from $2 million donated from USAID that additionally helped fund the Bangweulu project [25]. In addition to these projects, an estimated 7.4% of Zambian homes have solar PV installed, although the installed capacity of these systems is not reported [4].

Prior to 2019, Zambia only had 1.1 MW of installed capacity in the form of small-scale or micro-grid facilities. The largest of these facilities, Kitwe Riverside solar PV facility, is owned by Zambian firm CEC. This US$1.5 million, 1 MW grid-connect site was the largest solar PV generation facility in the country prior to 2019 and first began generation in 2018 [2]. In 2018, the Kitwe site supplied 0.93 GWh of electricity [2]. Although, the plant's current installed capacity is only 1 MW, the Kitwe Riverside plant possesses 40 hectares of land through which it can expand its total installed capacity to between 15 and 20 MW [2].

The three other solar PV facilities in Zambia are micro-grid based serving local communities. The first of these created was a 60-kW site in Mpanta village in Samfya District, Luapula Province. As of 2018, this remained the largest micro-grid solar installation in the country [2, 26]. Zambia's first solar PV and battery storage facility services 450 households and other buildings in eight villages [26]. The facility first began generating in 2014, and it was created in a joint partnership between Kafita Co-operative Society and the Rural Electrification Authority [26]. The second largest solar PV micro-grid facility is the 30 kW Muhanya Solar Mini-Grid in Sinda District, Eastern Province [2]. The site began generating in 2017 and currently services 60 households within a 1.1 km area [2]. The final and smallest solar PV facility is the 10 kW Mugurameno micro-grid in Chirundu District, Lusaka Province [2]. This site currently services up to 900 customers [2].

Although not yet significantly exploited, the country has significant solar energy potential. The average solar irradiation in Zambia is 5.5 kWh/m^2/day, and the country experiences an average of 3000 sun hours annually [3]. Average specific photovoltaic output in the country is 1812 kWh/kWp [28]. The areas with the lowest photovoltaic output are still above 1600 kWh/kWp, while some areas in northern Zambia may exceed 2300 kWh/kWp [3, 28]. It is estimated that solar, in conjunction with wind, geothermal, and coal, has the potential to increase Zambia's installed electricity generation capacity by 6000 MW [29]. A 24-month study conducted in 2017 by the Energy Sector Management Assistance Program of The World Bank explored Zambian solar potential [30]. Global Horizontal Irradiation (GHI) and Direct Normal Irradiance (DNI) measurements at six sites throughout the country were used to create 25-year prediction models [30]. Based on these models, 25-year minimum values with 90% probability for the six sites ranged between GHI values of 1964 kWh/m^2 to 2061 kWh/m^2 and DNI values of 1727 kWh/m^2 to 1962 kWh/m^2 [30].

Zambia's energy sector development planning accounts for utilizing this solar potential to increase install generation capacity. The development planning envisioned 300 MW of additional installed solar capacity by the end of 2021 and an increase in total capacity of solar, geothermal, wind, and coal combined of 15% by the end of 2030 [29, 31]. To increase solar capacity, the government issued 153 licenses and permits for the manufacture, importation, and installation of solar energy systems between 2017 and 2018 [2]. The government also initiated the Renewable Feed In Tariffs (REFiT) Strategy to use tariff revenue to fund 100 MW of additional solar capacity [2]. The funds will be awarded to solar projects up to 20 MW in an effort to increase investment in the Zambian solar industry, and it aims to develop upward of 800 MW in additional capacity by encouraging investment [2].

Of the future projects in development, the largest is a 150 MW wind-solar PV hybrid project by Upepo Energy Zambia Ltd [32]. The feasibility study for this project was awarded a grant by the US Trade and Development Agency [32]. Zambia's GET Fit and REFiT programs have so far awarded six proposals, each one 20 MW of capacity, for the development of future solar PV facilities [33]. Two were awarded to Building Energy & Pele Energy for the Bulemu East and West sites, two were awarded to Globeleq and Aurora Power Solutions for the Aurora Sola I and II sites, and two were awarded to InnoVent and CEC for the Garneton North and South sites [33]. Zambia's Rural Electrification Authority aims to expand Zambia's micro-grid solar PV capacity by adding a 300-kW facility in Lunga, Luapula Province, as well as a 200-kW facility in Chunga, Central Province [34]; 2170 households combined are believed to be powered from these two projects [34].

As of 2018, there was no electricity generation via concentrated solar power (CSP) in Zambia [2, 35]. Zambia's only present option for accessing for solar thermal generated electricity would be to import it from fellow SAPP member South Africa. South Africa possesses 500 MW of operational CSP facilities [21, 36]. These facilities are operated by Eskom and the largest of which is 100 MW in size [36]. One such facility is the Eskom operated 100 MW Kathu CSP plant which utilizes the solar potential of the Kalahari Desert [21, 36, 37]. Eskom plans on expanding its CSP installed capacity to 600 MW by 2030. There are presently no other reported planned projects for CSP plants in fellow SAPP member states from which Zambia could import electricity in the foreseeable future [21, 36, 37]. However, there is a future planned project (Kalulushi) to be conducted within Zambia itself by Chinese firm Shinohydro. It is to take place within the Copperbelt Province, and its reported capacity ranges from 200 to 400 MW [38, 39]. The expected investment by Shinohydro is US$548 million [38].

In addition to CSP plants, Zambia plans to utilize solar thermal energy in the form of solar water heaters. ZESCO is undergoing a project to install 350,000 solar water heaters in the country in an effort to reduce demand during peak hours of the day [3]. This effort could potentially reduce peak electricity demand by 150 MW by replacing the electric water heaters with those that utilize solar thermal energy [3]. The project is project to cost US$180 million [3].

Wind

As of 2020, Zambia does not possess any installed wind energy generation capacity [4]. As a member of the SAPP, Zambia is able to import electricity from neighboring nations with installed wind capacity [3, 21]. As of 2016, 4% (2492 MW) of the SAPP installed capacity was wind energy. This was exclusively generated in South Africa [21]; 142 MW of capacity are planned to be installed in Tanzania and Namibia, which would provide additional sources for the importation of electricity from wind energy sources [40].

Zambia has declared that wind energy will be one component of its National Energy Policy to expand installed electricity generation capacity. To achieve this, it plans to engage in resource mapping to find exploitable sites to install wind energy capacity [4]. At a height of 100 m above ground, many areas in western, central, and eastern Zambia have average wind speeds of at least 6 m/s [41]. The nation believes these wind speeds are sufficient for electrical energy generation [4].

Although no projects are under construction, there have been exploratory studies for wind energy generation. A World Bank ESMAP program tested meteorological masts at eight potential wind hotspots. They measured wind speeds at the 130 m height, and it found average speeds of 6.9–8.0 m/s at those eight sites [42]. They concluded from these results that hypothetical 100 MW capacity wind farms at each of the locations could produce between 303.3 and 394.7 GWh per year [42]. The construction of a 200 MW wind farm has been proposed to be constructed at Katete, located within one of the Eastern wind hotspots. The project currently is in the meteorological mast exploratory phase [43, 44]. The project by Zambian firm Mphepo Power plans on 120 m height windmills and to begin construction in 2021 [43, 44]. Additionally, a 150 MW solar-wind hybrid project with battery storage by Zambian firm Upepo Energy has been awarded a grant by the US Trade and Development Agency [32, 45]. This grant is awarded in the hope that US firms invest in the Zambia energy sector using American technologies to address energy needs [32]. This Masaiti Energy Center solar-wind hybrid project will be built in the Copperbelt Province, and it is presently in the "feasibility study" phase [32, 45].

Hydropower

Hydroelectric power makes up the majority of Zambia's electricity generation installed capacity. As of 2018, 82.76% of all installed capacity was hydroelectric dams [2]. This puts Zambia's total installed hydroelectric capacity at approximately 2399 MW [2]. Eighty-three percent of all electricity produced is expected to be generated from hydroelectric sources [3]. This is an increase from just 60% in 2017 [3]. The increase is due to the expansion of both large-scale and small-scale as well as mini-hydroelectric capacity. Although it is the predominant electricity generating source in the country, hydro only produced 9% of the total energy consumption in the country as of 2010 [3]. This is due to the primary source of total energy consumption in Zambia being the burning of biomass for heating and cooking [3].

With 2337 MW of installed capacity, the state-owned Zambia Electric Supply Corporation (ZESCO) is the primary hydroelectric stakeholder for hydroelectric power in the country [46]. The largest hydroelectric dam in Zambia, which is ZESCO owned, is the Kariba Dam. This dam straddles the border of Zambia and Zimbabwe along the Zambezi River where it flows into Lake Kariba [47]. The dam provides power for both Zambia and Zimbabwe. ZESCO owns the installed capacity on the North Bank of the river [2, 47]. Of this capacity 720 MW is the Kariba North Bank installation, with an additional 360 MW added in 2013 as part of the Kariba North Bank Extension [2]. These two sections combined provided 5208 GWh out of the total 16,189 GWh of electricity produced in Zambia in 2018 [2].

There have been concerns over the continuation of electricity generation at the Kariba Dam. Erosion of the rock floor at the riverbed and worry of the spillway's long-term operation led to the development of the Kariba Dam Rehabilitation Project [49]. This project aims to renovate the spillway and plunge pool to secure the longevity of hydroelectric power at the Kariba site. Construction began in 2017 and is scheduled to be completed in 2025 [49]. The project costs US$294 million and is funded by the European Union, World Bank, African Development Bank, Sweden, and the Zambezi River Authority [49].

The second largest and notable hydroelectric facility in Zambia is the Kafue Gorge site. Kafue Gorge has 990 MW of installed capacity, and generated 6527 GWh out of the total 16, 189 GWh of electricity produced in Zambia in 2018 [2]. Expansion of the Kafue Gorge site began in 2015, by Chinese firm Sinohydro [50]. This expansion included second, 750 MW, dam in the lower part of the Kafue Gorge [50]. Fifteen percent of the funding for the $300 came from the Zambian government with the rest coming from Chinese sources [50]. The project was planned to be finalized by the end of 2020 but is currently still under construction [3, 46, 50].

The Kafue Gorge Lower expansion is the largest of the planned future hydroelectric sites. A majority of Zambia's 6000 MW of hydroelectric potential is currently untapped [3]. Since 2013, Zambia has installed or has announced plans to install an additional 2800 MW of capacity [3]. Small and mini-hydro have been part of Zambia's development plan to complement the large-scale hydro sites. By 2018, ZESCO increased its small-scale hydro generation by 110.6 GWh. An increase of 110.6 GWh since 2017 [2]. This generation has primarily come from its Lusiwasi (12 MW), Chishimba Falls (6.2 MW), Musonda (10 MW), and Lunzua (14.8 MW) small-hydro facilities [2, 46]. As of 2020, ZESCO has 155.6 MW of planned or commissioned projects to build new small-scale hydro sites or to expand the capacity of existing sites [46]. As part of the government's REFiT strategy, funds have been allocated for an additional 100 MW of small-scale hydro capacity to be awarded to selected project proposals. These will be awarded to projects up to 20 MW each in an effort to increase investment into Zambian energy industry [2].

Ocean Energy

As a landlocked nation, Zambia has no installed capacity or potential for ocean or wave energy. There is not any installed ocean or wave capacity as part of SAPP's electricity generation profile, so Zambia is presently not capable of importing any electricity from ocean or wave sources in order to meet its demand [21]. Should the coastal countries members of SAPP (Angola, Namibia, Tanzania, Mozambique, and South Africa) install ocean energy capacity in future that may provide Zambia the ability to use electricity generated from this renewable energy source [21]. However, there are currently no planned projects for ocean or wave energy in the Southern African Power Pool's plans; the majority of planned projects focus on hydroelectric or thermal generation facilities [35].

Geothermal Energy

As of 2020, there is 240 kW of installed geothermal capacity or geothermal electrical power generation in Zambia [3, 51]. All other geothermal energy activity conducted so far in the country has been in the form of exploratory projects aimed at discovering the geothermal energy potential in the country, as well identifying geothermal hotspots which can be exploited. In the 1980s, there was an exploratory effort which identified potential sites meeting the minimum criteria for geothermal energy production of a minimum temperature of 130 °C within 4 km of the Earth's surface [3, 52]. Studies identified seven hot springs sites with geothermal energy potential (Kapisya, Lupiamanzi, Lubingu, Chongo, Chikowa, Chinyunyi, and Kasho) [51]. Zambia's first geothermal plant was built at the Kapisya site. However, the limited maximum capacity of this plant is 240 kW, and due to its limited output, the plant only services local communities, fisheries, and resorts [51].

Presently, the only geothermal energy development taking place in Zambia is done by Kalahari GeoEnergy, a private Zambian firm. Kalahari GeoEnergy reached an agreement with the Zambian government in 2011 to perform exploratory surveys of geothermal hotspots along the Bwenga River located in the country's Southern Province [3, 8]. The firm has drilled 18 wells to study the potential of this region with the aim to eventually construct a 10–20 MW power plant at the site [53, 54]. Successfully studies so far suggest that a 15 MW geothermal plant is viable along the Bwenga River, and the firm is continuing feasibility studies with the goal to eventually develop an energy generating facility [8, 53, 54]. Outside funding has come to Kalahari GeoEnergy in the form of a US$3.2 million loan from Renewable Energy Performance Platform (REPP), a British investment firm specializing in small to medium renewable energy activity, to develop additional wells verifying the feasibility of a power plant [53]. The US Trade and Development Agency has also provided Kalahari GeoEnergy with a grant to develop a 10–20 MW plant with the goal of encouraging US businesses to invest in improving Zambian electricity reliability [54]. Studies conducted by Kalahari suggest that up to 1000 MW of installed geothermal capacity could potentially be installed in the Kafue trough area [14].

Biomass

Biomass is the largest source of energy in Zambia, comprising 70% of all energy consumed [3, 4]. However, the majority of this is not for electricity production but instead for household cooking and heating purposes. It is estimated that in 2011, the burning of biomass in the form of wood, charcoal, biogas, pellets, and briquettes provided 284 PJ of energy [3, 4]. The majority of the population is dependent upon biomass to meet heating and cooking needs; biomass is used by 57% of the urban population and by 97% of the rural population [3].

Currently, there are three electricity generation facilities utilizing biomass in Zambia [3, 14]. These are sugarcane processing facilities which use most of the energy generated internally, with little directed onto the grid. These sites utilize biogas created from the processing of sugarcane as the fuel source. The largest of these at Nakambala Sugar which possesses 40 MW of capacity and processes 120,000 tonnes of biogas [14]. A 24 MW facility at Consolidated Farm Ltd and a 3 MW facility at Kafue Sugar utilize similar generation methods as the Nakambala factory [3, 14].

Although little biomass generated electricity is injected into the national grid, there is significant potential for its development. It is estimated that Zambia possesses 2.15 million tons of potential biomass resources [3]. One biomass assessment places the potential energy generated from this source at 310 PJ per year [14]. Another assessment states that the biomass energy potential of Zambia could provide a maximum of 498 MW of additional installed capacity [4]. The largest components of the biomass potential are agricultural waste (73%) and forest residues (17%) [14].

Although there is significant potential for installing additional biomass capacity, there are no planned projects for additional installation. The government aims to increase biomass sources to 3% of the national installed capacity by 2030 [14]. Its current methods of achieving this are promotional campaigns and making 100 MW worth of biomass projects applicable for the GETFiT and REFiT programs [2, 4, 14]. So far, no awarded funds from the GETFit and REFiT programs have been given to biomass projects [55]. One concern over the utilization of biomass as a fuel source is its decreasing supply. Presently, Zambia possesses 50 million hectares of forests, but the amount is decreasing between 250,000 and 300,000 hectares a year [4, 14].

Biofuels

Present biofuel production in Zambia is micro-scale; there is not widespread distribution of biofuels nationwide [9]. Several small, biofuel producing firms exist in Zambia; however, current production is internally used or only distributed to local communities [9]. The government has issued standards for blending biofuels with petroleum products for the production of 10% ethanol gasoline and 5% biodiesel, as well as has begun issuing licenses for biofuel production [2, 10]. The aim of this is to alleviate the petroleum product importation demands.

Historically, there have been 3 ethanol and 12 biodiesel projects authorized for the development of biofuels, but as of 2013 only 6 of the biodiesel projects had been implanted [9]. Estimated land usage for biodiesel feedstock cultivation is 3925 hectares [9]. Zambia has taken steps to increase production for national use. The Biofuels Association of Zambia (BAZ) has been established and is made up of biofuel and feedstock producers and planned producers [10]. As of 2020, the Ministry of Energy and the BAZ were using Zambian firm Thomro for the familiarization and assessment needed to implement the Biofuels National Program [56]. In 2020, Zambia also obtained support from the Brazilian Bioenergy, Ethanol, and Sugarcane association for technological guidance in developing a biofuel industry [56].

Approximately 14% of Zambia's 16,540,700 hectares of arable land is cultivated [10]. There is a significant amount of land that could be cultivated for biofuel feedstock; 3925 hectares out of the 985,432 hectares that have been authorized for previous projects are currently utilized [9]. The feedstocks natively grown that have been used previously or have been planned for use in biofuel production are jatropha, palm oil, and sugarcane. Of these, only jatropha has previously been cultivated [9, 10]. The University of Zambia has also conducted feasibility studies into the use of sweet sorghum [10].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

Battery storage technology implemented in Zambia's energy sector so far has been small-scale as part of mini and micro-grid developments, in the form of supporting the three solar PV sourced micro grids in for the communities of Mpanta (60 kW), Muhanya (30 kW), and Mugurameno (10 kW) [2, 34]. These battery banks are only sized to support the local area and not to supply electricity in support of the national grid.

Country's Future Storage Direction

Most new battery storage projects planned will be in support of further micro-grid installations or similarly small-scale projects. Examples, of these projects are the 300-kW solar PV and mini-grid planned for Lunga and the 200-kW solar PV and mini-grid planned for Chunga, both being developed by Zambia's Rural Electrification Authority [34]. Foreign funding and investment have begun to support the development of PV and battery storage mini/micro grids in the country. The US Trade and Development Agency (USTDA) awarded a $750,000 grant to Zambian firm Standard Microgrid for the development of such systems [54, 57]. REPP agreed to a loan for UK firm Buffalo Energy to develop 100 MW which will include mini-grid technologies along with other renewables [58]. The only large-scale planned project is the 150 MW solar-wind-battery storage hybrid project by Upepo Energy [32]. The size of the battery storage system is not available as the project is presently in the feasibility phase using USTDA funding [32].

Zambia does possess some potential in locally exploitable resources for battery production. In 2019, 1.3 thousand tonnes of cobalt were mined domestically [59]. An additional 270 thousand tonnes of cobalt are within its known reserves [59]. This provides opportunities for domestic battery production or investment from foreign battery producing firms.

Although Zambia is highly dependent on hydroelectric there is no pumped hydro storage facilities in the country. As of 2020, there are no planned projects to install pumped hydro sites. However, there is pumped hydro within the SAPP so Zambia could import energy released from these facilities [60]. Pumped hydro exists within South Africa most notability at the Ingula Pumped Storage Scheme (1332 MW) and the Drakensberg Pumped Storage Scheme (1000 MW), which are both owned by Eskom [61, 62]. SAPP's current project planning for new facilities through the year 2040 does not plan on expanding upon its total pumped storage capacity of 2912 MW [60].

Carbon Footprint

Most Recent Carbon Output

Estimates of the total carbon footprint for Zambia vary between approximately 5 million metric tons of carbon dioxide equivalent (Mt CO2e) as reported by the International Renewable Energy Agency (IRENA) and 7.14 Mt CO2e as reported by the US Energy Information Agency (EIA) [13, 63].

Historical Trends of Carbon Footprint

Total carbon emissions for Zambia have increased significantly over the last decade. From 1995 to 2010, total carbon emissions ranged between 1.9 and 2.47 Mt CO2e [13]. However, total CO2 emissions have increased by approximately 4.2 Mt CO2e since the 2010 value (~2.3 Mt CO2e) [13]. According to IRENA, total CO2 emissions increased by 33% from 2013 to 2018 [63] (Fig. 4).

Types and Main Sources of Pollutants

The sectors which contribute the most to Zambia's total carbon emissions are transportation, industrial, and "other" sources, while electricity, heating, and building usage contribute the least [13]. These trends have been consistent since 2013. In 2018, Electricity and Heat generation only contributed approximately 0.2 Mt CO2e [13]. Of this 0.2 Mt CO2e, 22% is due to electricity and heating generation using oil as a fuel source, and the other 78% is from using "Coal + others" as a fuel source as defined by IRENA [13]. A significant part of these emissions is due to 110 MW of installed oil-fueled and 300 MW of coal-fueled electricity generation installed capacity [2]. However, because Zambia mostly relies upon hydroelectricity for electricity generation, the CO2e generation per GWh of electricity produced is lower than world averages. Only 13 tonnes of CO2e are emitted per GWh of electricity produced (tCO2e/GWh), while African and World averages are approximately 610 tCO2e/GWh and 425 tCO2e/GWh, respectively [13]. On a per capita basis, Zambians emit 0.3 Mt CO2e per person which is below the Sub-Saharan African average of 0.8 Mt CO2e per capita as well as the World average of 4.6 Mt CO2e per capita [64].

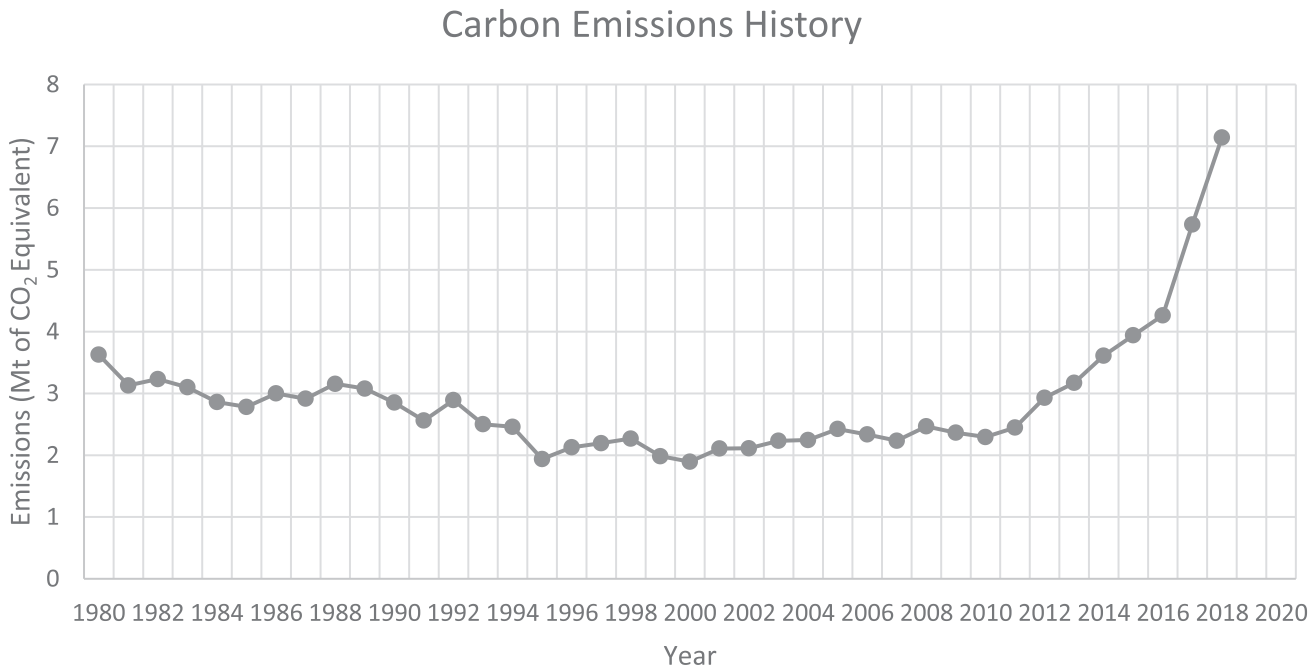

Fig. 4 Zambia's total carbon footprint, in terms of Mt CO2e, from 1980 to 2018. Zambia's total emissions have remained relatively low per unit of electricity generated due to its heavy use of hydroelectricity; however, there has been a significant emissions increase over the last decade

Energy Resiliency

Electrical Grid

The majority of Zambia's national grid transmission and distribution is owned by ZESCO, and the primary regulatory authority of energy in the country is the Energy Regulation Board (ERB). The transmission system operates at the 330 kV, 220 kV, 132 kV, 88 kV, and 66 kV voltage levels [2–66]. As of 2017, the total line length of the transmission system was approximately 8019 km [65]. This was an increase of 800 km since 2016 due to expansion of the 132 kV lines [65]. The total line length and system parameters of the distribution side of the electrical grid are yet to be confirmed as of 2016, although distribution voltage levels of 33 kV and 11 kV are reported [2, 66]. As of 2016, there are 568,000 connections to consumers at the low voltage, distribution level [66]. In Zambia, 31.4% of households have access to electricity [4]. There is significant disparity between urban and rural electrification, as 67.3% of urban households and only 4.4% of rural households have electricity access [4].

Two major international connections exist for the Zambian electricity grid. These are a 260 MW connection to the Democratic Republic of the Congo (DRC) and a 1400 MW connection to Zimbabwe [35, 66]. Between 2015 and 2020, SAPP had planned for five new interconnections involving Zambia: a 600 MW Zambia-Zimbabwe-Botswana-Namibia connection, a 1500 MW Zambia-Zimbabwe-Namibia-South Africa connection, a 500 MW Zambia-DRC connection, a 200 MW Zambia-Malawi connection, and a 400 MW Zambia-Tanzania connection [35]. Over the last decade, Zambia has exported more electricity than it has consumed to other SAPP nations except for 2011 and 2016 [2]. Most recent electricity importation and exportation for 2018 and 2017 were 152.24 GWh and 1250.41 GWh, respectively [2]. This has been a sharp decrease since a recent peak electricity importation of 2184.9 GWh in 2016 [2].

Climate and Natural Disasters

Climate change is projected to have a significant impact upon the nations of Southern Africa as well as those nations' ability to generate electricity. Average temperatures in the region have increased by 1 °C over the last 40 years and may continue to rise to a total increase of 4 °C by the end of the century [5]. Additionally, lower annual precipitation levels and an increased frequency and/or intensity of extreme weather events, such as droughts and tropical storms, are projected. Increased intensity of these events has already impacted SAPP countries and their energy sectors. For example, Tropical Cyclone Idai caused storm surges, flooding, strong winds, and debris. The effects of this storm decreased Malawi's hydroelectric capacity by 270 MW and caused disruptions to the electrical grid [5].

Such effects of climate change are likely to negatively impact Zambia's energy generation capabilities. Zambia has historically been extremely reliant on hydroelectric power to meet electricity demands with over 80% of its electricity generated from hydroelectric dams. Higher temperatures will lead to increased evaporation of dam reservoir water. This, combined with the increased frequency and/or intensity of droughts, will significantly decrease hydroelectric dam electricity output. Zambia has already seen these effects [5]. In 2016, Kariba Dam saw its reservoir water levels decrease to 12% which led to black outs and the rationing of electricity [5]. As previously discussed, 2016 was the most recent year in which the country saw a peak in electricity importation. African hydroelectric capacity is projected to decrease by 3% throughout the twenty-first Century due to the impacts of climate, which will result in the total loss of 130 TWh of energy [5]. This is even greater for Zambia as its hydroelectric capacity is expected to decrease by 7% but possibly up to 14.8% [5]. This decrease in capacity and reduce in ability to provide electrical power to the grid will significantly impact Zambian grid reliability, as well as its resiliency to recover from interruptions.

Grid Resiliency

Climate change will have a nonmarginal effect on Zambia's ability to generate electricity, however, this is not the only factor affecting its ability to provide power to consumers. Zambia's regulatory authority, the ERB, rates its generation, transmission, and distribution entities on several compliance factors including maintenance, safety, and security of supply [2]. In 2018, ZESCO operations scored an average of 76.7%, below the 87% target goal, and independent power producers scored between 85.99% and 97.23% [2]. Issues arising from instances of noncompliance lead to ZESCO transmission and distribution losses of 5.25% and 10.45%, respectively, as well as IPP reported total losses of 2.7% [2]. In 2018, the ERB reported 27 major power systems disturbances, typically interruptions of supply to at least 1000 consumers and greater than 5 system-minutes long. This number was 30 major power disturbances in 2017 [2]. An inability to meet demand reliability 100% of the time, as well as possess complete grid resiliency to supply power to all consumers in case of interruptions has led to historic implementation of load shedding. ZESCO implements province-based and nationwide load shedding schedules in order to address the challenges of meeting peak demand [6].

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

Zambia has historically been reliant on other countries to meet its transportation and fuel needs. Zambia does not extract any crude oil domestically and must import all crude oil and petroleum products [2]. The country's main artery for this is the TAZAMA pipeline connection to Tanzania. Through this pipeline, up to 800,000 MT of oil is imported annually to be processed by the 850,00 MT/year capacity IDENI refinery, Zambia's only petroleum refinery [2]. The refining of the crude oil from Tanzania is not enough to meet the annual petroleum consumption (1,344,908 MT in 2018), and the rest must be imported by the government or private entities through other means [2]. Unlike oil, there is significant domestic coal production. However, coal importation still occurs, amounting to 97 short tonnes of imported coal in 2018 [2, 13].

Zambia does import electricity, but it does not typically require a large amount of foreign generated electricity. In most recent years, Zambia exported more electricity than it imported. In 2018, electricity importation was 152.24 GWh while it exported 1250.41 GWh [2]. However, it may be forced to rely upon importation from other SAPP member states during years of drought, as was seen in 2016 [2, 5]. A hyper-reliance on hydroelectricity will cause the country to import more than it is able to export during years of decreased generation from its dams. As roughly 80% of its electricity generation installed capacity is from hydroelectric dams, it is possible that Zambia will become more dependent on importing energy from its neighbors due to effects of climate change [2, 5].

Relations with Global Community/ Socioeconomic Influence

Zambia maintains mostly cordial relations with other nations, although some relation straining issues exist such as border disagreements with Botswana and Zimbabwe [1, 67]. Zambia maintains economic and political ties with its neighbors of other countries in the region through its membership in the Southern African Development Community (SADC), through which SAPP was established, and the Common Market for Eastern and Southern Africa (COMESA) [67]. It is additionally part of larger international organizations such as the United Nations, World Bank, International Monetary Fund, African Union, and African Development Bank [67]. Zambia has also agreed to the Paris Agreement under the United Nations Framework Convention on Climate Change. It submitted its first Nationally Determined Contribution (NDC) in 2016 as well as an updated version of it in 2020. In its NDC, Zambia defines its focused strategies for Climate Change mitigation as "sustainable forest management," "sustainable agriculture," and "renewable energy and energy efficiency" [68].

Zambia has received significant foreign aid and foreign investment, including investment in the country's energy sector. The United States provides US$500 million a year to assist in economic development, democratic reform, and fighting HIV/AIDS among other things. The USTDA and USAID have specifically invested in Zambia's solar, wind, and microgrid developments [25, 32, 54]. Other foreign investment into the Zambian energy sector has come from the World Bank, European Union, African Development Bank, Russia, and China [17, 25, 38, 49]. One issue of concern that Zambia will need to address in order to attract further foreign investment and maintain cordial international relations is that of the large-scale debt that many African nations face. In 2020, Zambia defaulted on its debt when it did not make a US$42.5 million payment to a creditor. It is possible that this will influence foreign investment or its ability to secure loans for future energy infrastructure projects [69].

Education

Zambian public universities do not offer any majors with a specific focus of renewable energy engineering or technology. However, some universities offer engineering programs with courses about renewable energy or are related to the renewable energy engineering field. Civil Engineering majors are offered courses in dam engineering, hydrology, and hydraulic structures [70, 71]. Mechanical Engineering students at the University of Zambia and Copperbelt University have a specific course on renewable (alternative) energy [72, 73]. Electrical Engineering programs offer power electronics courses. These courses include at least some focus on renewable energy technologies or would at least discuss technologies useful for the grid integration of renewables. These electrical engineering programs also offer courses useful for maintaining the entire energy grid, such as power systems analysis and power system protection [71, 74, 75]. Although not a renewable engineering focus, the Mukuba University offers a Bachelors of Science in Environment and Climate Change program [76].

Summary

Current Energy Situation

The Zambian energy sector has historically been very reliant on hydroelectricity to meet its energy demands with hydroelectric power constituting over 80% of the country's installed capacity [1–4]. Although the country is generally a net exporter of electricity, the country still faces some difficulty meeting peak demand and load shedding occurs as a result [6]. Decreased hydroelectric power generation due to the effects of climate change will put further strain upon the nation's ability to meet demand, and during years of significant reduction in hydroelectric output, Zambia will likely be a net importer of electricity [2, 5]. Zambian energy importation infrastructure will likely need to be expanded. This is due to the country importing all of its petroleum products as no crude oil is extracted domestically [1, 2]. The majority of the population does not have access to electricity as only 31.4% of households are electrified; 4.4% of rural households and 67.3% of urban households [3, 4].

Future Energy Situation

Zambia will continue to be reliant upon large-scale hydroelectric and coal plants for a majority of its installed capacity as future plans include new power plants from these energy sources [2, 4]. However, electricity generation will see diversification as technologies with little or no previous use are planned to see expansion, mostly solar and mini-hydro sites [2, 4]. This diversification is likely to see a significant increase in the number of privately owned firms entering the industry. Traditionally, the majority of Zambia's electricity generation sites have been operated by a state-owned firm [2, 4]. Additionally, there will be an expansion of the biofuels sector to assist in meeting the country's transportation demands, but a majority of the sector will still be fueled by imported petroleum for the foreseeable future [2, 4]. Funding for energy sector developments will come from public and private Zambian sources; however, foreign aid and investment will also be needed [2, 4].

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Zimbabwe

Slobodan Petrovic and Matthew Sherland

National Energy Introduction

Zimbabwe is a landlocked, southern African nation home to around 14,830,000 people [1]. Zimbabwe, formerly part of the British colony of Southern Rhodesia, has been an independent nation since 1980 [2]. Historically, Zimbabwe's energy sector has focused primary on coal-fueled thermal plants and hydroelectricity. These two sources currently make up over 95% of the country's total installed electricity generation capacity [3]. Electricity and transportation energy consumption make up a minority of the total annual energy consumption. Biomass, mostly forms of wood fuel, makes up 61% of total energy consumption for heating and cooking needs of the population [4] because only 37% of Zimbabwean households have access to electricity (13% of households in rural areas and 83% of urban households) [4].

Zimbabwe's faces several energy-based challenges including a lack of rural electrification and a lack of available installed capacity to meet electricity demands. Although nameplate installed capacity is over 2300 MW, only 1400 MW is readily available to meet a peak electrical demand of 1700 MW [5], in part due to aging and maintenance issues for many of its existing power plants. Additionally, Zimbabwe has no domestic crude oil or refined petroleum products production and is reliant on the importation for all its refined petroleum products needs [3].

Energy Policies

The primary polices which define Zimbabwe's energy policies are the 2012 National Energy Policy, the 2019 National Renewable Energy Policy, and the Biofuels Policy of Zimbabwe. The National Energy Policy sets forth policy objectives for the country to develop sustainable economic growth, improve energy affordability, improve legal and institutional framework for energy sector development, promote research and development for the country's energy sector and energy technologies, and develop the exploitation of renewable energy sources [4]. The National Renewable Energy Policy sets forth objectives to increase nonlarge-scale hydroelectric installed capacity to 2100 MW by 2030 (or to 26.5% of the total electricity supply), as well as to install 250,000 solar water heaters to reduce the electricity demands for heating [5]. The Biofuels Policy of Zimbabwe attempts to reduce the petroleum consumption and importation demands by increasing the number of participants in the biofuels industry, increasing the blending of ethanol with petrol to 20% to 2030, and increasing the blending of biodiesel with traditional diesel to 2% by 2030 [6].

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Domestic Resources

Zimbabwe has multiple forms of renewable and nonrenewable energy available for exploitation. There are known domestic deposits of coal, uranium, and lithium. Currently, there are not proven oil, natural gas, or geothermal deposits in Zimbabwe, although exploratory efforts for these resources exist [7]. Zimbabwe has significant amounts of hydroelectric and solar potential, much of which is not exploited [8]. Wind potential is not sufficient for electricity generation in most of the country; however, there are a few hotspots in which capacity could be installed [4, 8]. Biomass and biofuels are currently being exploited with the aim for expansion, and the cultivation of sugarcane, cassava, and jatropha has enough arable land available to meet biomass and biofuel goals [6, 8].

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Breakdown of Energy Generation "Mix"

Energy Generation Mix

Renewable energy sources make up almost half of all installed capacity for electricity generation and they generate a majority of all GWh of electricity supplied. They make up the vast majority of the total energy consumed by all means including electricity; however, most of this is due to biomass being consumed to meet the majority of Zimbabweans heating and cooking needs. Not all forms of energy are officially reported or are too difficult to be measured currently, and thus are not included in the Figs. 1 and 2 below. Examples of this would be water heating performed using solar water heaters or electricity generated by single solar module, household systems in rural areas not connected to the grid. For the purposes of this energy generation and consumption overall breakdown, such energy use is deemed insignificant.

Energy Consumption Mix (Fig. 3)

Fossil Fuels

Oil

Zimbabwe does not extract any crude oil domestically [1, 7]. The country currently does not possess a petroleum refinery. All petroleum products consumed in Zimbabwe must be imported, and these products must be in a refined state. Estimates in 2015 place refined petroleum product importation at 3600 metric tons (26,400 bbl./day) [1]. The majority of this importation is done though the National Oil Infrastructure Company (NOIC) of Zimbabwe via the Beira-Feruka-Harare pipeline [9]. This pipeline imports multiple forms of refined fuels into the country from Mozambique. In 2018, the total importation of petroleum products was over 1.393 Mt (1.623 billion liters) [3]. Of this, 0.79 Mt (921 million liters) was diesel, 0.53 MT (616 million liters) was petrol, 0.06 Mt (74.6 million liters) was Jet A1 aviation fuel, and 0.01 Mt (11.7 million liters) was paraffin [3]. Importation of refined fuels increased by roughly 0.286 Mt (333 million liters) since 2017 [3].

A project to begin domestic petroleum refining has been initiated. A US$1 billion project by Zambian firm Zueth Petroleum aims to complete Zimbabwe's first petroleum refinery by 2023 [10]. The project goals are to construct a facility capable of processing 6821 metric tons (50,000 barrels) per stream day of crude oil and natural gas [10]. The project is still in development, and $300 million of the US$1 billion needed has been secured so far [10].

Zimbabwe presently possesses no proven oil reserves from which domestic crude oil may be extracted. Initial oil exploration in the country was conducted in the 1990s by Mobil [11]. However, the Mobil project only acquired exploratory data and did not prove the existence of crude oil deposits [11]. Australian firm Invictus is currently conducting oil and natural gas exploration projects in Zimbabwe using the Mobil project's data for assistance [11]. The project is being conducted in the Cabora Bassa Basin in northern Zimbabwe in the areas of Mzarabani and Msasa, and estimated costs for the exploratory wells are US$10 million [11].

Zimbabwe currently has no oil-fueled thermal plants generating electricity for the national grid. Previously, the Dema Power Station contributed 200 MW to the country's total installed capacity [3]. The Dema station was a diesel-fueled thermal plant that was designed as an emergency peaking

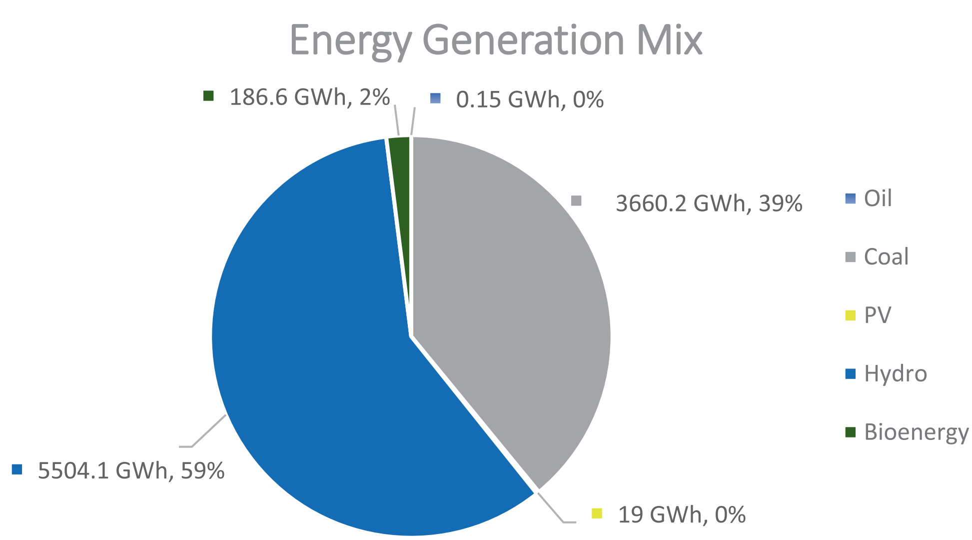

Fig. 1 Breakdown of electrical energy generated from existing sources in Zimbabwe as of 2018. Zimbabwe generated 0.15 GWh from oil during this year; however, its only oil-fueled facility shut down in 2018. It is reflected in Fig. 3 that there is no longer any oil-fueled installed capacity [3]

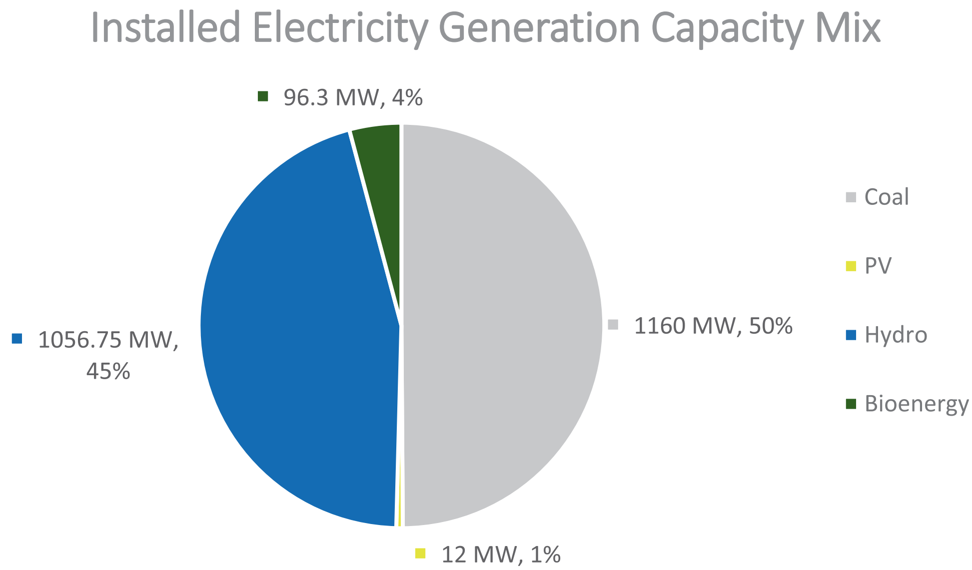

Fig. 2 Breakdown of the installed capacity for electricity generation from all reported facilities in Zimbabwe as of 2018. Coal and hydroelectric facilities have traditionally made up the vast majority of installed capacity and will likely continue to do so for the foreseeable future even though there are plans to increase solar PV utilization [3]

power station. This station was shut down in 2018 and is not currently contributing to the national electricity supply [3]. As of the end of 2018, there were no licensed projects for future installation of petroleum-fired thermal plants [3].

Coal

In 2018, domestic coal production in Zimbabwe was 2.15 Mt (2.37 million short tons) [7]. This has decreased from a peak production of 5.79 Mt (6.38 million short ton) of coal in 2014 [7]. Domestic consumption of coal in Zimbabwe was 2.15 Mt (2.37 million short tons) in 2018 [7]. Domestic consumption has decreased since the highest peak in recent years of 3.47 Mt (3.83 million short tons) which occurred in 2015 [7]. Historically, coal exports have exceeded imports. In 2018, 0.05 Mt (59 thousand short tons) were exported while only 0.03 (34 thousand short tons) were imported [7].

Historically, Zimbabwe has been heavily reliant on coal for electricity production. Currently, the total installed capacity for coal-fired plants is 1160 MW, a little more than half of the total installed capacity in the country [5, 12–15]. This is divided among four thermal plants, all operated by the government-owned Zimbabwe Power Company, a subsidiary of the Zimbabwe Electricity Supply Authority [5, 12–15]. Installed capacity and generation capability have decreased over time due to maintenance issues. An example of this is the Bulawayo Power Station which initially had an installed capacity of 120 MW [14]. However, it has since been derated to 90 MW and only generates a mean power of 30 MW [14]. The conditions and capabilities of these plants are part of the reason Zimbabwe faces a deficiency between power supply and demand. Nameplate total installed capacity is over 2300 MW. However, only 1400 MW may be supplied while peak demand in 2019 was 1700 MW [5].

There are a number of coal-fired thermal plants projects in various stages of planning or construction. Although there are numerous projects to expand installed capacity, not necessarily will all of these projects be completed as some are still undergoing feasibility studies or seeking funding. The most notable coal project underway is the Sengwa Power Station which will have a nameplate capacity of 2400 MW [3]. The US$3 billion project is a joint venture between Zimbabwean firm RioZim and the Chinese firm Gezhouba Group [16]. This project is likely to not come online for some time as it is still seeking additional investors [3, 16].

The most notable projects currently under construction are expansions and upgrades to Zimbabwe's current coal-fired thermal plants. Hwange Power Station, currently Zimbabwe's largest operating thermal plant with a capacity of 920 MW, is undergoing the installation of two additional units which will increase the station's total capacity to 1520 MW [12]. Bulawayo Power Station is undergoing a refurbishment in which its older, decommissioned units and cooling towers will be demolished. This is to make room for new boiler equipment which will extend the longevity of its still operating units by an additional 15–20 years [17].

As of 2019, Zimbabwe had 553 million short tons of proven coal deposits [7]. It is believed that there 2 billion short tons of provable yet undiscovered coal deposits capable of being mined [18]. The total possible undiscovered coal deposits in the country may be at least 10.6 billion short tons [18]. However, additional exploratory studies would be needed to confirm the coal deposit potential.

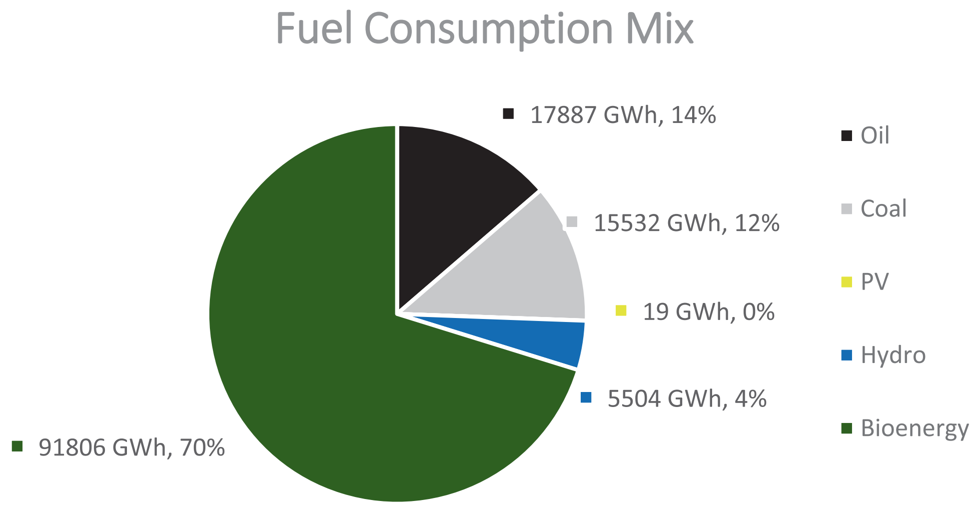

Fig. 3 Breakdown of total energy consumption in Zimbabwe during 2018 from all sources including electricity, transportation, cooking, and heating. Biomass makes up the greatest energy consumption due to its heavy use for heating and cooking [3]

Natural Gas

As of 2019, Zimbabwe does not produce or extract any natural gas domestically [1, 7]. Presently there are no thermal plants that are natural gas powered in the country, and natural gas does not contribute to meeting the country's electricity demands [1, 3]. Due to lack of production of natural gas and lack of installed capacity for natural gas thermal plants, there is no importation or exportation of natural gas in Zimbabwe [1, 7]. As of 2018, there are no future projects to install capacity for natural gas-fired plants which have received government licensure [3].

Presently, Zimbabwe has no proven deposits of natural gas through which it could exploit to contribute to the national energy demands of the country. Previous oil and gas exploration was performed by Mobil in the 1990s [11]. Currently, natural gas and crude oil deposits exploration is being performed by Australian firm Invictus. The firm is making use of the Mobil exploratory project's dataset to survey and drill in the Cabora Bassa Basin in northern Zimbabwe [11]. Although deposits have yet to be discovered, the firm has estimated that mean values of undiscovered natural gas deposits range at 9.25 trillion cubic feet with an additional 294 million barrels of condensate [11]. Should natural gas deposits be discovered through the Invictus project, electricity generation via gas-powered thermal plants would become feasible. The firm has already signed a Memorandum of Understanding with Tatanga Energy to supply 730 billion cubic feet of natural gas, should it be discovered, so that a 500 MW thermal plant may be installed [11].

Nuclear Energy

Zimbabwe does not possess any nuclear power plants, and none of the electricity generated in the country is done so through nuclear sources [3, 4]. There are no current planned or licensed projects to construct a nuclear reactor in the country [4]. Electricity generated via nuclear sources is available to be imported into Zimbabwe due to the country's membership in the Southern Africa Power Pool (SAPP). Within SAPP, there is 1860 MW of installed capacity for nuclear energy. All of this capacity exists within South Africa and is owned by the firm Eskom [19].

Although there are no planned projects for installing capacity for nuclear energy facilities, in recent years, Zimbabwe has been updating its legal framework regarding nuclear technology and is studying the feasibility of nuclear power implementation into its energy sector. As part of its National Energy Policy, Zimbabwe has stated the objective to explore the feasibility of nuclear energy and to explore the possibility of using nuclear energy to diversify its energy generation techniques [4]. Zimbabwe aims to develop its own nuclear energy capacity, or if that proves infeasible, to export fuel sources to be used for nuclear power [4]. Part of its strategies to perform this, as laid out in its National Energy Policy, is to work in conjunction with the International Atomic Energy Agency (IAEA) and the African Regional Cooperative Agreement for Research Development and Training (AFRA) to strengthen its legal and regulatory framework, as well as gain outside technical expertise and cooperation [4]. In 2020, Zimbabwean representatives met with IAEA officials to update its nuclear legal framework so that it will get it closer to international regulatory standards. Among what was discussed were updates to better adhere to the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management, as well as the Convention on the Physical Protection of Nuclear Material [20].

Zimbabwe possesses deposits of uranium should it choose to export nuclear fuel sources instead of utilizing them for domestic electricity generation. There are 1800 tonnes of uranium (tU) of proven/ reasonably assured deposits of uranium in the country, and these are found in the Kayemba-1 (Kanyemba) deposit in northern Zimbabwe [4, 21, 22]. Exploration of these known resources was conducted in 1980s and early 1990s, and US$6.9 million was invested in the exploration [21, 22]. No significant exploratory efforts were made since then. Zimbabwe possibly contains significantly more uranium deposits that are undiscovered, as reported speculative uranium deposits are thought to be 25,000 tU [21, 22].

Renewable Energy Generation

Photovoltaics (PV)

The installed capacity of solar PV technology in Zimbabwe is currently only 12 MW [23]. This is less than 1% of the total installed capacity in the country for electricity generating facilities [23]. The largest solar PV installation is the Riverside Power Station located in Mutoko [3, 24]. This installation was a private enterprise development by UK holdings group PGI. The current installed capacity of the facility is 2.5 MW [3, 24]. There are future plans to expand the installed capacity by an additional 7.5 MW, and this expansion project already has received licensure from the government [3]. A majority of Zimbabwe's solar installation are small-scale, single-household installations. Eighteen percent of households in the country have solar PV installed (24.7% of rural homes and 5.1% of urban homes) [8]. These are typically one solar module systems, often do-it-yourself kits that power a few lights and a battery. The total installation capacity of these at-home PV systems is currently not known [8].

As of the end of 2018, there were planned solar PV projects and solar PV projects under construction which had received licenses from the government which would add over 814 MW to the country's total installed capacity [3]. Licenses for over 267 MW of solar PV installation were issued in 2018 alone [3]. The largest of these efforts are three separate 100 MW installations being developed by the government-owned Zimbabwean Power Company [3, 25]. These projects are to be constructed in phases and are aimed to be completed within the next few years. The Gwanda Solar Plant planned on first installing 10 MW by the end of 2020 and adding an additional 90 MW by the end of 2022 [25]. The first phase of the project cost US$14 million and is being developed by private Zimbabwean contract Intratrek Zimbabwe [25]. The government has also announced a deal with the United Arab Emirates for an additional 2000 MW of additional solar PV installation in Zimbabwe to be constructed in two 1000 MW phases [26]. The cost and timeline of construction for this installation has yet to be announced [26].

Zimbabwe has significant potential for solar PV throughout the majority of the country. Specific photovoltaic output in Zimbabwe ranges between 4.44 and 5.14 kWh/m^2 per day [27]. Annual solar irradiance for the majority of the country ranges between 1600 and 1900 kWh/kWp each year, with some estimates stating certain areas are approximately 2000 kWh/kWp a year [3, 27–29]. The central and western regions of the country experience the highest average annual solar irradiance (1800–1900 kWh/m^2 per day) [27].

Zimbabwe does not presently possess any large-scale concentrated solar power (CSP) facilities currently harvesting solar thermal energy, nor does it have any planned projects to install such capacity [3, 30]. Presently, all utilization of solar thermal energy in the country is in the form of small sized, typically single-household solar water heater units. These single-home solar water heaters are being used as one measure to address concerns about the country's energy demands. These solar Water heaters are installed in households to address needs for heating and cooking. It is estimated that between 250,000 and 300,000 of these units were installed across the country in 2012 [8]. The current goal is to install an additional 250,00 units by 2030 [5]. This would cut down on biomass use, or other heating fuel sources, for heating and cooking needs.

Zimbabwe's only access to electricity generated from solar thermal technology would be to import that electricity from South Africa [19, 31]. The South African firm Eskom currently operates 500 MW of capacity of CSP facilities [31]. The largest of these plants are 100 MW, such as the Kathu 100 MW CSP plant located within the Kalahari Desert [31, 32]. Eskom projects up to 600 MW of CSP facilities will be under its operation by 2030 [31, 32].

Wind

Zimbabwe currently possesses no installed capacity for generating electricity through wind energy [3]. The country's only access to electricity generated from wind energy would be by importing such electricity from other member states of SAPP. As of 2016, SAPP entities own 2492 MW of installed wind capacity [19]. There was a previous pilot program for wind energy installed in Temaruru in 1999; however, the project eventually ended when the local community could not afford the maintenance and replacements parts for the turbines [4, 33].

Wind energy potential for electricity generation is low throughout a majority of the country. Average winds speeds in most areas are around 3 m/s, which is not high enough for sufficient electricity generation [4]. However, areas with these lower wind speed have been identified as areas in which wind can be used for water pumping instead of electricity generation [4]. Although installing wind energy capacity for electricity generation is unsuitable for most of the country, several wind hotspots (areas of wind power density of at least 200 W/m^2) exist in Zimbabwe, mostly in the western and northeastern regions of the country [33].

The International Renewable Energy Agency (IRENA) has estimated that these hotspots have the potential for 45,690 MW of installed capacity [34]. However, a majority of this (39,300 MW) is in the lower range of power densities (200–250 W/m^2) [34]. Total potential energy generation for these hotspots was estimated at approximately 80 TWh [34]. The Zimbabwe Energy Regulatory Authority (ZERA) has worked with IRENA to appraise five potential sites for installing wind energy capacity (Mavhuradonha, Karoi, Plumtree, Shangani, and Mtroashanga) [3]. Current estimates value potential capacity of 250 MW at each site, but further feasibility studies need to be conducted [3]. The government has additionally targeted 100 MW of installation at Mamina as part of its System Development Plan [29].

Hydro

Hydroelectric Power had historically played a crucial part of Zimbabwe's energy sector. As of 2018, the installed capacity of hydroelectric dams was 1056.75 MW, which makes hydroelectric power currently the second largest electricity generation source in the country in terms of installed capacity [3, 12, 35]. Although it is only second in terms of installed capacity, hydroelectric is the largest generator in the country for amount of electrical energy produced. In 2018, hydroelectric power produced 5504 GWh of electricity for the national grid out of a total of 9348.47 GWh produced by all of Zimbabwe's active electricity generating plants [3]. Hydroelectric energy has increased by 39.7% since 2017 when 3850 GWh of electricity was produced from hydroelectricity [3].

The largest and only large-scale hydroelectric dam in Zimbabwe is the Kariba Power Station. The dam is built along the Zambezi River which defines the border between Zimbabwe and Zambia, and it supplies electric power to both nations [35]. Zimbabwe's installed capacity lies on the south bank of the river. This dam was completed in 1962 with an original installed capacity of 666 MW [35]. Multiple capacity expansion improvements to the dam have been conducted over time. The most recent of which was the installation of 300 MW in 2018 which brought the total installed capacity of Zimbabwe's portion of the dam to 1050 MW [35]. This made the Kariba South Bank Power Station Zimbabwe's largest facility in terms of installed capacity surpassing the 920 MW Hwange coal-fired thermal plant [12, 35]. The other existing hydroelectric power stations within the country are mini-hydro facilities in the Eastern Highlands which have a total combined capacity of 6.75 MW [36]. These mini-hydro facilities, which are independently owned, produce 126.78 GWh of power in 2018 [3].

Although Zimbabwe has historically been reliant upon installing hydroelectric capacity to meet its energy demands, the majority of Zimbabwe's hydroelectric potential has yet to be exploited. The Zambezi River, from which the bulk of the country's hydroelectric power is derived, has a total potential of 3400 MW for installations on the south bank of the river that is Zimbabwean controlled [8]. This leaves approximately 2350 MW of potential currently unexploited, resulting in an unexploited potential of 13,200 GWh of electrical energy per year [8]. Zimbabwe's interior river systems possess an additional 430 MW of potential capacity and 88.4 GWh a year of potential electrical energy [8]. The vast majority of these interior rivers are also unexploited [8].

Zimbabwe presently has multiple large-scale schemes under development for future hydroelectric installed capacity, all of which on the Zambezi River, which would split power evenly between Zambia and Zimbabwe. However, none of these are currently under construction. The largest and furthest along in the development process is the Bakota Gorge Hydro Electric Scheme [37]. If completed, this project would add an additional 800 MW to Zimbabwe's energy sector with an additional 800 MW built on the Zambian side of the river [37]. Feasibility studies and assessments have been performed for the project, and it is currently seeking funding for the US$4.5 billion construction [37, 38]. Additional proposed projects include the 1200 MW Mupata and 1000 MW Devil's Gorge hydroelectric dams, each evenly splitting their capacities between Zambia and Zimbabwe. However, these sites do not have present construction and funding plans but are rather proposed sites for future installations [29, 39, 40].

Additional future hydroelectric installations will be taking the form of mini/micro-sized facilities. As of 2018, there were projects comprising of a total of 15.94 MW of capacity which had received licensure from the government [3]. These projects are in various stages of feasibility studies, funding, or construction. In 2018 alone, 6.84 MW worth of projects had received a license [3]. Once completed, most of these projects will be operated by independent power producers except for the 5 MW Great Zimbabwe Hydro Power Plant which will be operated by the government-owned Zimbabwe Power Company [3].

Ocean

Zimbabwe possesses no electrical power generating facilities that exploit ocean or wave energy [3]. Zimbabwe is a landlocked nation, and thus does not have any potential to utilize these renewable energy sources for power generation. The possible way for Zimbabwe to consume electricity generated from ocean or wave energy would be to import such electricity from another SAPP member state. Several SAPP countries, such as South Africa, do possess coastlines from which ocean or wave energy facilities could produce power [19]. However, there are presently no such facilities within SAPP members' states, and there are no present plans to construct ocean or wave energy facilities within SAPP [19, 30].

Geothermal

Zimbabwe presently does not have any geothermal energy power plants, nor any planned projects for exploiting geothermal energy [3]. Currently, the country does not have the capability of importing any electricity generated from geothermal sources as there is no geothermal power plants presently operated by any SAPP members [19]. There is a planned 150 MW project in Tanzania aimed to come online in 2025, but until then, Zimbabwe will not have the ability to import geothermal energy generated electricity [30].

Approximately 50 MW of potential capacity has been identified to exist within Zimbabwe [41]. This potential was identified in 1985, and since then, no significant exploration of Zimbabwe's geothermal potential has been performed [41]. Without further exploration it is unclear what Zimbabwe's true geothermal potential may be. It is possible that Zimbabwe may have unidentified areas of geothermal due to the country being near nations in which the Great Rift Valley, which stretches along eastern Africa, is located [41, 42]. Presently 900 MW of capacity is installed in other nations to exploit the geothermal potential of this region [42]. It is possible that some SAPP member states, such as Tanzania, may be able to exploit this potential as well and export geothermal generated electricity to Zimbabwe. However, only the single 150 MW geothermal plant in Tanzania is planned so far [30].

Biomass

Biomass currently is the greatest fuel source for energy consumption in Zimbabwe. The vast majority of this is for uses other than electrical power generation [4, 33]. 63.5% of Zimbabwean households are reliant upon biomass fuel sources, mostly firewood, for cooking [33]. This is done by 94% percent of households in rural areas [33]. Only 6% of rural households have access to electricity to meet cooking needs [33]. Due to this reliance on firewood to meet cooking needs and heating, wood consumption is 61% of the total energy use in the country [4, 33].

Although biomass makes up the greatest fuel source for energy consumption in the country, only a fraction of the electrical energy generated comes from biomass sources. As of 2018, the total installed capacity of biomass power plants was 96.3 MW [3]. There are three Zimbabwean biomass power plants: the 33 MW Hippo Valley Estates Power Station, the 45 MW Triangle Power Station, and the 18.3 MW Green Fuel Plant [3, 33]. All of these facilities are privately owned, and they utilize cogeneration to meet energy needs. The Hippo Valley Estates and Triangle Estates power stations make use of bagasse, a residue byproduct from the processing of crops such as sugarcane, to power sugarcane processing facilities [4, 33]. Electricity energy generation from these facilities amounted to 147.1 GWh in 2018. A majority of the electricity generated from these is used internally by the power plants. Only 10–12 MW of capacity is generally available to power electricity to the national grid [4, 33]. The Green Fuel plant is an ethanol production facility which makes use of bagasse by-product from the production. Only 10 MW of the 18.3 MW capacity is used for the national grid while the rest is used internally [33]. In 2018, the Green Fuel plant produced 39.5 GWh of electricity [3].

Zimbabwe possesses multiple forms of biomass energy which could potentially be utilized. Traditional wood fuel ranges between 4.6 million tons per acre to 5.654 million tons per acre of forested area, and the country's forests could additionally produce 70,000 tons per acre of forest residue for a biomass energy source [4, 8, 33]. These sources could allow for an additional 150 MW of installed biomass capacity [33]. One concern over the use of biomass as a fuel source is deforestation. Presently 6 million tons of wood are consumed each year due to cooking, heating, and agricultural demands. This results in a loss of 60 million trees a year while only 10 million are planted annually [4].

Additional potential biomass fuel sources in Zimbabwe include animal and agricultural waste, sawmill waste, and municipal solid waste. Sawmill waste has 750,000 tons per acre of potential fuel which could add 16 MW of electricity generation capacity [33]. There was previously a 0.5 MW at the privately owned Border Timers facility, but it is no longer operational [3, 33]. There are projects in development for a 3.5 MW plant at the Nyanga Sawmill and a 3 MW plant at the Chimanimani Sawmill [33]. In addition to sawmill waste, the potential feedstock densities of animal waste is 4.48 million tons per acre, crop residue at 10.86 million tons per acre, and municipal solid waste at 957,000 tons per acre [33]. To increase the use of biogas, a National Biogas Program has led to 2000 biogas digesters being installed to provide small-scale utilization of biogas from municipal or agricultural waste [33]. Multiple cities have digesters installed in their sewage systems. However, only two units in Harare collect the gas as a potential fuel source, while the rest flare off the waste [33].

Biofuels

In order to increase biofuel production domestically, the national government initiated the Biofuels Policy of Zimbabwe. This was done in an effort to reduce demand for refined petroleum products (i.e., petrol and diesel), especially because in the country all petroleum products consumed must be imported [6]. Under this policy, petrol is mandated to be blended with biofuels so that they are at least 10% ethanol. The goal of the policy in to increase the blending ratio to 20% ethanol by 2030 [6]. By 2030, the goal is also to produce enough biodiesel so that diesel products are 2% biodiesel [6]. Additionally, the Biofuels Policy of Zimbabwe aims to increase the number of biofuel producers in the country and to increase the infrastructure and marketability for high-blend fuel (E85) [6].

There currently are three biofuel producers in Zimbabwe: Hippo Valley, Triangle Estates, and the Green Fuel Plant [3, 6, 33]. All three of these facilities are currently utilizing sugarcane as a feedstock to produce ethanol. Production capacity for the Triangle and Hippo Valley Estates combined is 40 million liters of ethanol annually, and capacity for the Green Fuel facility has ranged between 54 and 100 million liters annually [33]. In 2018, Hippo Valley and Triangle Estates together produced 23.7 million liters and Green Fuel produced 57 million liters. Presently, there is no significant biodiesel production [3].

Presently, 54,000 hectares are used within the country for sugarcane cultivation [6]. 35,000 to 45,000 hectares alone would be needed to produce enough ethanol feedstock to meet the 2030 goals of the Biofuels Policy of Zimbabwe [6]. Most land suitable for sugarcane production is in the southeastern regions of the country, with approximately 2.9 million hectares of suitable land [6]. Although not currently used, the cassava plant has been identified as another potential feedstock for ethanol production. Approximately 8.7 million hectares of suitable land for cassava cultivation have been identified, primarily in the northern and southeastern regions of the country [6]. The jatropha plant is the candidate feedstock for a national biodiesel program. It has been estimated that at least 100,000 hectares of land would need to be cultivated to meet the national biofuels policy [6]. Approximately 12.6 million hectares of land are suitable for jatropha production in Zimbabwe, and most of which is in the northern and eastern regions of the country [6].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

Although battery storage technology exists in Zimbabwe throughout the country, there are no large-scale battery storage units currently in service. Battery storage units are most often part of an at-home solar PV, and these systems are typically one solar module and one battery systems meant to only power a few lights and an electronic device charger [8]. The exact combined storage capacity of these units is unknown, but as of 2012, up to 18% of Zimbabwean households had these or similar systems installed [8]. Other uses for solar and battery storage systems are also small-scale and include powering electric stoves for rural areas and telecommunications towers. Battery storage technology usage may increase further as more solar-powered mini/micro grids are developed [33].

Country's Future Storage Direction

Zimbabwe possesses some natural potential for material used in battery storage technologies. In 2019, 1.6 thousand tonnes of lithium were mined in the country, and there are an additional 230 thousand tonnes in reserves as lithium deposits [43]. Foreign or domestic firms would be able to exploit this natural resource to invest in battery production.

There is currently no domestic utilization of pumped hydro energy storage technology within Zimbabwe. The country's electric grid only possesses potential access to energy generated from pumped hydro via importation from South Africa, a fellow SAPP member state [30]. All pumped hydro currently part of SAPP's installed capacity belongs to the South African firm Eskom. This is comprised primarily by the 1000 MW Drakensburg Pumped Storage Scheme and the 1332 MW Ingula Pumped Storage Scheme [30]. The Zimbabwe National Water Authority has reportedly reached an agreement with Swedish firm Ngonyezi for a proposed 2000 MW pumped hydro, 300 MW solar PV project for the Odzi River; however, no further development on the project besides the agreement has been reported [44].

Carbon Footprint

Most Recent Carbon Output

Statistical data for the total annual greenhouse gas emissions for Zimbabwe vary depending upon the source. On the lower end of the spectrum, the United States Energy Information Agency (EIA) states that the 2018 carbon dioxide equivalent (CO2e) emission in Zimbabwe were 9.1 million metric tonnes (Mt) [7]. On the higher end of the spectrum, IRENA reports that annual total CO2e emissions at approximately 12.5 million Mt in 2018 [23]. This is lower than the historical peak carbon dioxide equivalent emissions for the country.

Historical Trends of Carbon Footprint

Zimbabwe's highest period of CO2e emissions were in the late 1980s through most of the 1990s when annual CO2e emissions ranged between 12.3 and 14.7 Mt annually (based on EIA data) [7]. However, annual CO2e emissions have increased since the 2000s when the country emitted the lowest in recent decades; Only 7.3 Mt were emitted in 2008 [7] (Fig. 4).

Types and Main Sources of Pollutants

The largest source of CO2e emissions in Zimbabwe have historically been for electricity and heating, and these two sectors make up approximately half of all of Zimbabwe's annual CO2e emissions [23]. One reason for this is that coal accounts for over half of Zimbabwe's currently installed capacity for electricity generation. The only other electricity generation source with significant installed capacity is hydroelectricity, which should have little to no CO2e emissions as a result of electricity generation. The other major reason behind this is a majority of rural households in Zimbabwe utilize wood for their heating demands. Out of all electricity and heating energy sources, the IRENA reports that "Coal + others" is responsible for 99% of the CO2e emissions [23]. Natural Gas in this sector is 0% and Oil is 1% [23]. IRENA also reports that 757 tons of CO2e are emitted for every GWh of electricity generated (tCO2e/GWh), which is higher than the Africa and World averages of 610 tCO2e/GWh and 425 tCO2e/GWh, respectively [23]. As of 2016, Zimbabwe's CO2e emissions were at 0.8 metric tonnes per capita [45]. This is equal to the Sub-Saharan Africa average and well below the World average of 4.6 metric tonnes of CO2e per capita [45].

Energy Resiliency

Electrical Grid

The Zimbabwean nation electrical grid is operated by the state-owned Zimbabwe Electricity Transmission and Distribution Company (ZETDC). The operation of the grid is regulated by the Zimbabwe Energy Regulatory Authority. The energy grid operates on the Transmission level at voltages of 400 kV, 330 kV, 220 kV, 132 kV, 110 kV, 88 kV, and 66 kV [8]. As of 2010 there were 7408.8 km of transmission lines for the national grid with a total transformer installed capacity of 8829 MVA [8]. The distribution level of the energy grid operates at 33 kV, 22 kV, 11 kV, and 400 V [8]. As of 2010 there were 119,784 km of distribution lines with a total transformer installed capacity of 51,984 MVA [8]. Only 37% of households have access to electricity [4]. There is significant disparity in the electrification of urban households with access to electricity (83%) compared to rural households (13%) [2].

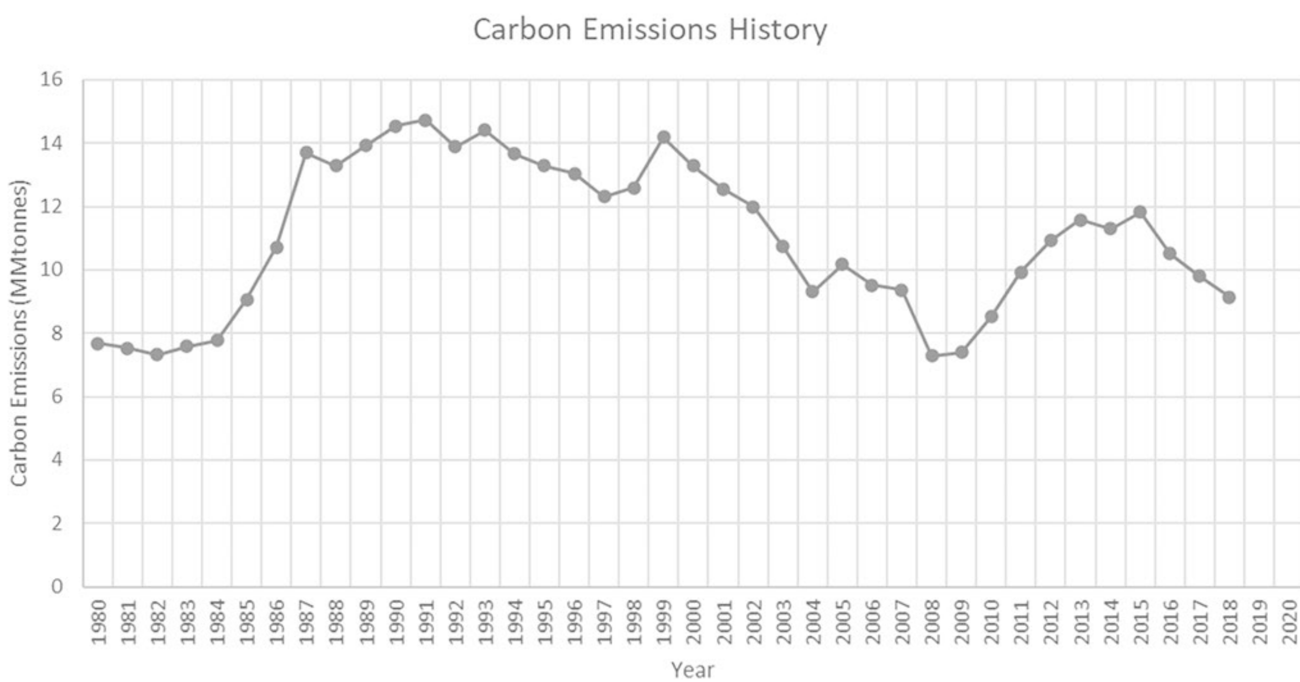

Fig. 4 Historical carbon emissions (Mt of CO2 equivalent) emitted from Zimbabwe from 1980 to 2016. The country has generally had a downward trend in emissions since the 1990s when they were at their peak

Four cross-border transmission lines exist between Zimbabwe and other SAPP nations. These are a 650 MW connection with Botswana, 500 MW connection with Mozambique, 600 MW connection with South Africa, and a 1400 MW connection with Zambia [30]. Four additional SAPP nation interconnections for Zimbabwe were planned for completion between 2015 and 2020. These are a 600 MW Zimbabwe-Botswana-Namibia-Zambia connection, and 1500 MW Zambia-Zimbabwe-Namibia-South Africa-Democratic Republic of the Congo connection, a 500 MW Mozambique-Zimbabwe connection, and a 650 MW South Africa-Zimbabwe connection [30]. Zimbabwe has historically been heavily reliant on importing electricity from other SAPP nations to meet its energy demands. The nation is contractually obligated to export 150 MW to Namibia [33]. Due to this and its own deficiency in available capacity to meet peak demand, electricity importation makes up 40.9% of all electricity consumed [8]. This was 5497 out of 13,322 GWh in 2009 [8]. Most of the imported electricity comes from Mozambique and South Africa who import up to 50 MW and 380 MW, respectively [33].

Climate and Natural Disasters

The impact of Climate Change is likely to have a significant impact upon Zimbabwe's Energy sector. Southern Africa has experienced a 1 °C increase in average temperature since the 1980s, and this average temperature will likely reach a 4 °C increase by the end of the twenty-first century [46]. This increase in temperature will cause increased evaporation of reservoir water for hydroelectric dams. Climate Change will additionally cause an increase in drought frequency, and in 2020, southern Africa experienced decreased annual precipitation [46]. An increasing frequency and/or intensity of extreme weather events due to climate change causes concerns of flooding, intense winds, and debris due to storms to potentially damage electricity generating facilities. Zimbabwe and other southeastern African nations have experienced this recently after being hit by Tropical Cyclone Idai. Damage from this storm reduced Malawi's hydroelectric capacity from 320 MW to 50 MW [46].

Zimbabwe's current reliance of hydroelectric power (approximately 1050 MW out of over 2300 MW of installed capacity) makes its energy grid's reliability and resilience susceptible to the impacts of climate change. This issue is compounded as hydroelectric power is an important part of Zimbabwe's plans for new generation facilities. Increased temperatures and frequency of droughts are projected to reduce African hydroelectric dam capacity by 3% by the end of the century [46]. This is even greater in Zimbabwe where there is a 7% expected decrease in hydroelectric capacity, but it will possibly decrease up to 14.8% [46]. Zimbabwe's only operating large-scale hydro facility, Kariba Dam, has already been experiencing the effects of climate change. Increased droughts and temperatures caused the dam's water levels to drop to 12% in 2016, leading to blackouts and power rationing [46]. The decrease in available hydroelectric capacity and chances of significant loss of output due to droughts or extreme weather events will cause a decrease in reliability meet demand, and it will reduce the capacity available to restore power to the grid in case of an interruption.

Grid Resiliency

The impacts of climate change on hydroelectric power are not the only factors influencing Zimbabwe's grid resiliency and reliability. Zimbabwe's largest source of installed capacity is coal-fueled thermal plants. As previously discussed, maintenance and aging issues with the coal plants have caused decreases in capacity and the need for renovation projects. Because of these issues, these plants are only available to provide power to the grid on a limited schedule due to forced outages and failures at the thermal plants [3, 5]. In 2018, the Hwange, Harare, Munyati, and Bulwayo coal plants were only available 66%, 22%, 49%, and 62% of the time, respectively [3]. Zimbabwe's largest coal plant, Hwange, possesses a nameplate capacity of 920 MW but only typically operates at 400–500 MW [33]. The disparity of nameplate capacity (over 2300 MW) to available capacity (approximately 1400 MW) prevents Zimbabwe from being able to reliability meet peak demand, and it potentially reduces the nation's resilience to supply/restore power to the grid in times of blackouts [5].

In 2018, 110 interruptions in service to electricity customers were reported with a total of 136,104 faults in the electrical grid [3]. The number of interruptions has decreased by 15 annually since 2017, but the number of faults increased by 4416 [3]. On average, it took 204 minutes to restore service to customers during the occurrence of interruptions and 276 minutes to "restore quality of service" due to a fault [3]. Service interruption to consumers led to a loss of 8.46 MWh [3]. Overall system performance resulted in 12.75% of total electrical energy being lost in the transmission and distribution network in 2018 [3]. Many of these reliability failures are the result of a lack of proper maintenance but also from theft of conductor material and transformer oil [3]. Due to factors affecting the reliability of electricity and the available capacity for the grid, load shedding regularly occurs, and this load shedding is scheduled by the Zimbabwe Electricity Transmission and Distribution Company (ZETDC). These ordinarily occur for 10 hours a day due to morning and evening peak demand periods but may last longer during times of significant power deficiencies [47].

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

Zimbabwe is dependent on fellow countries in the Southern African Development Community (SADC), under which the SAPP was created, to meet its energy demands. As Zimbabwe does not produce any crude oil domestically, nor does it possess a petroleum refinery, it is entirely reliant on importing its refined petroleum products from a pipeline connection with Mozambique [1, 9]. The annual importation stood at 1.623 billion liters in 2018 [3]. Although a national biofuels program is meant to alleviate the petroleum importation demands, Zimbabwe will remain reliant on foreign petroleum for the foreseeable future [6].

The country is additionally dependent on fellow SADC states to meets its energy demands as it can only meet 1400 MW out of its 1700 MW demand using its own power plants [5]. Concerns over meeting peak demand are worsened by a contractual obligation to export 150 MW of electrical power to Namibia [33]. These factors force Zimbabwe to rely upon importing electricity from South Africa and Mozambique [33]. This electricity importation made up 40.9% of all electrical energy consumed in 2009 (5497 GWh) [8]. Zimbabwe's largest generator of electrical energy, Kariba Dam, is shared with neighboring Zambia. Developments and operation for this dam, along with any future facilities built to exploit the hydroelectric potential of the Zambezi River, require cooperation between the two countries [35].

Relations with Global Community/ Socioeconomic Influence

Zimbabwe is a member of multiple international organizations including the United Nations, World Bank, International Monetary Fund, and African Union [2, 48]. It has signed the Paris Agreement, and in 2016, it submitted its first Nationally Determined Contribution (NDC) for the accord to the United Nations Framework Convention on Climate Change (UNFCCC) [49]. As a member of the SADC and the SAPP, it is also economically and politically tied to the other southern African nations. Zimbabwe's last significant participation in an armed conflict was its participation in the Second Congo War of the late 1990s and 2000s during which it fought alongside fellow SADC members Angola, Namibia, and the Democratic Republic of the Congo [48]. Zimbabwe's historical stance in international politics has been to be a member of the Non-Aligned Movement, whose member states do not side with one of the world's leading power blocs [2, 48].

Although Zimbabwe has had cordial relations in the past, many of its international relationships became strained during the leadership of President Robert Mugabe. The United States claims that during Mugabe's 37-year long leadership there were "undemocratic practices, human rights abuses… and public corruption" [2]. Despite strains on Zimbabwe's international relationships, the country still sees foreign economic aid and investments, including in its energy sector. Zimbabwe receives assistance from the United States Agency for International Development (USAID), and in 2019, it receives $318 million in assistance from the United States [2]. Investments in Zimbabwe's energy sector have also come from multiple other foreign sources including China and the United Kingdom [16, 24].

Education

There is one public university in Zimbabwe that offers students a degree program specifically tailored toward renewable energy. The University of Zimbabwe offers a Master of Science in Renewable Energy from its Department of Electrical and Electronic Engineering [50]. Other universities in Zimbabwe offer degree programs not specific to renewable energy but are useful for the renewable energy engineering field. The University of Zimbabwe and Harare Institute of Technology provide courses in electrical/electronic engineering and power systems, with the former offering a Bachelor of Science with Honours degree in Energy and Power Systems Engineering [50, 51]. Midlands State University's Department of Engineering and Geosciences offers a mechanical engineering program that promotes offering skills useful for workers in the energy sector, and the university plans to implement an electrical engineering program in the near future [52]. Chinhoyi University of Technology offers bachelors' programs for Fuels and Energy and Mechatronic Engineering [53, 54]. Although not specifically renewable energy or electrical engineering, Bindura University of Science Education and Lupane State University both offer Master of Science Degree in Climate Change and Sustainable Development programs [55, 56].

Summary

Current Energy Situation

Zimbabwe struggles to meet its energy demands using its own domestic resources and facilities, and thus relies heavily on the importation of fuels and electricity [3, 4]. The main reasons behind this are that installed capacity is insufficient to meet peak demand, aging and maintenance issue with coal plants reduce their electrical output, and Zimbabwe lacks proven oil deposits and petroleum refineries [1, 3, 7]. Annual increases in energy demands, increased electrification of rural areas, and decreased hydroelectric output due to consequences from climate change will further increase the strain of the country's energy sector [3–5, 7, 46].

Future Energy Situation

The country has historically been reliant on large-scale coal and hydro to meet its electricity demands [3–5, 7]. Future capacity installation in Zimbabwe will continue to utilize these technologies; however, the country will see some diversification of its electricity generation sources mainly with an increase in solar. A majority of the country's installed capacity has been state-owned and will continue to be for the foreseeable future, but the diversification of the electricity supply will introduce more private entities into the industry [3–5]. The government's expansion plans for the biofuel sector will likely result in a significant increase in biofuel production domestically and possibly result in a significant number of private firms entering this market [4–6]. Although there will likely be sustainable private and public investment into the energy sector, foreign funding and loans from governments, international organizations, and businesses will also be a significant contribution [4, 5].

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Part III

Asia

Cambodia

Slobodan Petrovic and James Martin

National Energy Introduction

Energy Policies

According to the IEA, Cambodia has stated a goal to increase its generation capacity via increased number of hydro dams and coal plants by 2025. This can contribute to improve self-sufficiency of power supply. Other policies include improving the electrical infrastructure by adding nearly 1900 kilometers of new transmission lines [1].

Trends in Generation Technologies

The data from the international energy agency shows a trend of rapidly increasing generation capacity and changes in the breakdown (Figs. 2 and 3) [2]. The total generation of 1060 GWh increased nearly eightfold to 8173 GWh in 2018. While oil fueled nearly 90% of the electrical generation in 2011, it has been phased out of the electrical sector in favor of hydro dams and, to a lesser extent, coal-fired plants. The 2018 generation from biofuel has tripled since 2011, and solar PV has quintupled. However, neither fuel source has ever been a significant portion of the total generation (Fig. 1).

Domestic Resources

While Cambodia has relied extensively on coal and oil, much of that is imported from other nations [2]. There is a 27,000 square kilometers overlapping claims area in which both Cambodia and Thailand have claimed rights to offshore oil drilling [3]. Despite the Prime Minister declaring the first crude oil venture a failure, nondisputed regions of the Gulf of Thailand claimed by the Cambodian Government are predicted to have large untapped oil and natural gas reserves [4].

The MME (Ministry of Mines and Energy) and MRC (Mekong River Commission) estimate that the rivers of Cambodia have a combined a theoretical generation capacity of 10 GW [5]. While only a fraction of Cambodia's resources have been exploited, Cambodia is seeking to construct more large hydro dams funded by Chinese firms [5] and the ADB [6] (Asian Development Bank).

History of Energy

France established Cambodia as a protectorate in 1863 [7]. Between the years 1887 and 1953, France established Colonial control over the Indochina Union, which contained Cambodia, Laos, and parts of Vietnam. During this era of colonialism, France did very little to exploit Cambodia's natural energy resources or change the economy, instead choosing to profit from imposing higher tax rates per capita in Cambodia and the rest of Indochina. Since Cambodia gained independence from the French following World War II, they have held control over their own energy resources, and the name "Indochina" fell into obscurity.

Breakdown of Energy Generation "Mix"

Fossil Fuels

World Bank data from 2000 to 2019 shows that fossil fuel has composed 7–15% of Cambodia's total imports [8] for most years and does not show as Cambodia having exported oil [9]. While the World Bank Data lists 1972 as the most recent year in which Cambodia was a fuel exporter, it is important to note that there is very little available data from

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1975 to 1995 due to the cataclysmic events that occurred in the years after dictator Pol Pot rose to power in 1975 [10].

Oil

According to the IEA (International Energy Agency), the Cambodian electrical sector has been decreasing the amount of oil used for generation since 2007. However, the demand for oil in Cambodia has been steadily increasing for roughly the same amount of time. Most of the oil demand is for imported ethane/LPG (liquefied petroleum gas), vehicle fuels such as diesel. The EIA (Energy Information Agency) states that motor gasoline [11] includes "conventional gasoline; all types of oxygenated gasoline, including gasohol; and reformulated gasoline, but excludes aviation gasoline."

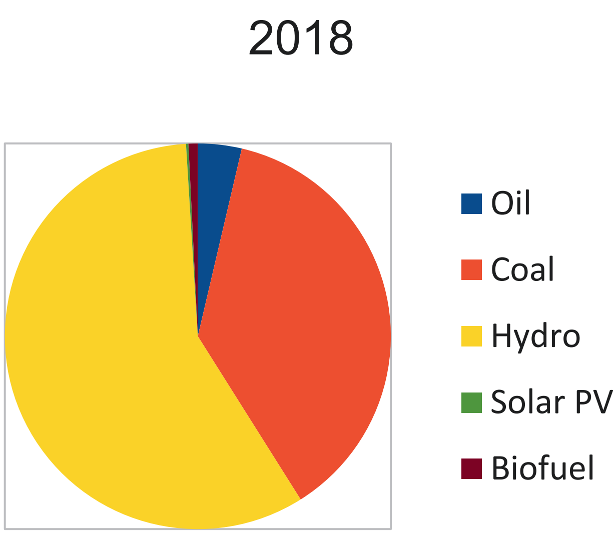


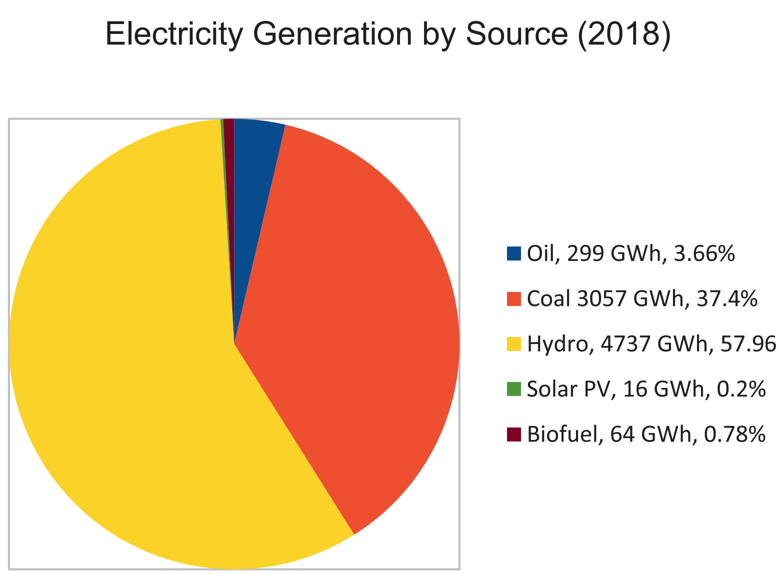
Fig. 1 Side-by-side comparison of breakdown of electrical generation in Cambodia in the years 2011 and 2018

Comparisons between the IEA data from 1995 to 2018 clearly shows that Cambodia has relied almost entirely on imported oil for its petroleum demand. Prior to 2020, most of Cambodia's oil was imported from other nations in Southeast Asia, such as Thailand, Singapore, and Vietnam. Other nations from which oil has been imported include Australia, the United States, the United Kingdom, India, China, and several EU member nations [3]. So as not to rely on imports, Cambodia has been planning major oil production operations since 2017.

As of 2019, no oil production had taken place in Cambodia due to a shortage of technical expertise and lack of investment regulations. However, Cambodia has been long known to be well-endowed with oil and gas deposits, and has recently made plans to exploit it. The Cambodian government and the Singapore corporation KrisEnergy signed a production sharing agreement in 2017. This agreement is intended to share the exploits of developing Block A, which is one of six blocks in the Gulf of Thailand marked for oil exploration by the Cambodian government. The 6278 square km block A is the most heavily explored of the six blocks. Chevron Overseas Petroleum and Moeco drilled 22 exploratory wells between 2005 and 2010, but KrisEnergy purchased most of their stake in zone A in 2014. There is also an area in the Pattani Basin, measuring of 27,000 square kilometers, called the OCA (overlapping claims area). Cambodia and Thailand have long disputed claims to this area, though only Thailand has extracted oil from the OCA [3].

While geological studies suggest that the OCA is rich in oil, it is uncertain how much of it Cambodia will be able to extract, and how soon operations can begin there. The Khmer Times [4] also reported major setbacks in oil ventures, partly due to KrisEnergy declaring bankruptcy. On December 29,

Fig. 2 Breakdown of the electrical energy generated in Cambodia by indigenous and imported energy resources as of 2018. (Source: IEA)



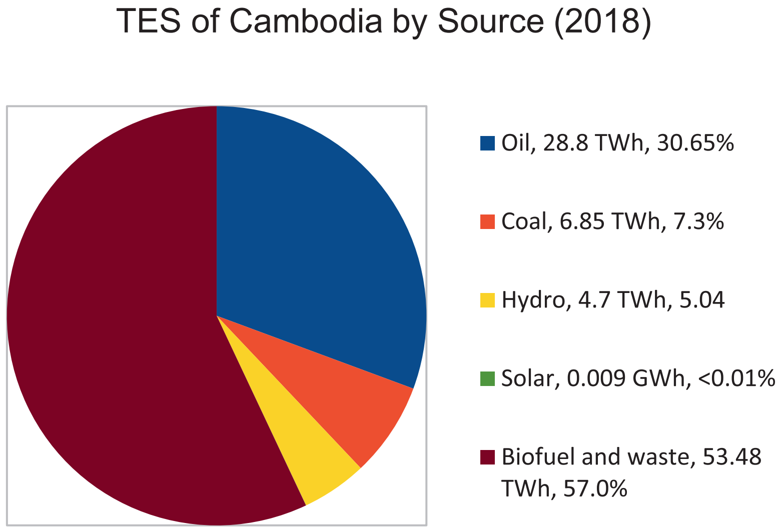


Fig. 3 Breakdown of the TES (total energy supply) in Cambodia as of 2018. (Source: IEA)

2020, Prime Minister Hun Sen announced that Cambodia's first ever oil venture was a failure due to failure to meet expected volume. Despite these uncertainties, the government is reportedly optimistic about the potential to extract an estimated 700 million barrels of oil from Block A.

Coal

As oil is being phased out of electrical generation, the demand for coal in the electrical sector is increasing to the point where it is the electrical sector's most important fossil fuel resource. It is a stated goal for Cambodia to increase its generation capacity by 25 via the construction of coal-fired plants.

The ERIA (Economic Research Institute for ASEAN and East Asia) energy outlook report [12] states that Cambodia is not a major coal producing nation. The IEA report on Cambodia from 2009 to 2018 clearly shows that the net coal imports is over 90% of coal's share of the total energy supply. Despite the popularity of traditional coal, many advocate for lowering the coal consumption due to the emission of nitrous oxides and sulfur oxides, in addition to the usual carbon emissions.

Natural Gas

The World Bank and IEA data for energy and import lists any natural gas consumption as of 2018. Cambodia does not currently produce, import, or export of any natural gas. However, the MME (Ministry of Mines and Energy) has announced [13] that LNG (liquefied natural gas) will provide 3.6 GW of electrical power by the year 2030. Due to a lack of suitable infrastructure and access to domestic resources, this goal will require foreign investment and imported gas. Minister of Mines and Energy, Suy Sem, announced that implementing LNG generation should promote clean the deployment of other clean energy technologies.

In January of 2020, Cambodian Natural Gas Co Ltd announced [14] a partnership with the Chinese company CNOOC Gas Power Group Co Ltd. for the purpose of importing LGN into Cambodia energy markets. While reports [4] suggest that offshore Block A may hold 3–5 trillion cubic feet of natural gas, efforts to extract it has failed due to the state of oil production in Block A, and the Bankruptcy of KrisEnergy.

Nuclear Energy

According to a 2020 report [15] on worldwide nuclear development plans, the WNA (World Nuclear Association) has classified Cambodia's nuclear program as category 7, meaning "Officially not a policy option at present."

Cambodia has never used nuclear [16] reactors as a means of utility-scale generation. Cambodia currently has no operational nuclear power plants and is years away from implementing a nuclear power program. However, Cambodia has expressed interest in constructing a nuclear power plant to cope with the growing demand for electricity and is considering starting its nuclear program with research reactors.

A research reactor [17] operates on the same principle of nuclear chain reactions as a nuclear plant's power reactor but on a much smaller scale. The action plan of developing a research reactor is often used to form the foundation of a national nuclear power administration program. This includes planning for the regulatory body, commissioning, construction, operation, maintenance, radioactive waste management, and decommissioning.

Cambodia has no steady source of uranium or other fissionable materials necessary for nuclear power reactors. However, unconfirmed reports suggest that Cambodia may seek to import nuclear isotopes from China in the event that the government decides to develop nuclear power.

Renewable Energy Generation

Photovoltaics (PV)

As of 2019, Cambodia's solar generation capacity was 155 MW [6]. The distributed nature of residential solar makes updated data collection difficult, though the IEA data suggests that roughly 25% of households in Cambodia are connected to residential solar systems instead of (or in addition to) the utility grid.

The largest PV array is the 100 MW National Solar Park [6] currently under construction. In 2019, the total solar generation capacity was 155 MW, and the government of Cambodia plans to increase the capacity to 415 MW by 2022 [6]. Cambodia plans to build a 16 MWh battery energy storage system on the site of the National Solar Park [6]. The success of the solar and battery systems is predicted to inspire similar large solar projects in the future.

In theory, integrating solar battery energy storage into single-phase low-voltage AC distribution grids is an effective strategy for rural electrical distribution. IEEE [18] suggests promoting this strategy of distributed generation to alleviate issues related to grid reliability, and increase the rural electrification rate.

Wind Energy

Cambodia does not currently have any large-scale wind generation technology, but is in the process of developing wind farms. The Cambodian company Blue Circle has been conducting studies on the potential for wind power since 2016. In December of 2020, Blue Circle announced [19] that their proposed wind project in the Kampot Province is approaching the construction stage. If successful, this will be the first wind farm in Cambodia. The Kampot wind farm has the potential to generate 225 GWh of electricity per year, at an established price of 6.85 cents per kWh.

Being in the tropical zone of Southeast Asia, Cambodia has great untapped potential for wind power and experiences the effects of the Asian monsoons. In 2016, the Blue Circle released a study which estimates the wind capacity of 1.3 GW in the Kampot Province alone. Wind resource maps [20] of Cambodia show that the maximum annual mean wind speed, at the height of 50 meters above ground, is 5–6 meters per second, which can be found in the northeastern provinces. Since 2013, an improved system of wind measuring stations has been used to locate potential sites for new wind farms. The development of other future wind farms will depend on the successful operation of the Kampot wind farm.

Hydropower

Access to electricity is of great concern to communities near the Kamchay dam. The electricity supplied to the households near the dam are not supplied by the dam itself, but mainly imported from Vietnam or sold by private entities at high prices. Due to the capital's economic needs, most of the energy from the dam goes to Phnom Penh. Many village households cannot afford the fees required to connect to the electrical grid. Despite the initial shortcomings, Cambodia is believed to have a hydro capacity of 10 GW, over 50 times the capacity of the Kamchay dam [5].

Since 2006, Chinese firms and the Cambodian government have been constructing large hydropower dams [5]. The largest Chinese firm investing in hydropower is an SOE (state-owned enterprise) called Sinohydro. The installed capacity of the Kamchay dam, Cambodia's first large hydropower dam, is 194 MW. Sinohydro started construction in Bokor National Park in 2006, and operations began in 2011. Several larger hydropower dams have been proposed, including controversial locations at Sambor and Stung Treng.

Cambodia has also considered building dams along the Mekong river in Stung Treng and Sambor, the latter of which the CDC (Council for the Development of Cambodia) [1] believed to have a potential for 450 MW output. However, the government suspended all dam projects along the mainstream Mekong River [19] until at least the year 2030. The reason cited were the disastrous effect new large dams would have on the livelihood of those who depend on the river and on the river's fragile ecosystem.

Ocean Energy

Currently, Cambodia does not exploit wave or tidal energy for electrical generation. While more developed Southeast Asian Nations are exploiting ocean energy, Cambodia is not on the forefront of these new developments. Cambodia currently does not have the infrastructure [21] necessary to construct a plant to develop wave or tidal energy plant.

The IUCN [21] (International Union for Conservation of Nature) reports Cambodia has 435 km of coastline on the Gulf of Thailand, which covers approximately 18,000 square kilometers. Cambodia has the natural resources to exploit ocean energy, but very little research on the subject of Ocean power is limited.

Geothermal Energy

Cambodia does not currently exploit geothermal power for electrical generation or have any form of geothermal plant. There is only one region in the Kampong Speu Province that has any geothermal activity visible above ground, and the potential for other geothermal sources has not been assessed [22]. There have been no announcements about plans to assess the potential for new geothermal sites or develop the known geothermal site in Kampong Speu.

Biomass

Like in many developing countries, it is common for people in rural areas to use biomass in the form of wood and charcoal for the purposes of heating and cooking. Because of the distributed use of biomass, it is difficult to get accurate data on the cumulative biomass power used.

The Electricity Authority of Cambodia reports that biomass accounts for less than 1% of Cambodia's electrical generation. Unlike Cambodia's solar and wind energy, there are no large central biomass plants, as biomass is mainly used at the household level. All sources report that the majority of biofuel used for energy is sourced from waste, including garbage, agricultural waste, and discarded plant matter.

Reports [23] indicate that future plans to generate electricity from waste-fueled biomass plants have been delayed due to the high costs, and due to unforeseen difficulties that have been attributed to COVID. However, Cambodia and Thailand entered a partnership in 2010 for a biomass gasification project that would produce flammable gases such as CH_4 and H_2 [24]. In May of 2018, UNIDO (United Nations Industrial Development Organization) announced [25] that the two partner nations have drafted policies for biogas electrical generation and have funded biogas feasibility studies. Depending on the results of these studies, Cambodia may have potential for biomass gasification plants.

Biofuels

According to the IEA data from 2018, biofuel made up 57% of the total energy supply but only 0.78% of the electricity capacity. In scope of renewable energy only: biofuel composed 92% of Cambodia's total renewable energy supply in 2017, but only 3% of electricity generated from renewable sources in 2019 came from biofuel.

Unlike the large hydro plants, there is no large centralized biofuel plant that provides electricity to the capital. The largest biofuel plant in Cambodia is Banteay Meanchey Province, and it powers a mini-grid that supplies electricity to 360 households [26].

There are three main forms of biofuel [26] that are viable in Cambodia: straight vegetable oils, bioethanol, and biodiesel. Straight vegetable oil for automotive fuel requires engine modification, which may make it unfeasible. Pure bioethanol can work in some fuel-flexible engines, so a bioethanol-fossil fuel mix works better in some cases. Bioethanol can be produced in Cambodia from cassava crops.

Biodiesel is attractive because it can be easily produced in a form that most diesel engines can use without modification and because of the prevalence of the jatropha plant. Jatropha can be cultivated as an energy crop and processed into biodiesel.

One of the greatest challenges to exploiting the energy-rich biodiesel crops is the lack of proper technology for harvesting large quantities of Jatropha and the past failures of biodiesel investment programs [26]. These challenges can be overcome by regulating investments in biodiesel farming ventures and improving the harvesting technology.

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

A 2018 World Bank report found that despite the high electrification rate, 26.1% of households are off the grid, mostly residential-scale PV systems with small-scale battery energy storage [27]. Larger scale systems are currently under development.

Country's Future Storage Direction

September of 2020, ADB approved a $127.8 million loan, part of which will be used to fund a battery energy storage system. The pilot BESS will be located near the 100 MW National Solar Park currently under construction and have a storage capacity of 16 MWh. It should also help with integrating renewable generation sources into the national electrical grid [6]. The future of large-scale battery systems will depend on the successful implementation of this project.

A study released at IEEE Industrial Electronics Society conference in October of 2020 analyzes the potential future of small-scale battery systems Cambodia [18]. In theory, integrating solar battery energy storage into single-phase low-voltage AC distribution grids is an effective strategy for rural electrical distribution. In the context of the government expanding the transmission network, such a strategy has wide-ranging implications for distributed generation, depending on the future development of residential PV systems.

Carbon Footprint

Most Recent Carbon Output

According to the source CAIT data [28], the 2018 carbon footprint is 10.54 million metric tons of CO_2, (0.97 metric tons per capita) and 20.3 million metric tons of CH_4 (metric tons per capita). Most of the CO_2 emissions are from energy consumption, and most of the CH_4 is from agriculture (Figs. 4 and 5).

Historical Trends of Carbon Footprint

According to the same World Bank data, the number in CO_2 per capita had steadily increased from the years 1990 to 2017, after which the curve decreased for the first time since the 1990s. Historically, the decrease in emissions appears to be from the heat/electricity and other combustion, while manufacturing and construction related emissions are increasing (Fig. 6).

Types and Main Sources of Pollutants

The most significant pollutants are CO_2 and CH_4. According to the most recent complete data set from 2018, the source of most of the CO_2 comes from the transportation sector and the generation of electricity. The emission of CH_4, which is historically much higher than CO_2 emission levels, comes mainly from the agricultural sector. There is also a relatively small emission of N_2O, the sources of which are agriculture, waste, and various forms of energy consumption.

Energy Resiliency

Electrical Grid

Cambodia's electricity imports, mostly from Thailand and Vietnam, exceed its electrical generation, and its cost of electricity is much higher than most [5].

Government policy has made energy development a high priority, citing a "boost economic productivity and quality of life" [6]. The current electrical transmission infrastructure has reached a point where it ensures a minimum of interruptions, the gird must be reinforced, and the transmission capacity must be expanded.

Cambodia is placing high priority on fighting energy poverty through developing hydropower, reaching out to Chinese firms for investment in the infrastructure [5].

On September 11, 2020, the ADB [6] (Asian Development Bank) issued a $127.8 million loan to develop grid infrastructure to improve the reliability and stability of the supply to the capital and three other provinces. This includes new transmission lines, $6.7 million for Cambodia's first utility-scale BESS and plans to expand renewable energy programs. ABD has loaned over $200 million to the Cambodian energy sector since 1994. The electrical authority has announced plans to construct thousands of kilometers of new transmission lines ranging from 115 to 230 kV and 10 new substations.

Due to geographical features such as valleys, streams, and rivers, Chinese investors and the Cambodian government wish to use hydropower as a means of promoting economic growth, increasing energy security, and fighting energy poverty [5]. MME (Ministry of Mines and Energy) and MRC (Mekong River Commission) estimate a theoretical generation capacity of 10 GW, but less than a third of that capacity had been constructed by 2016.

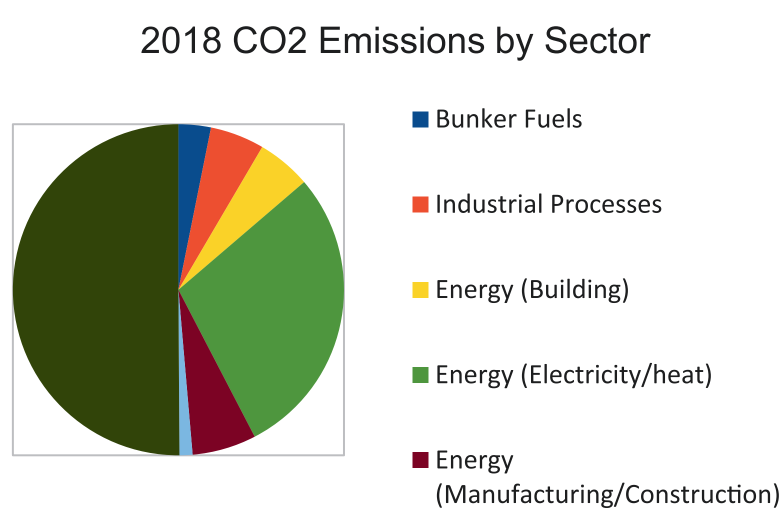


Fig. 4 Breakdown of carbon dioxide emissions by sector in 2018. (Source: Climate Watch Data)

Cambodia's geography and geology make it difficult to accurately assess the potential for geothermal power. The countries supply of oil and natural gas requires offshore drilling, but the difficult operations to extract those resources have been unsuccessful.

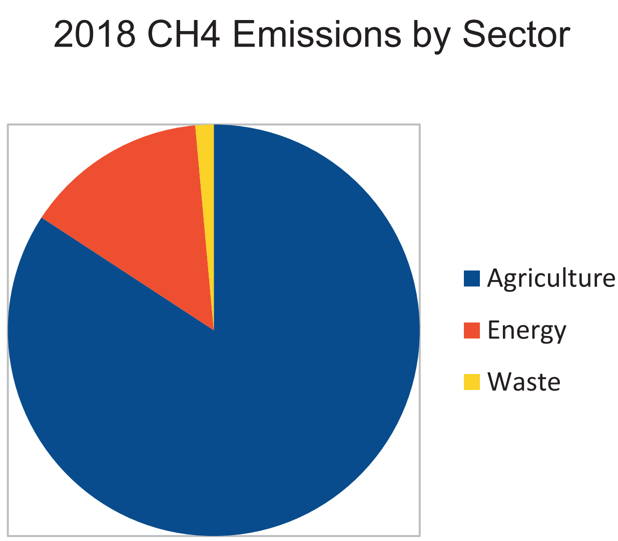


Fig. 5 Breakdown of methane emissions by sector in 2018. (Source: Climate Watch Data)

Climate and Natural Disasters

Cambodia has 435 kilometers of coastline on the Gulf of Thailand, which covers approximately 18,000 square kilometers [21]. This contains both untapped potential for ocean energy generation and natural disasters. Coastal areas of Cambodia experience frequent flooding and monsoons, and climate studies indicate that these may increase in the coming decades. Different climate models predict anywhere between a 2% decrease in rain to a 15% increase in rain by 2100, as well as rising sea level. Predictions for the increase in sea level by the year 2100 have been revised upward several times since 2007, which will have drastic impacts on, among other things, Cambodia's potential for hydro power and all generation sources near the coastline.

Studies suggest that there is an identifiable link between household energy conservation and climate change [29]. Both the frequency and magnitude of extreme weather events are increasing. This includes windstorms, rainstorms, droughts, floods, and heat waves worldwide, which is particularly troublesome to humans in developing countries, such as the residents of coastal Cambodia. Unfortunately, much of Cambodia depends on agriculture, fishing, and other climate-sensitive industries. The results of this study indicate that first-hand experience of hazardous aspects of climate

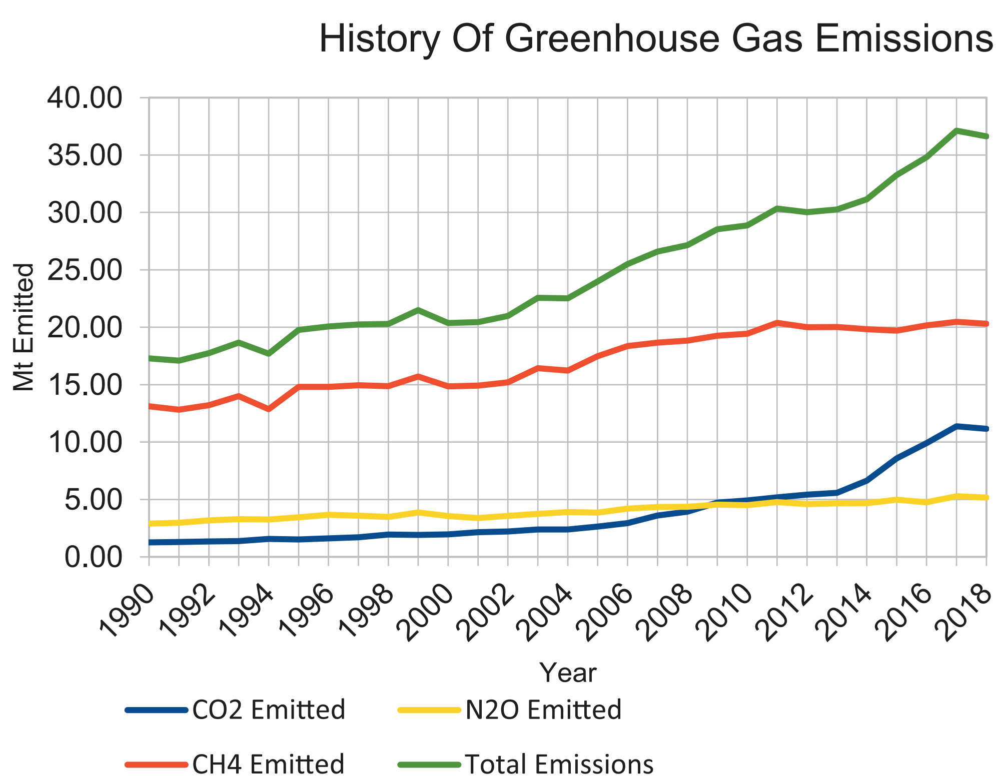


Fig. 6 Historical emissions of the three main greenhouse gases emitted by Cambodia: Methane, nitrous oxide, and carbon dioxide. (Source: Climate Watch Data)

change has positive correlation with reductions in energy consumption in households in coastal Cambodia.

The government still faces many challenges in larger scale climate change mitigation, including a lack of budgetary funds and reliable disaster control resources. The government also has very limited institutional, personnel, and technical capacities. However, in recent years, the CCCO (Cambodia Climate Change Office) and CCCA (Cambodia Climate Change Alliance) have improved the cross-sector and cross-regional coordination and have created an institutional setup for climate change education.

Grid Resiliency

The Council for the Development of Cambodia has also announced the intention of improving the transmission infrastructure by adding 1889 kilometers of new medium and high voltage transmission line [1]. This will not only improve the grid resiliency but also boost the strategy of distributed generation via single-phase low-voltage AC distribution [18]. This strategy has wide-ranging implications for distributed generation, depending on the continued development and maintenance of residential PV systems.

Geopolitical Circumstances

Cambodia is a member nation of the ASEAN (Association of Southeast Asian Nations). Nations of the ASEAN are facing a challenging transition to renewable energy. This includes new energy architecture, new government policies, upgrading technology [30]. Energy security and sustainability are also important considerations.

Reliance on Foreign Fossil Fuels

The energy mix of ASEAN is currently over 80% fossil fuels [30] and is attempting to shift to renewable sources. The most recent World Bank report states that fossil fuels, most of which are imported, compose 37.95% of the total energy supply and 41.06% of the electrical generation. The future of ASEAN's energy landscape will rely on the clean use of fossil fuels, including the relatively low carbon footprint of LGN, and coal that emits less sulfur oxides and nitrous oxides. However, this will have to be balanced against the security and sustainability concerns, as well as pricing and affordability.

While Cambodia has been making efforts to domestically produce oil and natural gas, initial efforts have been less than successful. In 2017, the Cambodian Government and the Singapore company KrisEnergy signed an agreement to jointly develop offshore oil drilling in Block A and share the rewards. Unfortunately, KrisEnergy is now bankrupt, and the partnership dissolved as a result. Currently, the future of domestic fossil fuel development is uncertain, but Cambodia is rich with untapped oil and gas resources.

Relations with Global Community/ Socioeconomic Influence

The United Nations Industrial Development Organization is working to educate the government and the people about the effects of climate change. UNIDO is also a supporter of the joint Thai-Cambodian biomass gasification project.

However, not all relations with the neighboring nation of Thailand are cordial. Cambodia and Thailand have an ongoing diplomatic dispute about overlapping claims of offshore drilling sites in the OCA.

Education

UN studies have stated that the state of climate change education is poor. History of Education Quarterly attributes this to a combination of the nation's historical poverty and the last effect of Khmer Rouge's 4-year reign of terror [10]. However, recent studies suggest that there is an identifiable link between household energy conservation and climate change [29]. The UN believes that the state of climate education has improved since the beginning of the century.

Summary

Current Energy Situation

The demand for oil and coal has been greatly increasing for the past decade, which has resulted in increasing amounts of fuels imports, mostly from neighboring ASEAN nations. Since 2017, Cambodia had been relying on its now-bankrupt partner KrisEnergy for developing domestic oil reserves [3]. For electrical generation, coal and hydro power have been used extensively to increase the total generation capacity, while oil has been mostly phased out of the electrical sector. While geothermal and ocean power are believed to have potential, very little research exists on either subject (particularly geothermal).

Future Energy Situation

The *Journal of Energy, Sustainability and Society* released a study in March of 2021 that explores ASEAN's plausible possibilities for reducing emissions and achieving energy savings by use of energy modeling [30]. This paper also assesses the extent of the changes to the energy mix under different policies. The results recommend increasing the use of renewable energy, adopting clean fossil fuels, and developing energy infrastructure that is resilient against climate change.

The IMF (International Monetary Fund) predicted the ASEAN economy to contract by a greater amount than the 2008 recession and temporarily reduce energy demand and CO_2 emissions. The IEA (International Energy Agency) reports the global energy demand increasing by a factor of 10 between 1999 and 2019, and Asian countries and developing countries make up half the growth in the demand for gas. ASEAN will need more energy to guide its economic growth [30].

The ERIA (Economic Research Institute for ASEAN and East Asia) has also compiling data on coal-fired generation and climate change create predictive models [31]. Specifically, ERIA is looking into the possibilities for clean coal technologies under two different possibilities: BAU (Business as Usual) and APS (Advanced Policy scenario), the latter of which assumes that stronger political measures for energy saving will be taken. The BAU scenario predicts that Cambodia's electrical demand in 2040 will be 38.2 TWh, 34.1% of which will be from coal. The APS scenario predicts that Cambodia's electrical demand in 2040 will be 25.73 TWh, 43.88% of which will be from coal. The APS scenario includes using coal with lower sulfur and nitrogen contents and emitting few types of toxic gas.

Due to the economic cost, Cambodia has been reaching out to international partners and investors for energy development. The continued development of hydro dams depends largely on Chinese firms such as Sinohydro [5]. The largest PV and energy storage projects are funded by the ADB, and the outcome of those projects will have lasting repercussions on the development of Cambodia's renewable energy initiatives. Domestic fossil fuel development has been less successful, and Cambodia will likely shift focus to developing renewable technologies, such as biomass gasification and biofuel crops [4, 24, 26]. At present, it appears that hydro, PV, and biomass are likely to be Cambodia's dominating sources of renewable energy, though wind and ocean power also shows promise.

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China

Slobodan Petrovic and Melanie Leyson

National Energy Introduction

China borders 14 countries in Asia and has a coastline length equivalent to 14,500 km [1]. They are the fourth largest country in the world and have the highest population at almost 1.4 billion [1]. Some areas are sparsely populated due to terrain, while others are extremely dense in population, outranking many smaller countries in Asia and Europe [1]. The areas with the densest populations are around the Yangtze and Yellow River valleys, the Xi Jiang river delta, the Sichuan Basin, and in and around Beijing and Shenyang [1]. The country is 100% electrified with an estimated consumption in 2019 of 6568 TWh [1, 2]. It is estimated that in 2019 China exported 21.7 TWh of electricity and imported 17.2 TWh [1, 2]. In 2019, total installed capacity was 2011 GW and generation reached 7.3 PWh of which 69% was from fossil fuels, 18% was from hydroelectric plants, 5% was nuclear power, and the remaining 9% was from other renewable sources [2].

Energy Policies

At the end of 2020, President Xi committed to lowering China's carbon dioxide emissions per unit GDP by over 65% from their 2005 level in addition to increasing the share of renewables in primary energy production up 25% by 2030 [3]. In July 2021, they established an emissions trading system because select companies in China account for nearly 12% of global carbon dioxide emissions [3]. The most recent Five-Year Plan (14th) for Economic and Social Development covers the years 2021 through 2025 and sets a target to reduce carbon dioxide "intensity" by 18% and another target to reduce "energy intensity" by 13.5% throughout the years covered by the plan [3]. The plan sets intentions to closely monitor and control levels of fine particulate matter and ozone and essentially reduce pollution emissions in northern China by 75% by the end of 2025 [3].

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Trends in Generation Technologies

Figure 1 shows the historical energy consumption by source in China from 1965 to 2019. It is clear that renewables are rapidly increasing their share of the mix.

Domestic Resources

China has domestic fossil fuel resources in the form of bituminous, anthracite, lignite, and brown coal with over 50% of their reserves being of high quality coking-grade bituminous coal [5]. They also have significant oil and natural gas reserves. They have many rivers and already utilize a lot of hydropower. They are rapidly expanding their use of solar and wind power and are slowly expanding nuclear power capacity. Additionally, they are using some ocean power for small projects. They currently utilize biomass and biofuels, and those industries are expected to expand in the coming years to meet climate goals.

History of Energy

China has never been colonized. They have always been in control of their own domestic resources and energy industry.

Breakdown of Energy Generation "Mix"

Energy Generation Mix

Figure 2 shows the electricity generated by each source in 2020. It is clear that coal dominates the market but hydropower provides a significant amount of electricity as well.

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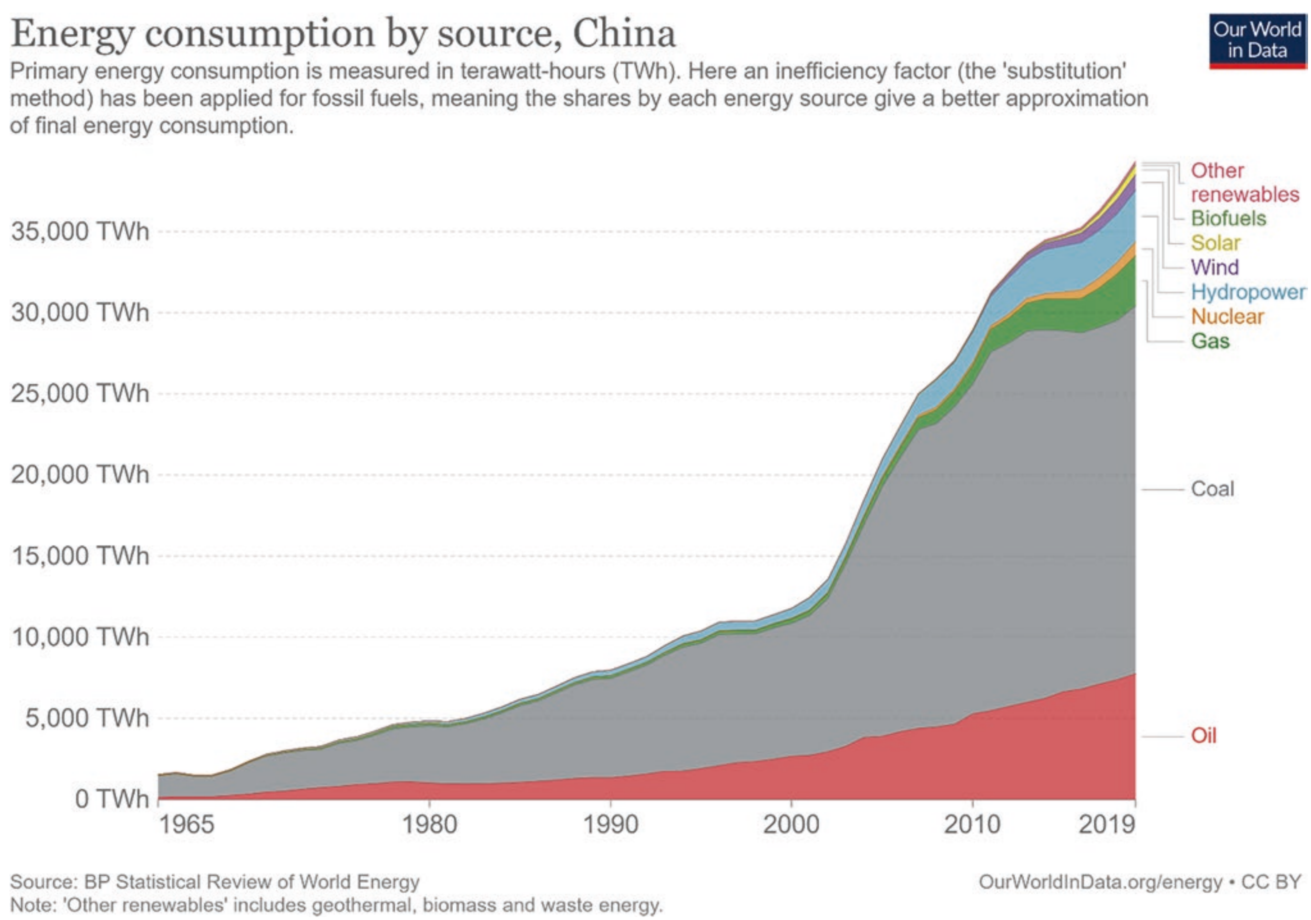

Fig. 1 Energy consumption by source [4]

Energy Consumption Mix

Figure 3 shows the energy consumption by fuel type in 2020. Coal still dominates, but oil and natural gas hold a bigger portion of the energy consumed than they do for the electricity generated. This is due to oil and natural gas being used for nonelectrical energy use such as for vehicles and household applications.

Fossil Fuels

Oil

China is the world's second largest consumer and importer of oil after the United States [8]. In 2018, China had an estimated crude oil production of 3.773 million bbl/day and 25.63 billion bbl in proved reserves [1]. Data from 2015 indicates that they imported 6.71 million bbl/day and that they exported 57,310 bbl/day [1]. Historically, China has not released a lot of information about their oil reserves, but in 2017 they claimed to have nine major reserve bases throughout the country with a combined capacity of 37.7 million tons [9]. And in November 2021 they agreed to release some of their reserves along with other nations in an effort to reduce inflation of oil prices so their exports will likely increase [9].

In 2018, the NRDC collaborated with the Energy Foundation China to launch the China Oil Consumption Cap Plan and Policy Research Project, which will help develop ways for China to lessen their reliance on oil [8]. The goal is for oil consumption to peak at 720 million tons by 2025, reach "Beautiful China" levels of 600 million tons by 2035 and meet a carbon neutral consumption level of 420 million tons by 2050 [10]. There are five major factors in reducing oil consumption as outlined by the plan which are to reduce demand, improve efficiency, replace oil with alternative sources of energy, optimize industry structures and product portfolios, and encourage clean use [10]. Of those five, replacement and efficiency will be the most important, accounting for 85% of oil reduction potential [10].

China has both on and offshore oil wells and some yet untapped shale oil resources that are becoming accessible due to advancing technology. PetroChina is beginning a project to drill for shale oil in Gulong where there are more than

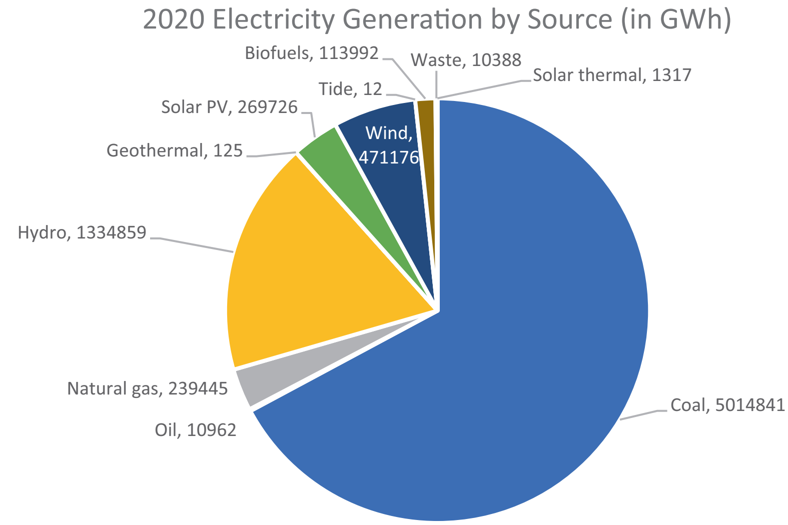

Fig. 2 Electricity generation by source [6]

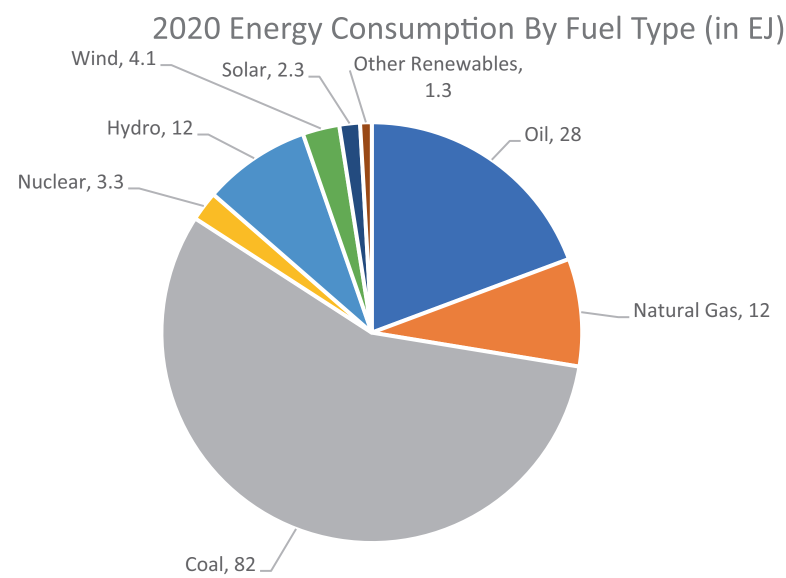

Fig. 3 Energy consumption by fuel type [7]

nine billion barrels of proven reserves [11]. So, although they plan to reduce oil consumption over the next several decades they are still attempting to produce more.

Coal

Coal accounts for a majority of the fossil fuel electricity generation in China with a capacity of 1191 GW at the end of 2019 [2]. The coal plants are well advanced and employ supercritical and ultra-supercritical technologies as well as newly developed designs and techniques for integrated gasification combined cycle plants [2]. The main coal reserves are located in the north and northwest parts of the country and require nearly half of the country's rail system to transport the coal to demand centers throughout China [2]. In 2015, it is estimated that China produced 11.51 million bbl/day of refined petroleum products, exported 848,400 bbl/day, and imported 1.16 million bbl/day [1]. In 2016, they consumed about 12.47 million bbl/day of refined petroleum products [1].

China mines both anthracite and bituminous coal in underground and surface mines to create coking coal, gas coal, and anthracite coal products [5]. The highest value coal they produce is over 6000 kcal/kg and comes from the four provinces of Gansu, Ningxia, Shaanxi, and Shanxi [5].

In 2013, the NRDC launched the China Coal Consumption Cap Project and encouraged China to set its first cap on coal consumption in the 13th Five-Year Plan [8]. The details of that cap were to reduce the share of coal to 58% or less by 2020 which they did [8]. The 14th Five-Year Plan does not set such specific goals in terms of the share coal should have in the total mix by 2025, but it does still emphasize the need to expand alternative sources of energy and replace coal with electricity where possible [12].

Natural Gas

In 2017, China produced 145.9 billion cubic meters of natural gas and imported another 97.63 billion cubic meters [1]. They consumed most of that in the amount of 238.6 billion cubic meters and exported only 3.37 billion cubic meters [1]. In 2018 their shale gas production, which is still in early stages of development, was 10.5 billion cubic meters [13]. The China National Petroleum Corp. expected consumption to exceed 300 billion cubic meters in 2020 of which half would be produced domestically [2]. At the beginning of 2018, it was estimated that China had almost 5.44 trillion cubic meters of natural gas reserves [1]. Pipelines have been built for ease of importing and exporting natural gas. The largest one they have is the Power of Siberia pipeline that connects Russia to the southern and eastern parts of China with a capacity of 38 billion cubic meters per year [2].

The 13th Five-Year Plan set goals for natural gas production to increase up to 170 billion cubic meters and promoted this through subsidies and tax breaks [13]. The plan is to increase the share of natural gas in the total energy consumption up to 14% by 2030 (compared with the 2019 amount of 8%) [13]. Natural gas is considered a cleaner but more expensive alternative to coal so many policies were made to promote using natural gas instead of coal and to streamline the natural gas supply chain [13]. But these policies were relaxed in 2018 after many northern cities experienced natural gas shortages in the winter [13]. To further reconcile the shortages, China has turned to importing liquefied natural gas and in 2019 they were the largest LNG importer in the world with a total of 130 billion cubic meters over the year [13]. China is rapidly building LNG terminals on the coastline and is expected to have a regasification capacity of 153 billion cubic meters by 2023 [13].

Nuclear Energy

In 2021, a draft of the Five-Year Plan included goals to reach 70 GW of nuclear capacity by the end of 2025 [2]. At the end of 2019, they had reached a capacity of 49 GW [2]. But they will have to increase that capacity up to 554 GW by 2050 in order to help limit the global temperature rise, which would increase the share of nuclear to the total energy mix up to 28% from 5% [2].

The National Nuclear Safety Administration (NNSA) was established in 1984 and is responsible for licensing all nuclear reactors and other facilities throughout the country [2]. The NNSA also licenses staff for facilities of nuclear manufacturers, installers, and reactor operators [2]. They certify designs, inspect equipment, and carry out radiation testing and protective measures [2]. China holds nuclear safety as a top priority, going so far as to host operational safety review team missions and conducting extra safety reviews of each plant every year [2]. Nuclear approval processes temporarily halted after the Fukushima accident in 2011 until a new nuclear safety plan was accepted in 2012 [2]. The Fukushima accident also caused delays in the construction of many planned inland plants while possible river pollution and depletion was reviewed [2]. The State Council Research Office has advised against rapid implementation of nuclear power and suggested restricting target capacities in order to avoid placing undue demand on the supply chain and causing quality control issues [2]. The SCRO also brought to attention the fact that while nuclear power plant workers can be trained in 4 to 8 years, “safety culture takes longer” at the operational level [2]. If the nuclear capacity is increased too rapidly, then there could be deadly consequences if safety protocol is not properly followed.

As they expand their nuclear capacity, China plans to become self-sufficient in all aspects of the nuclear cycle. This means they are working to produce all the uranium they consume. As of 2021, they still rely on purchasing one-third of their Uranium fuel supply on the open market, they get one-third from Chinese equity in foreign mines, and the last third is obtained from domestic supplies [14]. China National Nuclear Corporation holds a monopoly in the country’s nuclear market and is the only supplier of domestic uranium [14]. China is a self-proclaimed uranium-rich country with estimated reserves around 200,000 tU in 2016 [14]. New uranium has been discovered in the north and northwest sandstones as well as deep hydrothermal sites, lignite, granite, volcanic, and black shale [14].

Renewable Energy Generation

Photovoltaics (PV)

China leads the world in solar power deployment and manufacturing [15]. The installed solar capacity at the end of 2019 was 202 GW which was up 45% from the 175 GW they had at the end of 2018 [2, 15]. In 2020, they consumed 639 TWh of solar energy which was up from 555 TWh in 2019 [7]. China has excellent solar resources, especially in Western regions however air pollution is a major factor in efficiency losses of solar panels [15]. The 13th Five-Year Plan established a goal to have 153.6 GW of solar capacity by 2020 and set targets for individual provinces which they had already surpassed by 2019 [15]. Their Five-Year Plan for solar energy development has specific goals for solar panel technologies and innovation, including a goal to produce commercialized monocrystalline silicon cells with an efficiency of at least 23% and commercialized multicrystalline cells with an efficiency of at least 20% [15]. The Ministry of Science provides most of the funding for the advancement of solar technologies, and the government rewards high efficiency, low-cost solar panels with subsidies and construction quotas [15].

As of 2021, the largest solar park in China is the Huanghe Hydropower Hainan Solar Park with a capacity of 2.2 GW [16]. This is the second largest solar park in the world and also includes 202.8 MWh of storage capacity [16]. The plant was developed by the state utility company Huanghe Hydropower, cost US$2.31 billion, and began operating in fall of 2020 [16].

Construction on new solar parks began in October of 2021 in the northwest Qinghai Province which will cost US$10.1 billion and have a capacity of 11 GW [17]. Additionally, a project is under construction in Kubuqi, Inner Mongolia [17]. It is being developed by Elion and Three Gorges New Energy [17]. The project is expected to come online in 2025 with a capacity of 2 GW and a storage capacity of 300 MW [17].

Wind

For several years, China has led global wind power deployment [18]. At the end of 2019, China had an installed wind capacity of 210 GW (including some offshore wind), which accounts for about 5% of total electricity generation [2, 18]. In 2020, China consumed 1138 TWh of electricity from wind turbines [7]. There are significant wind resources in the northern and western provinces [18]. The 13th Five-Year Plan had goals for 210 GW of grid-connected wind power to produce 420 TWh of electricity by 2020, of which 5% was intended to come from offshore wind farms [18]. In spring 2019, the National Energy Administration called for an immediate halt in development and construction of wind power projects in Xinjiang and Gansu as well as Inner Mongolia and parts of Shanxi, Shaanxi, and Hebei in order to address overcapacity and risk of curtailment in those locations [18].

China's largest offshore wind farm is the Jiangsu Qidong farm off the coast of the Nantong Province [19]. The wind farm has a capacity of 802 MW and utilizes 134 wind turbines over an area of 114.5 square kilometers [19]. The whole project was constructed between April 2020 and December 2021 when it was fully integrated into the electric grid on December 25 [19]. The farm is owned and developed by Jiangsu Huawei Wind Power Co and Qidong Hua Er Rui Wind Power Technology Co [19]. It was constructed and engineered by PowerChina Huadong [19].

China Three Gorges Corporation has recently constructed three offshore wind projects adding 800 MW to China's wind capacity [20]. One project, called Jaingsu Rudong, is located in China's Yellow Sea and has three separate areas with a total capacity of 1.1 GW [20]. The project was fully connected in early 2022 and will produce 2.4 TWh of electricity every year [20].

Hydro

China has the largest hydropower capacity in the world, leading other nations by more than three times, and they also lead in new hydropower construction [21]. The installed hydroelectric capacity in China at the end of 2019 was 356 GW [2]. In 2020, China consumed 3333 TWh from hydropower [7]. China is home to the world's largest dam, the Three Gorges Dam located on the Yangtze River in Hubei which has a capacity of 22.5 GW [21]. The dam became fully operational in 2012 after planning began in the 1980s [21]. Northern provinces have little hydropower potential and thus little development, but the southern and western parts of the country have lots of potential and lots of development [21]. The 13th Five-Year Plan called for hydropower to supply roughly 5600 TWh of electricity by 2020 which as a goal was not met, but when it is, the National Energy Administration estimates will avoid roughly 3.5 Gt of carbon dioxide [21]. The plan also outlines goals for hydropower capacity to reach 470 GW by 2025 including pumped hydro [21]. It is clear that expanding hydropower capacity is a priority for the Chinese government as any renewable capacity will help to limit further pollution while still meeting demand.

The Baihetan Hydropower Station is one of many recently constructed in 2022 [22]. It is located in southwest China and has 16 Francis turbines representing a capacity of 16 GW [22]. This particular project is acclaimed as the most technically difficult hydropower project constructed in the whole world due to the double curvature arch dam, all underground powerhouse, and domestically manufactured and highly efficient turbines [22]. The whole project cost US$34 billion and connects to the ultra-high voltage line in the Jiangsu province [22].

Ocean

China has roughly 18,000 km of shoreline and almost 7000 individual islands [23]. It is estimated that the potential tidal power is 110 GW, while tidal stream capacity could be 14 GW, and wave power could provide 13 GW [23]. In 2011, China had 426 tidal energy dam sites with a total installed capacity of 21.8 GW and annual generation of 62 TWh [24].

The region with the largest wave energy density at 28.99 kW/m^2 is in the North Hangzhou Bay with the potential to provide 3830 MW [23]. While the potential is there, the technology has not yet reached utility scale and efficiency benchmarks to be fully implemented and connected to the grid [25]. Some tidal power projects are being implemented to power remote outposts on small islands, supplementing diesel and some solar and wind power [25].

The largest tidal power plant in China is the Jiangxia power plant with an installed capacity of 3.9 MW [26]. It is a tidal barrage with six turbines that became operational in 1980 and had its most recent turbine added in 2006 [26]. The turbines operate in ebb and flood tides and produce 7 MWh of electricity every year [26].

China is home to several test sites for ocean energy. One such site is located in Wanshan Island where wave energy units will be manufactured, installed, and tested [27]. Currently two wave energy converters have been installed to carry out real sea tests [27]. They have a combined capacity of 1 MW and were developed at the Chinese Academy of Sciences and the Guangzhou Institute of Energy Conversion [27].

Geothermal

In 2019, China had a total installed geothermal capacity of 27.78 MW, the 18th largest geothermal capacity in the world [28]. The 13th Five-Year Plan called for 1.1 billion square meters of new geothermal heating and cooling areas to be developed for a total of 1.6 billion square meters, and for the installed geothermal capacity to increase to 530 MW [29]. Ideally, the increase in geothermal capacity would offset 70 million tons of standard coal every year [29]. The first geothermal plant was built in 1970 in Fengshun [28]. The first high-temperature geothermal power station was built in Tibet and began commercial operation in 1977 [28]. China has considerable Hot Dry Rock (HDR) resources which can be cost effective for enhanced geothermal system power plants [28]. However, abundance of efficient resources does not necessarily mean suitable land for development near demand centers [28]. So geothermal power faces many challenges in China even though the resource is available.

The largest geothermal power plant in China is the Yangbajain power plant built in the 1977, and additions throughout the years have brought it to the current installed capacity of 26 MW [30]. It has a peak power output of 140 GWh, but annual production has begun to slow to a rate of 100 GWh [30].

China is expected to increase geothermal power and will do so in part through a joint venture with Iceland through the Sinopec Green Energy Geothermal Development Co [31]. The company plans to grow its business of geothermal space heating by 25% over the next 5 years [31]. With China's low to mid-temperature resources, power generation is hard to implement but space heating is effective [31]. Additionally, domestic oil company PetroChina plans to develop geothermal resources in their oil fields in Huabei, Dagang, and Jidong [31].

Biomass

China's Biomass Energy Industry Promotion Association released a report in 2021 which called for more government support of utilizing biomass for energy [32]. It is estimated that China produces nearly 900 million tons of agricultural and forestry waste every year, but only 90 million tons are currently used for power generation [32]. If all the biowaste was used to produce electricity, it could offset the use of nearly 400 million tons of coal [32]. It is expected that about US$184 billion will be invested in the biomass industry between 2021 and 2025, which should increase the amount of biowaste used for energy up to 3050 million tons as well as generate around 1 million domestic jobs [32]. Some challenges to fulfilling the biomass potential are the high costs of collecting, transporting, and storing the raw materials so subsidies will become increasingly important to the biomass industry in China [32]. China already uses municipal waste for energy. In 2018, they treated 130 million tons through incineration for energy, and this accounts for 40% of the total municipal solid waste they collect [33]. It is expected that agricultural and municipal waste will be increasingly used for energy and specifically heating needs throughout China to offset their reliance on fossil fuels.

The company with the largest installed capacity of biomass power is Kaidi Eco with 1386 MW [33]. In 2018, they generated 2.6 TWh of electricity from biomass [33]. In 2020, China installed 1.51 GW of biomass plants in the first half of the year using fuel from municipal waste, agriculture and forestry waste, and biogas [34]. The top five provinces for energy delivered by biomass during that time were Shandong, Guangdong, Jiansu, Zhejiang, and Anhui and the top provinces for new installations were Guangdong, Jianxi, Hebei, Guanxi, and Shanxi which makes it clear that biomass is being used and installed all over the country [34].

Biofuels

China has had wavering policies concerning biofuel due to the transient nature of grain prices and corn stocks [3]. Biofuel has not been a part of any plans to reduce carbon dioxide emissions even though it has potential to help China reach their goals [3]. China's biofuel industry and policies seem to be independent of their climate goals and policies. There have been some mandates to establish a nationwide E10 blend, but most efforts are suspended before their goals are reached [3]. In 2021, fuel ethanol consumption was estimated at 4.2 billion liters which represents an increase of more than 50% from 2020 consumption and production was expected to be 3.4 billion liters, which is less than 2020 due to high feedstock prices [3]. They were expected to import 800 million liters of fuel ethanol mostly from the United States to supplement their lack in production and still meet demand [3]. Additionally, China exports used cooking oil based biodiesel to the European Union, and they produce fatty acid methyl ester (FAME) biodiesel at a relatively stable rate of 2.5 billion liters per year [3]. Exports of hydrogenation-derived renewable diesel have expanded in recent years, this fuel has a capacity of 1.3 billion liters per year and is expected to double if planned projects are completed [3]. There is conflicting information coming from the State Council and the NEA wherein the State Council advocates for strict control of the expansion of fuel ethanol processing while the NEA supports expanding the development of all liquid biofuels [3]. As such, China plans to support provinces that have fully or partially adopted the E10 mandate and postpone the mandate in other areas [3].

The largest fuel ethanol producers are SDIC Jilin Alcohol and Henan Tianguan, each producing 887 million liters every year from corn, wheat, and cassava [3]. The largest biodiesel producer is Zhuoyue New Energy with a capacity of 632 million liters of FAME per year [3].

Currently biofuel producers in China use conventional fermentation technology with feedstocks of corn and rice [3]. But significant resources are being invested within the industry to expand production to include advanced biofuels such as cellulosic bioethanol as well as coal and industrial flue gas-based synthetic ethanol [3]. Full adoption of these advanced technologies would increase the biofuel capacity, but they have extremely limited governmental support [3].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

The battery energy storage market is rapidly expanding around the world and especially in China. In 2020, China installed energy storage alongside energy production installations at such a high rate, they increased energy storage capacity by 580 MW, an increase of over 400% and accumulated a total capacity of 35.6 GW [35]. This incredible installation rate is due in part to the peak carbon and carbon neutrality goals and more specifically to various provincial policies requiring energy storage with new projects [35]. Pumped hydro accounted for the largest portion of installed capacity at 31.79 GW followed by electrochemical energy storage with a capacity of 3269.2 MW made up mostly of lithium-ion batteries (2902.4 MW) [35].

The top provider for electrochemical energy storage in 2020 was CATL with an installed capacity close to 600 MWh [35]. The total energy storage related investment in China in 2020 reached US$1.16 billion composed of venture capital, generation companies, grid companies, solar companies, and local governments [35]. Six major characteristics of China's energy storage industry in 2020 were identified by the China Energy Storage Alliance and they are as follows: policies increased the pace of energy storage industrialization; a trend for integrating energy storage emerged; long-term markets were established, innovative business models made headway; there were breakthroughs in energy storage technologies and costs fell; and many parties are entering into the energy storage industry [35]. It should be clear that energy storage will play a large role in meeting the 14th Five-Year Plan's goals for peak carbon and carbon neutrality.

Country's Future Storage Direction

The Five-Year Plan also set goals to develop pumped hydro faster, and its capacity is expected to reach 65 GW by 2025 [35]. Large scale compressed air energy storage is also making headway with a 100 MW expander passing all tests and reaching design targets at the Chinese Academy of Sciences in 2020 [35]. Compressed air storage is expected to have wide applications in tandem with many renewable energy technologies due to its high capacity, long life, and safe operating conditions. Flywheel energy storage is already utilized and is expected to expand in capacity mostly in the oil well drilling industry, rail transit, UPS backup power supply, and potentially in the automobile industry in the future [35]. There are molten salt thermal storage demonstration projects under way in China with a total capacity of 520 MW with more under construction to reach a total capacity of 899 MW [35].

Carbon Footprint

Most Recent Carbon Output

China's 2020 emissions are estimated to have been 13.8 Gt and current policy projections reach 14.5 Gt in 2030 [36]. While this is within range of their peak carbon goals outlined in the 14th Five-Year Plan, it is not enough to meet the Paris agreements 1.5 degree Celsius limit and is more consistent with a global warming of 3 degrees Celsius [36].

As mentioned, the 14th Five-Year Plan includes goals to build low-carbon energy systems and construct low-carbon cities [12]. The document strives to "deepen the fight for pollution prevention and control" and promote practices that reduce pollution and carbon use to improve the overall environmental quality of China [12]. As mentioned, there is a goal to reach peak carbon emissions by 2030 and reach carbon neutrality by 2060, and they will do this by implementing stringent pollution control policies, working on large carbon sink projects, and strengthening innovative low-carbon technologies for widespread use [12]. It is expected that energy consumption will be reduced by 13.5% per unit of GDP over the 5 years, and carbon dioxide emissions will decrease 18% per unit of GDP over the time period [12].

Historical Trends of Carbon Footprint

In 2017, it is estimated that China's carbon dioxide emissions from energy use amounted to almost 11.67 Gt [1]. The World Bank states that economic loss due to pollution is almost 6% of GDP [2]. The highest rate of growth of carbon emissions from China happened between 2000 and 2010 during which emissions rose from 4 Gt to 10 Gt [36].

Types and Main Sources of Pollutants

China has high levels of PM10 and PM2.5 as well as SO2 and NOx [37]. The two main contributors to air pollution are coal combustion for power, industrial processes and heating, along with vehicle exhaust [37].

Air Quality

China is well known for its extremely polluted air with levels exceeding international health standards by a great amount. Studies have shown that air pollution contributes to 1.6 million premature deaths per year in China and has reduced the average life expectancy in many cities due to air pollution causing cardiovascular and pulmonary disease [37]. As such, air pollution is an important topic for residents and policy makers in China. In 2013, the measurements of fine particles (less than 2.5 micrometers) rose up to 993 micrograms per cubic centimeter in Beijing [2]. For reference, the World Health Organization suggests a density more than 25 micrograms per cubic centimeter is unsafe [2].

Energy Resiliency

Electrical Grid

China's electric grid was established in 1879 with DC generating units to provide energy for lighting in Shanghai [38]. Then in 1882, the first public electricity power plant was built in Shanghai with 16 steam engine generating units and in 1888 a 15 kW generator was built in Beijing to provide power to the Imperial Palace [38]. Power plants and lines were added in the following years, and in 1912 the Shilong Dam was the first hydraulic station to operate in China after 2 years of construction [38]. 1929 saw the formation of the Construction Commission to develop standards for voltage and frequency, and then the Resource Commission was formed in 1935 to survey hydroelectricity [38]. These commissions were later combined along with the National Economic Commission and the Ministry of Trade and Industry into the Ministry of Economy in the year 1938 [38]. In the early 1940s, the first high voltage lines were constructed in northern China to transmit electricity at 220 kV between Shuifeng, Anshan, Andong, and Dalian [38]. In 1949, China had a national capacity of 1.8 GW which just continued to grow with a few setbacks from stagnating production of coal which were rectified by increased production of oil [38].

Now the electric grid system is run by the State Grid Corporation of China (SGCC) and China Southern Power Grid Co [2]. As demand increases, the grid must grow to accommodate each customer, so they are utilizing ultra-high voltage transmission lines up to 100 kV AC and 800 kV DC [2]. In 2020, SGCC invested US$170 billion into the grid of which US$72 billion was for ultra-high voltage transmission lines [2]. In August of 2021, SGCC revealed plans to spend US$350 billion to upgrade the system through 2025, including adding new ultra-high voltage power lines, more pumped hydro storage, and more EV charging stations [39]. Southern China has the Yunnan-Guangdong line that links hydro and nuclear sources while Northern China has a line linking Mongolian wind power to Shandong [2]. Additional projects have been started to build transmission lines linking the Chinese grid with Kazakhstan, Russia, Mongolia, and Pakistan [2].

Climate and Natural Disasters

China faces several types of climate and natural disasters. More than two thirds of Chinese territory are faced with flood threats and coastal regions are subject to tropical cyclones [40]. Northern China suffers from droughts, and all regions have earthquakes, fires, extreme heat, and extreme cold [40]. Almost 70% of the country is made up of mountains and plateaus which hold their own risks of different disasters such landslides and collapses [40].

Climate change increases the risk of super typhoons and intense rainfall leading to flash floods [40]. Additionally, droughts and heat waves will become more frequent as will cold spells [40]. China could face significant losses due to their rapid population growth and urbanization if they do not have proper disaster relief plans in place [40].

The prospect of increased flooding is not good news for regions with large hydropower capacity as dams could be breached and cause devastating damage and loss of life to local communities [41]. Evacuation procedures will need to be efficient and properly followed and even then, resulting damage could significantly impact food security [41].

Grid Resiliency

As demand for electricity and coal related pollution grows in all parts of China, they are faced with solving both problems at the same time. The implementation of more ultra-high voltage lines will help transport the energy from inland regions with many wind and solar resources to centers of demand in coastal cities [42]. However, according to China Energy News, many UHV lines are running at just over 60% of their designed capacity [42]. This is mainly due to technological limits and conflicts of interest between power generators, grid companies, and local governments [42]. This has led to rolling blackouts during periods of peak demand when the weather is unusually cold [42]. Stability of the electrical grid is a fairly well managed aspect of the Chinese energy industry with stringent demand response management at a local level. In the coming years, harsh weather conditions will only become more common and improving the interconnectivity of the electrical grid between provinces will preemptively solve a lot of the demand issues to come.

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

China is the world's largest consumer of energy, largest producer and consumer of coal, largest emitter of carbon dioxide, and largest investor in clean energy [43]. But their high demand for energy and coal in particular has led to increasing imports of coal and oil. Most of their imported coal comes from regional neighbors [43]. In 2019, they imported 77 million metric tons from Australia, 47.8 million metric tons from Indonesia, 36.1 million tons from Mongolia, and 29.2 million metric tons from Russia [43]. They used to import coal from North Korea, but UN sanctions have led China to suspend imports from them [43].

As for oil, China is the largest import of oil in the world with half of those coming from countries in the Middle East [43]. Political unrest in those regions threatens China's energy security since they rely so heavily on imported oil to fulfill their energy demand [43]. To address this issue China has begun investing heavily in Africa by offering economic development loans to African states in exchange for primary access to any oil reserves found in those regions [43]. Other avenues, which China is exploring to increase energy security, include improving maritime energy shipments and building a strategic petroleum reserve to protect against market shocks [43].

Although China is home to the world's largest shale gas reserves, they are difficult to access, and therefore China relies on foreign natural gas to meet their demand [43]. This natural gas is delivered by pipeline in the form of liquefied natural gas from Turkmenistan and Russia [43]. China is also increasing imports of natural gas from other countries such as Australia, Qatar, and Malaysia [43].

Relations with Global Community/ Socioeconomic Influence

China has agreed to follow the Paris Climate Accord, but it has been argued that they are not pulling their weight and doing all they can to reach the targets set by the agreement. In April 2021, China released a joint statement with the United States addressing the climate crisis [44]. The statement expresses commitment by both countries to adhere to the climate accords and to increase their individual efforts to meet the goals set forth [44]. They both realize the importance of limiting the global temperature increase to 1.5 degrees Celsius and recognize their past actions that have contributed to the climate crisis [44]. Both countries agreed to develop long-term strategies for carbon neutrality, maximize international investment in support of renewable and low-carbon energies in developing countries, and drastically reduce hydrofluorocarbon production and consumption [44].

The Republic of China was a founding member of the United Nations but was replaced when the People's Republic of China became the Chinese government in 1971 [45]. Regardless of the changing government and name, China has been an active member of the United Nations from the beginning and remains so to this day [45]. In 2018, China was one of the largest financial contributors to the UN, and an increasing number of roles within the UN are held by Chinese Nationals [45]. China has dispatched more than 50,000 peacekeepers since 1990 to almost 30 different missions, this is more members than any other permanent member of the security council have dispatched [46]. They eradicated poverty domestically and are committed to helping other nations do the same along with helping to fight climate change and build economies through the Belt and Road Initiative [46].

China and Iran share a friendly relationship and at the end of 2021 were in the midst of building an economic partnership [47]. The details of the partnership include China investing heavily in Iranian banking, telecommunications, ports, railways, and other projects in exchange for heavily discounted oil for the next 25 years [47]. China supports North Korea and at times has defied UN sanctions to assist North Korea in avoiding economic collapse [48]. Such an event would result in a massive influx of refugees over the border into China, and this is what they are trying to avoid by providing support to Kim Jon-Un's regime despite international disapproval [48]. China has friendly relations with Russia but they keep each other at arm's length, reluctant to rely too much on one another [49]. China is ruled by the Chinese Communist Party whose goals and views sometimes cause friction between other large nations in the world.

China has set goals to become carbon neutral by 2060, and this will be done through rigorous policies and drastic changes in the coming decades. This is further complicated by the fact that almost 80% of their coal-fired power plants have been constructed in the last 15 years [50]. These plants have long lifetimes so China will need to plan retrofits to reduce carbon emissions or risk losing precious capital if the plants need to be shut down. A report by the IEA reveals that the investment required to meet carbon neutrality is well within China's capacities and should be achievable with the right actions and trajectory [51].

Education

In the past, China's public education system has not had any formal curriculum focused on sustainability and environmental responsibility [52]. But the Earth Institute and the Tencent Foundation are developing sustainability modules for secondary schools in China [52]. The modules will promote understanding of how to adopt and apply sustainability principles and how to change personal behaviors to meet climate goals [52].

Summary

Current Energy Situation

In summary, China is highly reliant on fossil fuels; importing and consuming coal, oil, and natural gas at extremely high rates. But they are also aggressively installing renewable energy at high levels, especially solar PV and wind. They have made some progress with ocean energy and are improving biomass technologies to increase capacity and implementation into the energy sector. China has been a long time consumer of hydroelectricity and is home to the largest hydroelectric dam in the world, the Three Gorges. Due to their rapid economic expansion in the past and heavy use of fossil fuels, the air quality in China is at levels far beyond what is considered safe by the World Health Organization.

Future Energy Situation

China recognizes this shortcoming and has pledged to reach peak carbon by 2030 and to become carbon neutral by 2060. They will do this by further implementing renewable energies and shifting industries from coal-heavy technologies to electricity based technologies so the energy can be supplied by renewable sources. While they have not set forth any specific benchmarks for capacities of different renewable energies, they are committed to the Paris Accords and the most recent Five-Year Plan, the 14th, focuses on strategically transforming the energy industry to achieve carbon neutrality.

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Indonesia

Slobodan Petrovic and Pamela Jackson

National Energy Introduction

Energy Policies

With over 17,000 islands, Indonesia is an archipelago located in the Pacific Ring of Fire [1]. With a population near 269 million, Indonesia has the fourth largest population globally with over half located on the island of Java. When considering purchase power, Indonesia has the largest Southeast Asian economy and seventh largest globally. However, with provinces in over 6000 islands, attaining reliable energy supply in all areas is a challenge. Government policies have been used to influence the energy sector such as the energy subsidy started in 1965 which is considered welfare traditionally, but only 36% is utilized by low-income citizens [2]. There are recent policies aimed to incentivize fossil fuels, geothermal, and biodiesel generation with little attention to other renewables. Renewable energy (RE) growth has been stunted by the COVID-19 pandemic which ushered a higher focus on coal [3]. But there are targets set and capital being raised for green and renewable projects including solar and biogas with goals for lowering emissions, improving climate-resiliency and air quality, and aiding COVID-19 recovery. This includes prioritizing subsidies for the lowest income bracket [3] and using energy efficiency measures to reduce energy use 2% by 2025 and 1% yearly after that [1]. By incorporating energy efficiency actions on a large scale, energy reduction could potentially improve by 10–35%.

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Trends in Generation Technologies

Domestic Resources

Domestic resources for energy available in Indonesia include oil, natural gas, coal, geothermal, solar, wind, hydropower, tidal, and bioenergy with tidal energy yet to be tapped into. Figure 1 shows the percentage of total electricity generation by generation technology over time and projects targets until 2050 [4]. Oil is being significantly reduced as it is a costly import. Targets for 2028 include 9.7 GW produced from hydropower, 4.6 GW from geothermal, and 4.6 GW from solar [5]. The long-term goal is to lower oil to 0.1%, raise RE to 28%, and harness coal and natural gas at 47% and 25%, respectively [1]. This will be done by substantially increasing coal and natural gas production as well as adding more renewable generation [4]. The Indonesian power company, Medco Power, plans to start the RE portion by focusing on solar until 2024 when geothermal production will have a large expansion overshadowed only by hydropower, and hydropower will again have a large boost in 2027, accounting for 56% of RE generation by 2030 [6]. For total primary energy sources, oil holds a more leading role due to transportation use as shown in Fig. 2 [7, 8]. Oil and hydropower have a long history of application in Indonesia. Bioenergy is a significant source used for household cooking and biodiesel which is progressively being regulated to lower oil reliance. Geothermal has also been a predominantly used RE source that has abundant availability.

History of Energy

Indonesia started as a Dutch colony in 1885 producing crude oil in North Sumatera [2]. In 1960 after World War II, companies from the United States began exploration in Indonesia for energy resources. By 2018, Indonesian companies

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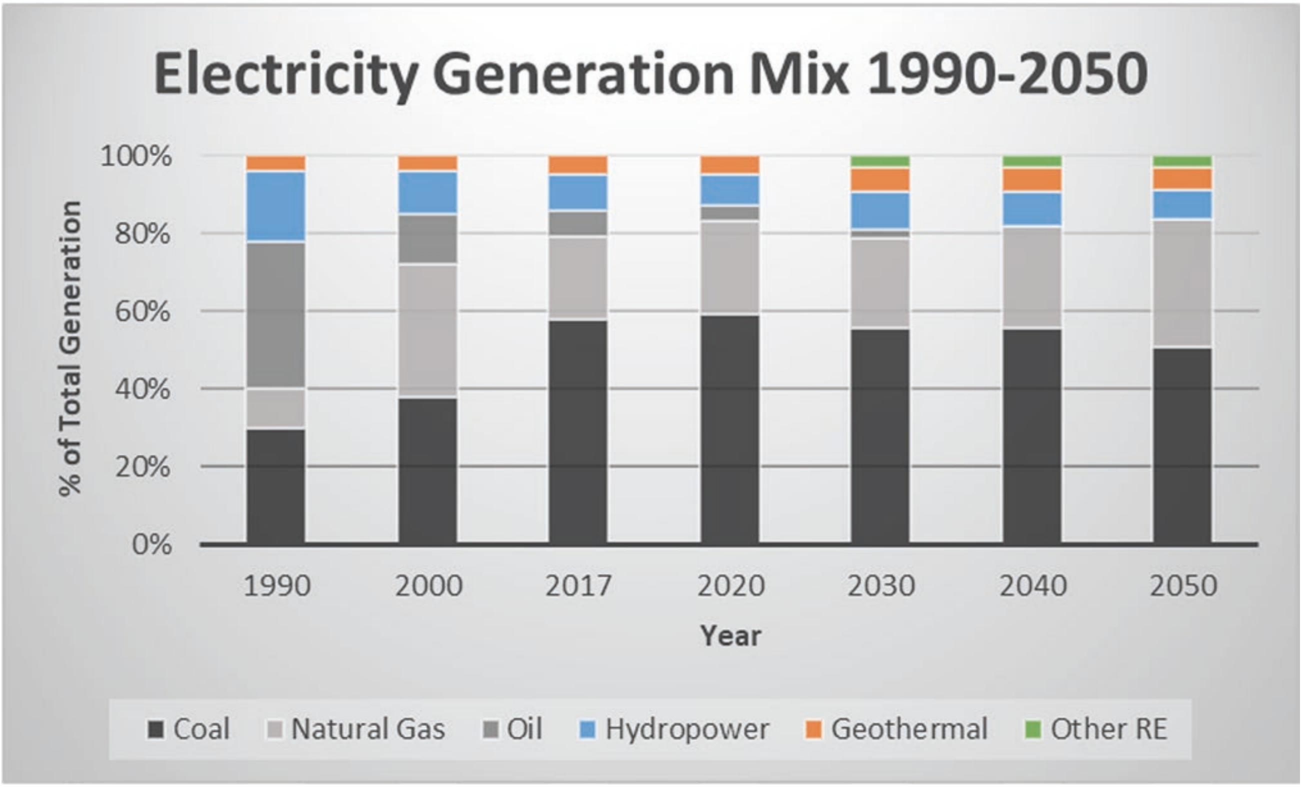

Fig. 1 Percent of total electricity generation in Indonesia by technology from 1990 and projected into 2050. Other renewable energy includes solar, wind, bioenergy, tidal, and hybrid and do not show below 1%. (Data used from [4])

produced below 40% of oil while the majority was produced by US energy companies. Indonesia exported surplus oil until 2003 when international rates of imports from the global economy began to affect oil subsidies prompting a decline in subsidies and oil use. Since 2010 regulations have conflicted with each other on RE incentives, necessitating updates to promote RE growth and make the appropriate grid preparations [1]. An example of a change might be switching the diesel fuel subsidy from incentivizing biodiesel and higher grades to subsidizing electric bus charging costs which would make electric buses a feasible option as well as offer benefits socially and environmentally.

Breakdown of Energy Generation "Mix"

Energy Generation Mix

Indonesia generated 56.6 GW in 2018 with the majority coming from the State Electric Company (PLN), a smaller portion of 13.3 GW from the private sector and 4.8% percent from rental power plants of 2.7 GW [9]. Future expansions have been allotted with 33,666 MW from independent power producers (IPPs) and 16,243 MW from PLN [5]. The generation for 2019 is broken down by technology in Fig. 3 [1, 11]. More than half of electricity was provided by coal, and only 13.3% is provided by renewables. There was also a small amount (less than 0.1%) of waste-to-energy used [1]. Hydropower has the greatest share of renewable generation with wind and solar having minimal application in Indonesia.

Energy Consumption Mix

The total final energy consumption in Fig. 4 shows that transportation used the majority of energy in 2019 which is where most oil is used [1]. Indonesia consumed 3.53 barrels of oil equivalent (boe) (20.16 GJ) per capita and is expected to reach 314 million tonnes of oil equivalent (toe) (13.2 billion GJ) and 943 million toe (39.5 billion GJ) by 2025 and 2050, respectively. Biofuels were used for cooking and biodiesel in 2018 at 17% of energy use and electricity was at 14% [12]. The electricity consumed in 2019 reached 181 TWh in the more populous areas of Bali, Java, and Madure and significantly less in other regions [1]. Indonesia has overcapacity of energy supply due to using optimistic growth numbers for demand forecasts where the discrepancies were further exacerbated by the setbacks during the COVID-19 pandemic. However, Indonesia imported 1553 GWh of electricity from a hydropower plant in Malaysia in 2020 [13]. In

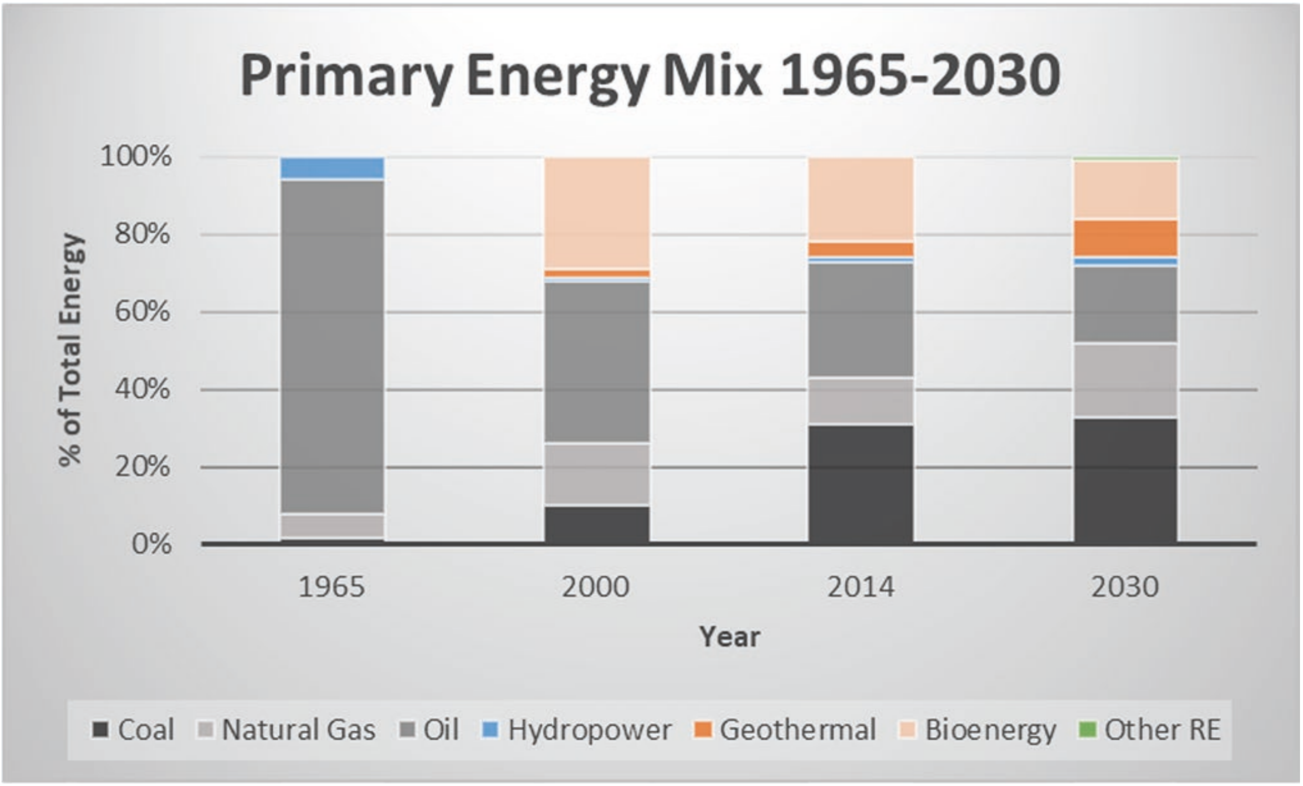

Fig. 2 Percent of total primary energy in Indonesia by technology from 1965 and projected into 2030. Other renewable energy includes solar, wind, tidal, and hybrid and do not show below 1%. (Data used from [7, 8])

terms of RE, 95% of consumption came from biofuels, and only 5% went toward electricity in 2017 [10]. Of that, 80% went toward households largely for cooking, 14% was used by industry, and only 4% of renewables were harnessed by the transportation sector.

Fossil Fuels

Oil

Indonesia's nine refineries in 2020 produced 259 million barrels (1.48 billion GJ) of crude oil [13] accounting for near 7% of electricity generation and the majority of primary energy due principally to transportation [1]. State-owned Pertamina provides 90% of the national refinery capacity [2]. Imports primarily from Singapore and Malaysia [2] were 79.7 million barrels (455 million GJ), and exports were 31.4 million barrels (179 million GJ), making Indonesia a net importer of oil [13]. 6.4 million tons (290 million GJ) of imported liquefied petroleum gas (LPG) in 2020 went mainly toward household cooking while only 1.9 million tons (85 million GJ) was produced domestically. LPG receives the largest fuel subsidy being sold at only a third of the market price [3]. Consumption of oil has been increasing since 2010 while domestic production has decreased and as the economy and transportation needs to grow, the gap between imports and production will expand [2], which has prompted government support of alternatives that can be sourced locally to offset reliance on imports and lower costs [1].

Indonesia has the second highest oil production in Southeast Asia at 12.02% [9] and occurs mostly on the west side of the country [1]. Half of the oil production in Indonesia was performed by foreign companies with Chevron and Mobil being the major producers. Pertamina is working to increase its share and is the largest Indonesian producer and does most of the transporting and distributing of oil domestically. Its oil stocks can provide for the country's consumption for 22 days, but there is no buffer for major supply interruptions [2]. Oil production is not meeting targets because the fields are aging, there are quality issues, and companies are not exploring due to unfavorable regulations for exploration and production [1]. Singapore has allocated one fifth of their storage for Indonesia [2]. Indonesia is well below the international standard of keeping 90 days of net imports in offshore reserves.

There were 2.48 billion barrels (14.2 billion GJ) of proven reserves in 2019 with an estimated 1.29 billion barrels (7.37 billion GJ) of hypothetical potential oil reserves [1]. The proven reserves are expected to last until 2030 but with the

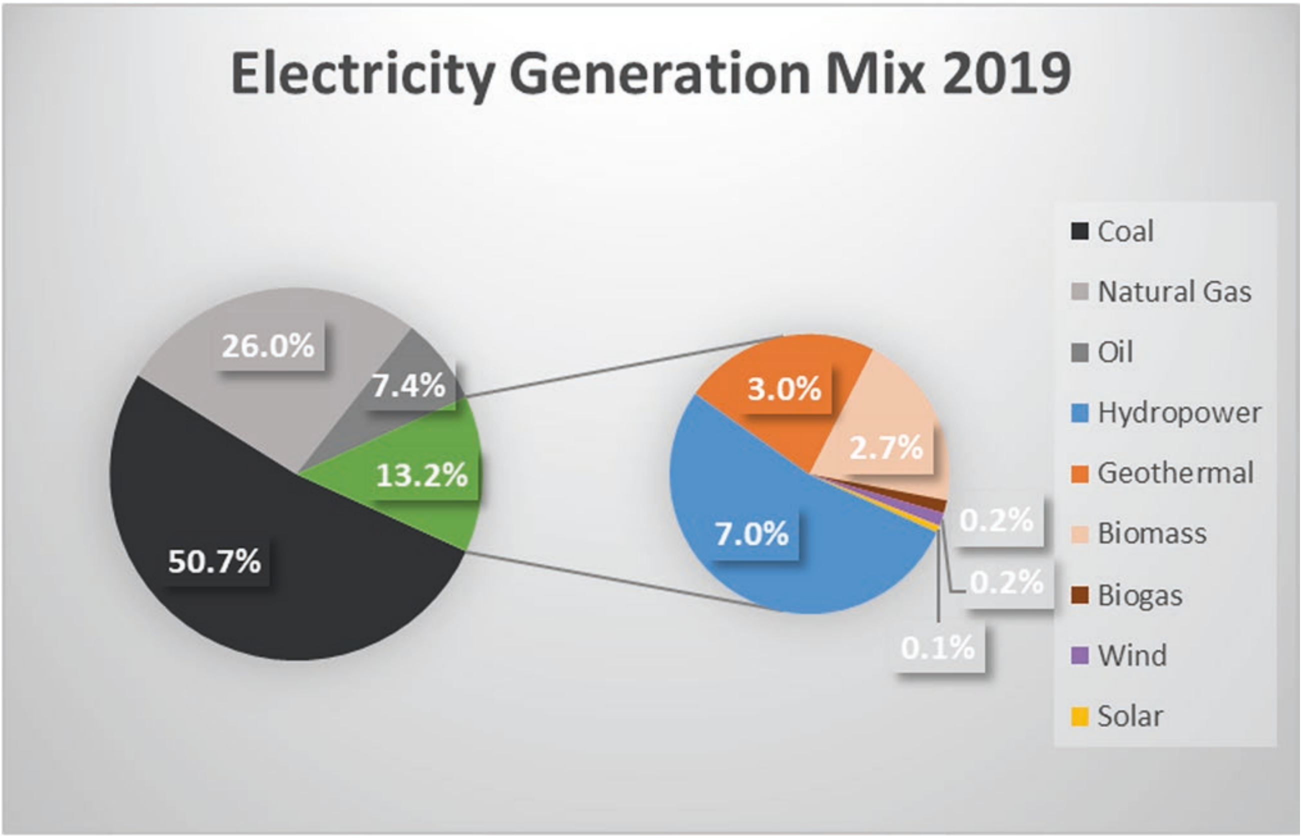

Fig. 3 Percent of total electricity generation in Indonesia by technology in 2019. (Data used from [1, 10])

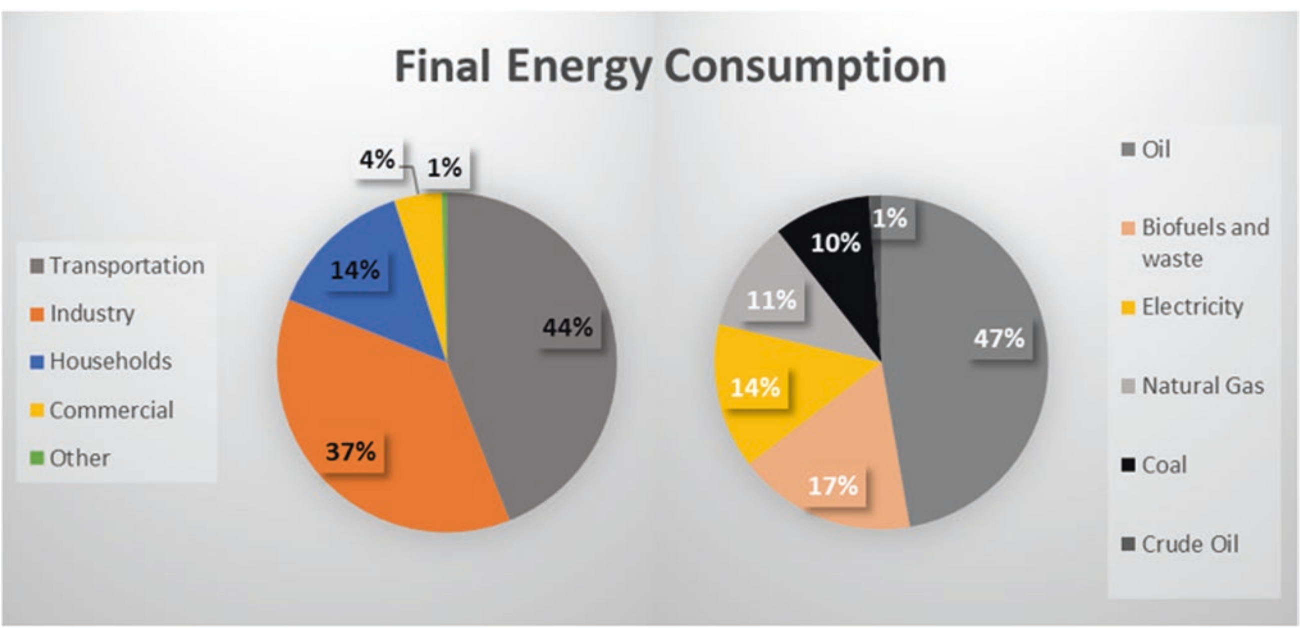

Fig. 4 Percent of final energy consumption in Indonesia by sector in 2019 (left) and fuel in 2018 (right). (Data used from [1, 12] based on IEA data from IEA (2018) Indonesia Key Energy Statistics, www.iea.org/statistics, All rights reserved; as modified by Pamela Jackson)

aging oil fields, this will require more investments [2], infrastructure updates, higher grade fuel use, and improved regulations [1]. More favorable policies are expected to attract foreign companies to explore and more advanced technology deployment that can lead to increased domestic production, but there is an amount of unpredictability stemmed from changing international prices and domestic regulations.

Coal

Indonesia produced 564 million tons (16.5 billion GJ) of coal in 2020, consumed 113.42 million boe (648 million GJ) [13], and generated over half of 2019's electricity with coal [1]. There are long-term contracts with most plants being in operation for less than 10 years [1] that require coal to keep a high percentage of the energy supply and even increase it regardless of cost changes such as eliminating the value added tax exemption for coal that could keep coal from being the cheapest fuel source [3]. In 2019, 80% of produced coal was exported and accounted for 11.2% of total energy exports as the primary energy export [1]. In 2020, Indonesia imported 8.76 million tons (223 million GJ) of coal and exported 405 million tons (10.3 billion GJ) primarily to China and India [13]. The price of coal and exports declined after the pandemic but have gone back up once China banned Australian coal [3]. Demand has been growing while international prices have increased, resulting in more coal exports and less domestic supply. Coal power plants have needed to consider rolling blackouts die to domestic coal supply deficiencies.

Indonesia has more than half of the coal reserves in Southeast Asia [9] of medium and low quality [1] mostly located in East Kalimantan and South Sumatra [13]; 2020 priorities for coal include improving quality and using gasification for syngas, and other petrochemical industry needs to limit the need for importing LPG [3]. The government has provided incentives to increase coal use and gasification projects from the largest coal companies are expected to substitute LPG imports up to 30%. There is also exploration being done with using coal produced dimethyl ether with induction stoves as an LPG replacement [1]. Another goal is to use greener technology when reaching these targets for growth [3].

There were 25.8 billion tons (655 billion GJ) of verified coal reserves in 2020 and 93.1 billion tons (2.36 trillion GJ) in hypothetical reserves reported by the Ministry of Energy and Mineral Resources Republic of Indonesia [13]. Electricity generation from coal is targeted to reach 27 GW by 2028 taking a share of up to 65% [1]. Current regulations are encouraging overproduction of coal while utilization of lower-quality coal is decreasing efficiencies [1]. Concerns for keeping coal at a high usage include increases in greenhouse gas (GHG) emissions, poor air quality, polluted water, and water shortages [8].

Natural Gas

Indonesia is the 11th highest natural gas producer globally and 2nd only to China in the region [1]; 2019 saw a production of 2.9 million standard cubic feet (MMSCF) (3060 GJ) of natural gas accounting for 18.5% of the primary energy supply and 26% of electricity generation. Domestic companies are increasing their share of oil and gas production in Indonesia from 60% in 2019 to 86% by 2050. Indonesia exported 20 million tons (987 million GJ) of liquefied natural gas (LNG) in 2019 which was the 7th largest global exportation. In country, natural gas is especially important for fertilizer, petrochemicals, and steel production.

Natural gas is mainly sourced from offshore near Sumatra and in East Kalimantan [1]. The proven reserves in Indonesia in 2020 were 43.57 trillion standard cubic feet (TSCF) (46.0 billion GJ), and 18.82 TSCF (19.9 billion GJ) were estimated as potential reserves [13]. This is less than half of the reserves that were available in 2010. The current policies and incentives do not promote investment or exploration [1]. The government is attempting to increase natural gas use by setting an energy mix obligation to decrease oil use. This includes distribution investment while setting a target for 46 million cubic feet per day (MMSCFD) (48,500 GJ per day) of coal bed methane by 2025.

Nuclear Energy

Nuclear energy was labeled a last resort energy option by the government, and there is no current nuclear energy use in Indonesia [14]. However, with a growing economy and goals of reducing GHG emissions, nuclear energy has kept a position of possibility. Starting in 1970, the government has worked with other countries in exploring the feasibility of harnessing nuclear power in Indonesia including floating power plants for smaller islands. There have also been measures taken to instill a positive public perception trend of nuclear power.

Indonesia has been reported to have the most experience with nuclear technology in Southeast Asia [15]. A research reactor built in 1964 reached a capacity of 2 MW in 2000, and plans for its decommissioning have been made after 2017. Another research reactor built in 1979 can produce 100 kW and is used for training at a local education program. In 2011, Bangka was considered as a location for a nuclear power plant since it was far from active volcanos and seismic activity. The hazard from tsunamis is also low and the population is small. West Kalimantan was also considered in 2013 for a small reactor where most of Malaysian electricity imports go. In 2014, nuclear power was included as a new renewable energy in the government's energy policy with a target of 4000 MW. These and all other plans for development have repeatedly been put on hold.

Policymakers have a 55% approval of nuclear energy in Indonesia and 27% disapproval [14]. The topics considered when deciding whether to deploy nuclear energy include the highest rated factor of political and social aspects such as public opinion which was 77.5% acceptance in 2016 [15], easing power outage rates, and the necessity of international aid and support [14]. Environmental concerns are the next highest factor in decisions and cover the goal of reducing GHG emissions and air pollution while assessing the durability of the plants in cases of natural disasters. Domestic nuclear technology is not sufficient, and Indonesia would have to use technology from other countries. The lowest factor in decision making is economic concerns of growth. While some fuel fabrication can be completed in country, and the National Atomic Energy Agency (BATAN) has estimated 78,000 tonnes of uranium in 2016 in Kalimantan and possibly West Papua, these are high-cost resources and Indonesia would have to rely on fuel imports from the United States [15].

Renewable Energy Generation

Photovoltaics (PV)

The total on-grid power supplied by solar power plants in 2020 was 123.8 MW, and off-grid power consisted of 34.55 MW from power plants and PV, 16.04 MW from public street lighting, and 10.90 MW from solar energy saving lamps [13]. The first grid-sized solar power plant project began in 2018 [1] by Vena Energy with funding from Asian Development Bank (ADB) and reached full operation of 21 MW in 2019 [16]. It is located in North Sulawesi requiring 600 people at maximum production to be capable of supplying 33,400 MWh per year.

Potential solar power available in Indonesia is estimated at nearly 208 GW [1, 3, 6] due to the availability of sun all year [11]. Only 22% of the solar energy available in Indonesia has been harnessed as of 2018 [10]. The majority of solar resource could provide up to 1400 kWh/kWp/yr, and a substantial area could also provide up to 1600 kWh/kWp/yr. The International Renewable Energy Agency (IRENA) found that using available rooftop space in Indonesia could provide up to 30% of water heating and 5% solar buildings cooling [8]. Solar thermal collectors could also be used for heat processes in the industry sector for up to 70PJ per year.

A survey conducted in 2017 of grid customer perception of PV found that of those who responded, 81% considered RE to be important and 58–92% knew about climate change [11]. The more knowledge they had on RE and climate change, the more concerned they were with it. No participants knew whether electricity provided by the grid or roof-top PV cost more, but it is expected that PV costs will continue to decrease in the future. In general, those with more education had more concerns about climate change and more support for PV. Those who experienced a less reliable grid also favored PV. The majority of respondents would like to have PV installed on their roofs and most of the ones who did not were worried about the strength of their roofs. This study suggests that awareness can increase customer demand, and solar can expect customer support in the future.

Government buildings have been mandated to install PV on their roofs, and a goal to reach 70 MW by 2021 with roof-top PV has been incentivized with favorable rates for selling solar power to the grid [3]. The target for all solar power by 2028 is 908 MW [1]. Paths for this include the following:

- Providing frameworks for roof-top PV
- Permitting reservoir use
- Developing storage
- Implementing small scale solar in rural areas to lower environmental impact
- Deploying mini grid pilot projects for research on attaining 100% electrification

IRENA has suggested that there is enough space and infrastructure in Java and Bali to house the majority of solar potential in this area that accounts for 70% of energy use and is expected to need an increase in supply [8]. It was found that 47 GW of solar energy could be supplied by 2030 which is well above government plans. This could be completed by changing government policies and using a mix of grid power plants and roof-top PV. One step in this direction is the new floating PV project that will start at 50 MW and then increase to 145 MW by 2022 [17]. It will supply the most solar power in Indonesia and provide more power than any floating power plant in Southeast Asia.

Wind

Wind capacity in 2020 was 153.83 MW on-grid and 0.48 MW off-grid for a total use of 475 GWh [13]. The first wind power plant, Tolo 1, was built in 2018 in South Sulawesi by Vena Energy providing 72 MW [1]. UPC Renewables installed a 75 MW in 2018 called Sidrap Wind Farm. Small wind projects make up the rest of wind energy production in Indonesia.

The wind energy's potential in Indonesia has been assessed at 60.6 GW [1, 6] with only 1% having been harnessed in 2018 [10]. At a height of 100 m, less than 260 W/

m^2 is available in most of Indonesia with only a small area reaching the 260–420,260 W/m^2 range. It is cited that wind speeds are only strong enough for large plants offshore [1]. While there are no policies specific for wind power as of 2019, the government has set a target of 1.8 GW of wind energy by 2025.

Hydro

In 2020, Indonesia's on-grid hydroelectric power plants provided 4.7 GW and 100 MW came from micro hydropower while 375 MW was supplied from mini hydropower [13]. There were also off-grid installations contributing 938 MW from hydropower power plants and 26.3 MW from micro hydropower, culminating in a total of 24,289 GWh supplied to customers. Hydropower accounted for 2.74% of the total energy supply in 2019 and 7% of the electricity mix as the largest share of renewable energy [1].

PLN built the largest hydropower plant, Cirata, in 1987 providing 1008 MW [18]. A study on the corrosiveness of the Cirata hydroelectric power plant documented the increasingly poor water quality from 2003 to 2013 that lead to increased maintenance for the damaged equipment and interrupted operations. Of the 41 Mini hydropower plants, problems have also been identified by 27 respondents of a 2018 survey including exceeding construction budgets, low profitability, and insufficient cash flow [19]. A 2017 study uncovered low quality with design, construction, operation, maintenance, and expertise [20]. They also struggled with electricity tariff rates, excessive loads, natural disasters, and disputes over water allocation.

Indonesia has potential for over 94 GW of hydropower [1, 6] with 75 GW coming from hydropower plants and 19.4 GW from micro and mini hydropower [2]. The government has set a target for 17.9 GW from hydropower plants by 2025 and 3 GW for smaller hydropower [1]. PLN plans to build a larger hydropower plant than the current one reaching 1.35 GW in 2025 to support the smelter industry in North Kalimantan [21]. Long-term planning for hydropower is hindered by a long permit procedure, rainfall pattern changes due to climate change, and concerns about the indigenous people, endangered species, and land that will be affected [1]. In hopes of reducing the impact of hydropower on the environment, research is being deployed for smaller projects in remote areas.

Ocean

Indonesia currently does not have any ocean power plants, but they do have a lot of potential. Two thirds of the country is covered by ocean and there are 54,716 km of coastline [22]. Wave models have found excellent wave potential exceeding 30 kW/m from March to November along the south and west of Indonesia [23]. Some areas have ocean potential all year and 1% of potential sites can reach over 60 kW/m. This results in an estimated 17.9 GW [1, 6] of potential practical energy classified as tidal, 2 GW of ocean wave energy, and 41 GW of ocean thermal energy [22]. The technical potential is even higher than what is estimated to be practical at 216 GW for all three ocean energy types.

There have been announcements of plans to add wave, tidal, and thermal ocean projects since 2015 [24]. In 2017, the presidential decree (RUEN) includes ocean energy development as part of the other RE category planned to reach 3.1% of the energy mix [22]. Notwithstanding the many plans, fully realized projects have yet to be completed. An example is the tidal bridge project planned for the Larantuka Strait supported by the Dutch government [25]. This is an area where residents only have ferries for traveling across, and a bridge would be beneficial. The project would be the first bridge and tidal combination as well as the world's largest tidal plant offering 40 MW of power. There are mitigations being made to account for whale passage, turtle nesting, and the 75 ferrymen who will be affected.

Geothermal

Indonesia had a geothermal capacity of 2.13 GW in 2020 from 16 power plants ranging in size from 2.5 MW to 376.8 MW [13]. Indonesia started geothermal development in 1918 with the first power plant built in 1983 delivering 30 MW and has moved today to be the second largest geothermal power producer in the world [26]. Most of the geothermal plants are water-dominated, but there are a few that use vapor [27].The largest power plant with a 376.8 MW capacity was developed by Chevron Geothermal Salak, Ltd [28] in 1994 [29]. It is owned by Pertamina Geothermal Energy (PG), located in West Java [13], and consists of three 60 MW turbines and three 65.6 MW turbines [28].

A low potential estimate of 23.8 GW of total geothermal energy with only 3.1 GW of proven potential is found to be located mostly in Sumatra and Java [13] and spread across 357 possible locations [26]. This is the largest geothermal potential globally [1] consisting of 40% of the worldwide availability [28]. Some estimates find the potential to reach as high as 29.5 GW [2] with only about 7% being used so far [1]. The largest potential location in Sumatra Utara could produce up to 970 MW and the second largest in West Java could provide 790 MW [9].

The government has set a target of producing 7.2 GW of geothermal energy by 2025 [1] which will propel Indonesia into the position as the largest geothermal energy producer in the world [26]. To reach these goals, the government has declassified geothermal as a mining operation in 2014 [27] and provided tax incentives and financing to help with risk mitigation of exploration in 2019 [1, 3]. Allowances have also been made for geothermal development in areas of the forest that have protected or conservation status.

Biomass

Indonesia produced 146.7 million tons (1.996 billion GJ) of biomass in 2019 and supplied a 1.7 GW electricity capacity [1]. The fuels used include palm oil at 33%, municipal solid waste at 32%, and agricultural waste at 24% [30]. From palm oil plants, the shells, fiber, and empty fruit bunches are possible resources [1]. Fuelwood was used by 40% of households in 2017 for cooking [8]. The resulting indoor air pollution has contributed to an estimated 165,000 yearly premature deaths.

There are several 30 MW biomass power plants in Indonesia with the first one being built in 2010 in North Sumatera managed by Growth Sumatera Industry [30]. Four more were built in 2013 all of which use firing technology. Other technologies in use and planned are gasification, sanitary landfill, and refuse-derived fuel. There are also 17 thermal power plants that use cofiring with coal and biomass [31]. Twelve of the current cofiring plants are located on Java, and 114 power plants total have been tested for cofiring.

It has been estimated that Indonesia could supply a potential 32.6 GW from biomass [1, 6], sourcing mostly from palm oil at 39% followed by rice husk at 30% [30]. This is made possible in part by the fertile volcanic ash soil and rivers numbering in the thousands that provide farming suitable areas on 12% of Indonesia [11]. More of the potential biomass might be used if there was more awareness about its use and funding was available for modern cook stoves [8]. Plant waste resources are subject to seasonality, and high transportation costs as well as competing with soil replenishment needs that curb the amount that may practically be used.

The government had 2019 plans for three new waste-to-energy plants [1]. The largest biomass plant at 35 MW is planned for 2022 in Jakarta utilizing municipal solid waste [30]. There is also legislation being drafted for mandating cofiring of biomass in coal power plants as an intermediary step toward eliminating coal in the future [32]. Cofiring in 52 of the largest coal power plants is estimated to reduce yearly coal use by 9 million tonnes (252 million GJ).

Biofuels

Indonesia had a yearly capacity of 13 million kL (420 million GJ) of biodiesel in 2020 and 40 thousand kL (844 thousand GJ) of bioethanol [13]. Production of biodiesel in 2020 was 8.59 million kL (280 million GJ), of which 8.4 million kL (274 GJ) was consumed and 36 thousand kL (1.17 million GJ) was exported [13] mostly to Spain [33]. The supply of biogas was 27.9 million m3 (614 thousand GJ) [13]. In 2019, 12.7 million households cooked using biofuels [1]. Indonesia produces the most palm oil in the world [1] at 55% in 2020 [2]. Palm oil is Indonesia's second largest export taking an 8.76% share [1]. Palm oil is mostly utilized in biodiesel, and the mill effluent waste from the processing can be used for biogas.

In 2012, the largest biodiesel plant was built for jet fuel [34] by Wilmar Nabati Indonesia [33]. It has a yearly capacity of over 1.7 million kL (55.4 million GJ) on the island of Java. The largest bioethanol plant is also located on Java with a yearly capacity of 30 kL (633 GJ) [33]. It was developed in 2013 [35] by Energi Agro Nusantara [33].

IRENA estimates that almost one quarter of RE supplied in Indonesia could be in the form of liquid biofuels used for transportation with yearly consumption in 2030 reaching 25 billion L [8]. The EU reduced its biofuel use as concerns about deforestation, pollution, and indigenous people pressures arose which in turn led Indonesia to increase its domestic biofuel use by mandate and subsidies [1]. Twenty percent biofuel was required for biodiesel in 2018 and 30% in 2020. Testing has been planned for increasing to 40% [1] with palm oil being the main source [2]. While a study on the energy return on investment of biodiesel found the ratio of energy used to energy output to be positive, it was very low and labeled as not developmentally feasible due to land use and restoration issues not included in the calculation [36]. This suggests that advancements in biodiesel production will need to be made if the country continues the trend of increasing biofuel use.

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

Indonesia has been storing fossil fuels whenever production outpaces demand, but energy storage suitable for RE has little traction. While energy storage consideration is advised, it must be weighed against the costs [1]. Solar without storage is encouraged for electricity reliability along with solar and storage. There are some mini solar-storage pilots being researched for remote areas. One currently operational project is a smart microgrid in Sumba that setup battery storage of 400 kW in 2012 that can supply power for 1.25 hours [37]. Of the batteries currently in Indonesia, most are used for combustion vehicles [28]. There is a market for two- and three-wheeled electric vehicles, and exploration for more electric vehicles including for public transportation indicate more batteries will be used in the future.

Country's Future Storage Direction

Pertamina is looking into RE produced green hydrogen and fossil fuel with carbon capture produced blue hydrogen to help reach clean energy targets for 2026 [38]. There has been some study on the possibility of deposits of scandium (Sc) used for solid oxide fuel cells and other rare earth metals in Sulawesi that could be used for domestic production [39]. On the carbon capture side, there are no specific goals, but there is an estimated 0.9 Gigatonnes of storage capacity for CO2 using depleted reservoirs from oil and natural gas extraction [28]. As part of the Sustainable Infrastructure Assistance Programs, carbon capture and storage technologies are in pilot testing with natural gas production [1].

PLN owns a pumped hydro energy storage project built by companies from South Korea, Italy, and Indonesia [28] and commissioned in 2018 [37]. It is projected to provide 1040 MW to increase peak capacity in Upper Cisokan in Java [28]. There are a few other projects being investigated for pumped hydro energy storage in Sumatra and Java. A study by researchers at the Australian Indonesian Centre identified 657 sites on Bali alone that could potential house pumped hydro energy storage in the range of 1 GWh to 100 GWh per site [40]. The combined potential of all sites reaches 2400 GWh with most sites being located off-river. It is projected that a few dozen sites providing below 1000 GWh could meet the needs of a 100% RE electrical grid in Indonesia. This would require less water than water is needed in fossil fuel electricity production and could be spaced across the archipelago at some of the many highly prospective locations found throughout the country.

Carbon Footprint

Most Recent Carbon Output

Carbon emissions reached 617.51 million tonnes of CO2 (Mt CO2) per year in 2019 [41].

Historical Trends of Carbon Footprint

Globally, Indonesia ranks 10th in most GHG emissions and 19th largest in per capita CO2 emissions [1]. Figure 5 shows that after 1970, Indonesia's CO2 emissions began to greatly increase reaching 617.51 million tonnes of CO2 (Mt CO2) per year in 2019 [41]. CO2 emissions increased by 20% in the 5 years from 2013 to 2018 [10]. Annual emissions are expected to raise as high as 1253 Mt CO2 by 2030 [8]. IRENA calculated that taking measures to reduce this could prevent 150 Mt CO2 emissions yearly by that time.

Types and Main Sources of Pollutants

By far the most GHG emissions in Indonesia come from changes in land use and forestry [1, 42]. Most methane and N2O is emitted by agriculture, and a significant portion of methane is also emitted by waste. Energy systems accounted for 38.8% of GHG in 2017 [1]. Electricity, closely followed by, and transportation are the sectors emitting the greatest CO2 with coal producing 85% of the CO2 emissions from electricity [10]. Several coal plants in Indonesia emit more CO2 per kWh than any coal plants in Malaysia or the Philippines, which highlights inferior technology use as a contributor to high emission levels [43]. Oil contributed 19.8% of all Indonesia emissions and 46% of emissions coming from fossil fuels in 2017 mostly due to transportation [2]. Indonesia is responsible for 2% of emissions coming from oil globally.

A life cycle assessment on palm oil biodiesel found that the plantation portion of the process has the biggest impact on the carbon footprint as well as the environment, ecosystems, and human health [44]. GHG emissions come from fossil fuels used on the plantations, draining peatlands, and changing the carbon levels in the soil and plants by using urea fertilizer and replacing native vegetation with other biomass. This includes production of N2O which is more damaging than CO2.

There are inequalities of GHG emissions throughout Indonesia [45]. A study found a link at the household level between per capita expenditures and emission inequality. The trends show that inequality rises once expenditures increase pass middle-income levels. This is supported by transportation being the largest contributor to the emission inequality suggesting that vehicle use from middle- and higher-income earners affects emissions more than other household activities and other income levels.

Some carbon emitted through human activity does not get tabulated in atmospheric emissions. Thirty percent of the rainforest which had covered half of Indonesia has been cut down to make way for human use [11]. The disturbances from deforestation of the peatlands causes carbon to not only be released into the air but into the water as well [46]. The carbon in the water has been called the invisible carbon footprint which makes its way into the coastal areas. These areas in Indonesia have become a carbon sink damaging marine ecosystems.

Air Quality

Out of 98 countries ranked in 2019, Indonesia came in as the sixth highest in air pollution with an average level of particle matter five times the recommended exposure amount from the World Health Organization (WHO) [47]. An example of

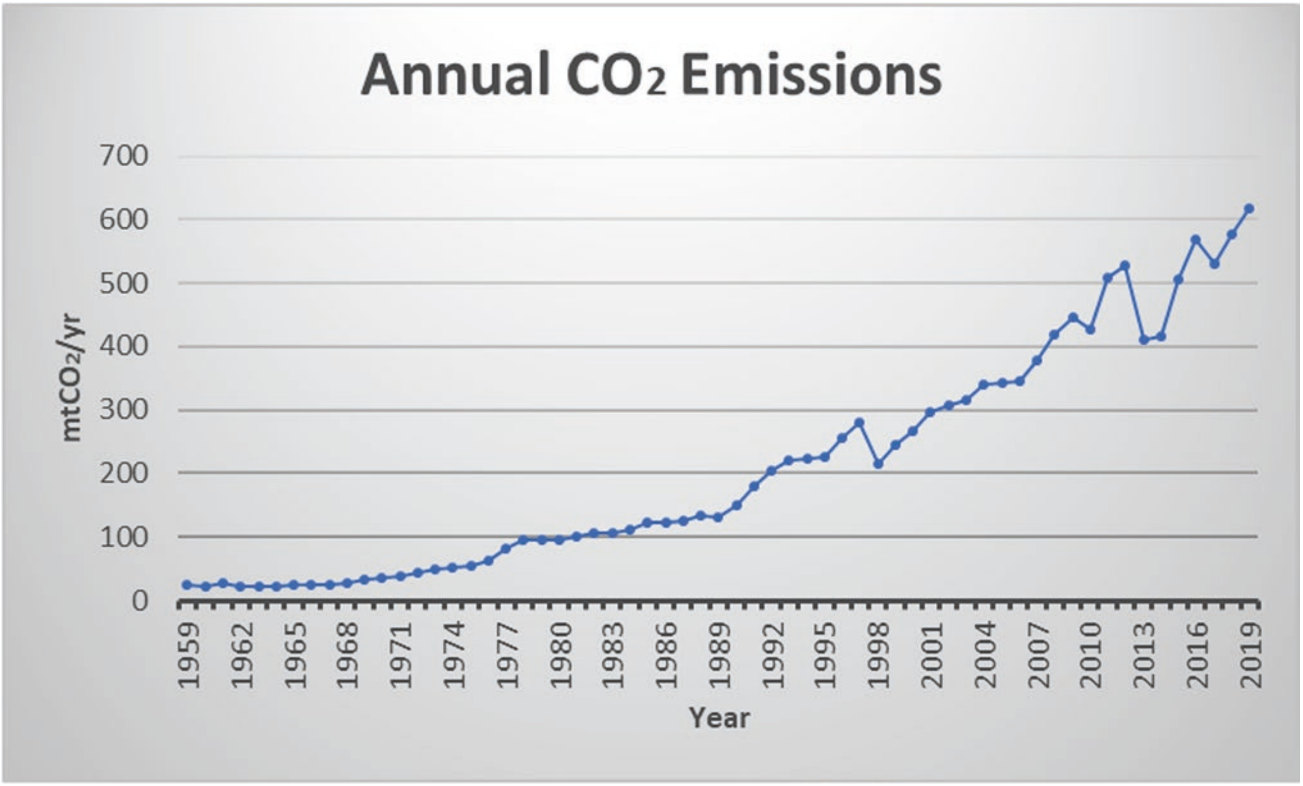

Fig. 5 Annual CO2 emissions in Indonesia from 1959 to 2019 in million tonnes CO2 per year. (Data from: [41])

the severity of air pollution is South Tangerang where for 10 months the air quality was classified as unhealthy and still unhealthy for those sensitive to air pollution during the remaining 2 months. Poor air quality has been correlated with increased respiratory symptoms in children in rural villages since 2004 [48] with 10 million children in danger of pollution associated health problems in 2019 [47]. Air quality is getting worse due to increased human emissions and especially extended dry conditions exacerbated by global warming leading to increased fire rates.

Forest and peatland fires are the main cause of air pollution in Indonesia. These occur naturally as well as by plantations clearing land for their own use [47]. An extreme example is the 5000 fires in October of 2015 that emitted 80 Mt CO2 in a single day. Fires regularly create a prolonged haze in Indonesia that is reliant on monsoon cycles and the Madden-Julian Oscillation and associated rains to clear out the contaminates in the air [49]. Due to the intense adverse effects of these conditions, the government should support cleaner air by restricting burning practices for plantations and helping cultivate sustainable farming [47].

Emissions from fossil fuel plants, industry, and transportation have a negative impact on the air quality in Indonesia [47]. A test to this was during the COVID-19 lockdown when many human activities lowered or ceased for an extended period of time [50]. CO2 emissions declined by 39.9% during this time, and there were also reductions seen in NO2 and SO2. The one pollutant to increase was PM 10 (particle matter less than 10 micrometers) which was attributed to a monsoon. These results suggest that the government could have a strong influence on lowering GHG emissions, but the specific means will need to be wisely and quickly decided to be the most effective.

Energy Resiliency

Electrical Grid

Electricity sales to the public began in 1897 in a Dutch colony and grew locally around larger towns [51]. Generation was locally owned, and hydropower was largely harnessed leading into a government stake in energy supply in 1917. In the 1920s, the government focused on two grid networks in Java. As demand and supply grew, new grids were created, and old ones were extended through various participants. Today the main grid is monopolized by PLN, but there are microgrids throughout Indonesia's archipelago harnessing solar, micro hydro, and diesel energy sources [1]. There are eight major networks and 600 separate grids across the islands of Indonesia, adding to 59,000 circuit kilometers (ckm) of transmission and 980,000 ckm of distribution lines that PLN is responsible for. The government has set a target within 5 years for adding another 19,069 km of transmission lines to aid in reaching 100% electrification. In 2019, Indonesia was at 98.86% electrification nationwide but less than half of the regions were more than 99%. The lower rated areas are more remote and so, more expensive to provide electricity for prompting increased interest in smaller private energy companies to help fill the gap. Large power plants and main grid connections are not feasible in these areas on smaller islands [11]. Notably, the 100% electrification goal lacks specificity on reliability [1]. To reach future demand and supply continual electricity across all of Indonesia, the infrastructure will need further developments.

PLN has budgeted for $14 billion in construction and $3 billion for upgrades by 2024 [1]. The private sector is expected to contribute to off-grid transmission lines. In Sumatra, a $600 million program is focused on grid reconstruction and new installations including improvements using distribution transformers, RE integration, and smart grids. The goal for this project is to improve PLN staff capabilities, increase customer satisfaction, and prepare for increased capacity. A similar program in Sulawesi and Nusa Tenggara having gained a $600 million loan from ADB, is seeking the same outcomes.

Indonesia is subject to frequent earthquake [14] and lightening caused blackouts [11]. Lightening causes 28–90% of the outages depending on the system with the smallest kV area being affected the most. Other causes for grid vulnerability include plant life, failure of equipment, and demand outpacing supply. There is also concern for coal shortages if exports continue to be highly favored of domestic use [3]. Official numbers report 0.5 monthly outages for 5.7 hours on average across Indonesia, but reliability can vary across different areas [11]. For example, the urban regions in Bali and Java are fairly reliable while blackouts can occur daily in more rural locations. A 2017 survey sent to three different cities asked about grid reliability and got responses from 68% of customers. A monthly range of 3–10 blackouts lasting 1–2 hours was reported varying by city and unstable voltages discovered by sudden dimming occurred for 18–50% of respondents. It was also noted that higher prices for less outages were supported by more than half of customers as untimely blackouts can be costly to their daily activities. A short fifteen-day report on the electricity supplied to the areas in the survey showed instances of blackouts and voltages dipping below the acceptable minimum.

Climate and Natural Disasters

Indonesia is centered around the convergence of the Eurasia, Pacific, and Australia tectonic plates and the Pacific Ring of Fire [11]. There are 76 active volcanos in the archipelago. Indonesia is ranked number one for number of earthquakes. Other natural disasters plaguing Indonesia include whirlwinds, typhoons, tsunamis, floods, landslides, droughts, and forest fires. In 2015 and 2016, 93% of natural disasters came from floods, whirlwinds, and landslides each with over a thousand occurrences and January and February had the highest occurrence of disasters [52]. A news report from January in 2021 stated 185 natural disasters in the first 3 weeks of the year compared to 297 disasters in the full month of January in 2020 [53]; 166 people died in those few 2021 weeks whereas only 91 had died the previous year in January. This included a 6.2 earthquake that killed at least 90 people in West Sulawesi, and a volcanic eruption in Java that spewed ash clouds as far as 4.5 km. All of the disasters combined in 2021's first weeks displaced 1.3 million people. The total number of disasters reported from 2020 was 2291. While these types of frequent disasters come with the geography, recent years have seen more frequent and severe cases. The government is citing increased rain as the perpetrator, but much of the increases can be attributed to deforestation and climate change. Ravaged peatlands can no longer absorb as much rainwater and deforested hills are great risks for landslides.

Weather patterns are already changing due to global warming and continuing to emit GHGs is aggravating the weather problems as well as ground issues [1]. Extracting fossil fuels and water for power generation and cooling damages the ground and jeopardizes water supplies subject to strengthening dry seasons. As the fifth largest population in lowland coastal areas, sea level rise is a significant concern for Indonesia. As efforts are made to move toward RE power generation, changes from climate change will need to be considered in future projections. Cloud cover changes and warming ground will affect PV output, although the overall implications are expected to be small [54]. Biomass feedstock output can also be negatively impacted by higher temperatures and damaged soil [1]. Indonesia's largest RE electricity source, hydropower, can be significantly hindered by changing rainfall patterns and river flow, putting higher risks on long-term projects.

The deadliest recent natural disaster in Indonesia (second in the world) was the Aceh under ocean 9.1 earthquake and tsunami of 2004 where 166,671 people lost their lives and 450,000 people were affected (more in other countries) [52, 55]. Figure 6 shows the aftermath of 100 ft (30.5 m) waves traveling 500 mph (805 km/h) devasted Indonesia. Power plants, capacity, and transmission in the Aceh area only received light damage, but the above-ground power distribution did not fare as well with most being knocked out by the tsunami [56, 57]; 170,000 people lost power for 3 days to 2 weeks [57]. The most damage to power plants include a 1 MW diesel power plant on the coast that was demolished and an 11 MW barge diesel power plant that landed 3 km inland but was otherwise unharmed. This example shows

Fig. 6 Aftermath of 2004 earthquake tsunami in Meulaboh, Indonesia. (Photo by Jennifer Rivera. Public domain [56])

that significant loss of life from a disaster does not necessarily indicate a larger risk to the energy industry.

Another recent significant natural disaster is the 2010 volcanic eruption in Yogyakarta that killed 277 people [52] (see Fig. 7 [58]). A large area was evacuated, and power lines were reported to be purposefully disrupted [59]. If there was more substantial power generation, supply, and distribution in the area, the lava flows could have severely damaged the grid's ability to supply electricity. Most volcanic risk is currently located in remote areas with minimal electrical infrastructure, but the risks are an important consideration for future energy expansions.

Grid Resiliency

Resiliency includes how well the system can recover from high impact events such as natural disasters and adapting by performing preventive measures after learning from such events [60]. Indonesia has had ample opportunities to learn from natural disasters and has made progress. PLN and other providers have plans for various situations. However, the current highest target for Indonesia is electrification followed by reliability and then resiliency, although solutions for each goal can help the others. For example, modular and smaller systems designed for remote locations using differing power sources and energy storage can increase reliability and resiliency in some instances by diversifying, increasing flexibility and modularity, and offering safer failures.

Indonesia can also look to other countries for lessons on resilience as a connection was reported between the recent Texas, US prolonged blackouts from extreme cold [61]. Texas was heavily reliant on "centralized thermal power generation" and could have benefitted from diversification and interconnections with the grid in other parts of the country [61]. Indonesia's mix has even greater risks with coal's heavy share as seen when the severe flooding at the beginning of 2021 cut off 80% of the coal supply to Java, causing a rolling blackout warning to be sent out as reserves dwindled to as low as 6 days' worth. Indonesia has made efforts to increase diversification but has gone in the other direction by increasing coal and natural gas use. As areas with excess capacity or demand grow, more interconnectivities may be considered which could also take advantage of RE source locations with high potential and low demand.

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

Indonesia's only net imports are for oil and oil products totaling 250,960 thousand boe (1.43 billion GJ) including LPG in 2020 and a minimal 1.6 TWh of electricity from Malaysia compared to the hundreds of TWh consumed [13]. Several measures have been taken to decrease the country's reliance on oil in order to reduce energy imports. In 2018, nearby Singapore and Malaysia supplied 70% of

Fig. 7 "A village covered in ash near Mt Merapi" by Jeong Park is licensed under CC BY-ND 2.0 [58]

Indonesia's oil imports with the rest coming mostly from members of the Organization of the Petroleum Exporting Countries (OPEC) [2].

Indonesia exported 124,214 thousand boe (709 million GJ) of natural gas and LNG and 232 thousand boe (1.32 million GJ) of biofuel [2]. Coal was also a net export accounting for the largest energy export of 1,664,445 thousand boe (9.50 billion GJ). This left Indonesia as a net energy exporter in 2020 as it has been for many years. With the large amount of energy exports, Indonesia has become reliant on them as an income and will continue to be barring substantial changes.

Relations with Global Community/ Socioeconomic Influence

It is projected that the relationship with low-cost labor in Indonesia with global companies will change since the onset of COVID-19 based on technological shifts and Indonesia's needs for energy financing [1]. Indonesia has received help from several countries to address their energy growth such as Australia, Japan, Russia, France, and Canada. As a member of the United Nations (UN) since 1950, Indonesia's government has partnered with other UN members to reach goals for democracy and extreme poverty eradication [62]. Indonesia is currently on the UN Security Council and Human Rights Council. Another active role for Indonesia is participating as the largest country in the Member of Association of South East Asian Nations (ASEAN) [62] that was formed in 1967 to bolster a stand against communism and support common interests amid tensions [63]. They work together and with other countries to address shared concerns peacefully including the current dispute with China over South China Sea usage. Indonesia is a democratic republic, but they partner with several different types of governments from different countries to solve varying issues.

In 2016, Indonesia adopted the Paris Agreement and committed to a 29% reduction in business-as-usual GHG emissions by 2030 [2]. With international assistance, the reduction will increase to 41% [1]. To reach this goal, Indonesia plans to increase RE's electricity mix share to 23% by 2025 [3] and eventually to 28% [1]. Some setbacks to these aims include COVID-19 delays [3], shortage of components for RE, and financing struggles [4]. Oil reduction is also planned to 20% by 2050, but this will include increasing natural gas and coal use along with RE [2]. China, Japan, and South Korean companies have supported the increase in coal use. But the monopoly on energy in Indonesia can offer a vehicle for the government to favor reforms toward renewables instead.

A remapping study by IRENA found that increasing RE use in Indonesia could bring down the energy system's overall cost [8]. The current RE goals are low since they were based on a high forecast of economic growth that was also stunted by COVID-19. Reaching the higher RE concentration suggested by IRENA is feasible but would require significant changes. However, it would include benefits such as reducing reliance on oil imports, increasing grid resilience by diversifying energy supply, and improve their endeavors along with the rest of the world to reduce the maximum effects from climate change. It was also estimated that when including costs associated with health issues and premature deaths along with a carbon price, Indonesia could save up to $15.7 billion annually by increasing its RE utilization.

Education

A critical component of increasing RE in Indonesia is expanding awareness and education on RE topics. Since the household energy use typically falls under the responsibility of the women in the home, providing them knowledge on effective use of energy resources could be a step toward sustainable practices through organizers of change [1]. It is predicted that women with sustainable practical knowledge entering the workforce will result in better health of Indonesia's environment and human experience. An example of small group efforts to affect change is the nonprofit, Synergi, that trains teachers and provides equipment for them to educate students on large and small RE solutions [64]. There have also been successful pushes toward introducing RE curriculum in vocational high schools that has led to 12 of them currently being based on RE [65]. A survey of students across 88 vocational schools in Indonesia found students had a good knowledge of RE concepts especially related to generation technologies on their island, but they lacked in awareness about the issues surrounding RE. Further education on RE can be found in several programs and projects throughout Indonesian universities.

Summary

Current Energy Situation

Indonesia primarily uses fossil fuels for energy and electricity generation. Steps have been taken to lower reliance on the only large energy import of oil by increasing domestic coal and natural gas used for power generation along with a modest increase in RE. As the world's largest producer of palm oil, Indonesia had also reduced oil use by increasing biofuels used in biodiesel as a mandated percentage. Indonesia is a significant exporter of coal, and favorable international trading conditions have jeopardized sufficient domestic supply. Indonesia has tapped into hydropower and geothermal resources as well as a modest amount of wind and solar which have helped bring electricity to most island areas.

Future Energy Situation

As a member of the UN and adopter of the Paris Agreement, Indonesia has committed to reducing GHG emissions by increasing energy efficiency and RE use. There are several RE projects being explored and completed to reach these goals such as a large floating PV plant and a bridge tidal plant. The great potential for RE use in Indonesia in order of greatest possible power supplied comprises of solar, hydropower, wind, biomass, geothermal, and ocean energy. A significant portion of RE utilization in Indonesia may also come from biofuels used for transportation. Solar thermal could provide a substantial source of energy for building water heating and industrial processes. Indonesia has been investigating the use of nuclear power and energy storage such as batteries and an abundant capacity for pumped hydro energy storage. All of these possibilities aside, Indonesia has made plans to increase coal and natural gas use as significant percentages of its energy mix.

The energy sector is highly influenced by government regulations with a dominant national energy provider, PLN, and smaller independent companies throughout the archipelago. This system could lead to substantial increases in RE and decreases in GHG above current goals if properly managed. Bolder action is needed to make significant improvements in carbon emission reduction and air quality such as policies and solutions directed toward forest and peatland fires. Attention should also be given beyond electrification and reliability, toward resilience. Indonesia is prone to a substantial number of natural disasters that disrupt energy processes, and they are expected to increase in severity. Reducing GHG emissions will put Indonesia in a position of not contributing to a main driver in the many risks it will face in the future due to climate change.

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Japan

Slobodan Petrovic and Nathan Margoshes

National Energy Introduction

Energy Policies

Japan is an island country located in the northwest Pacific Ocean. Japan's key energy policies are included in the Strategic Energy Plan for 2030, which is a comprehensive plan to reduce nuclear dependency, fossil fuel dependency, and increase the usage of renewables. The key principle behind this plan is the 3E+S (energy security, economic efficiency, environmental protection, and safety) principle. This includes maintaining their existing policies of "promoting comprehensive energy savings, increasing renewable energy, maximizing the efficiency of thermal power generation and reducing dependency on nuclear power to the extent possible…" [1].

Trends in Generation Technologies

Since 2011, Japan has seen a slow but steady increase in renewable energy generation. In the years immediately following the Tohoku earthquake, there was a steady rise in fossil fuel consumption, as it was necessary to make up for what was lost in nuclear generation. However, since the implementation of the Strategic Energy Plan for 2030, which was established in 2014, there has been a consistent decline in fossil fuel usage [2].

Domestic Resources

Japan is a country with very little natural fuel resources, so the majority of their fossil fuels must be imported [2].

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History of Energy

The only time in history that another nation had control over Japan was the Allied occupation of Japan following World War II. The occupation began in 1945 and lasted until 1952 when the San Francisco Peace Treaty took effect. During this time, Japan underwent military, political, economic, and social reforms [3].

Breakdown of Energy Generation "Mix"

Energy Generation Mix

Japan as a nation relies heavily on fossil fuels. Thirty percent of their electricity generation comes from coal, 33% from natural gas, 5% from oil, 7% from nuclear, 8% from hydro, and 15% from other renewables [2, 4] (Fig. 1).

Energy Consumption Mix

With energy consumption, transportation makes up the majority of the energy consumed with 40% coming from petroleum, 21% from natural gas, 26% from coal, 4% from hydro, 3% from nuclear, and 6% from other renewables [2] (Fig. 2).

Fossil Fuels

Oil

As mentioned, Japan has a large reliance on fossil fuels, while also being a country with very little natural resources. For oil, Japan is the fifth largest oil consumer in the world. They used an estimated 3.5 million barrels/day in 2019 [2]. This was mostly for transportation. Because Japan does not have significant natural resources, they are not a large oil

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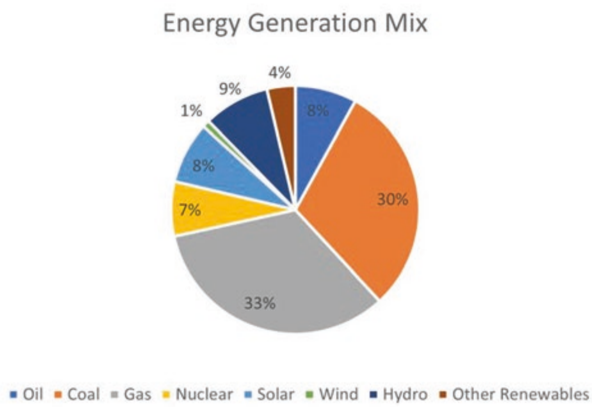

Fig. 1 The energy generation mix of Japan [2]

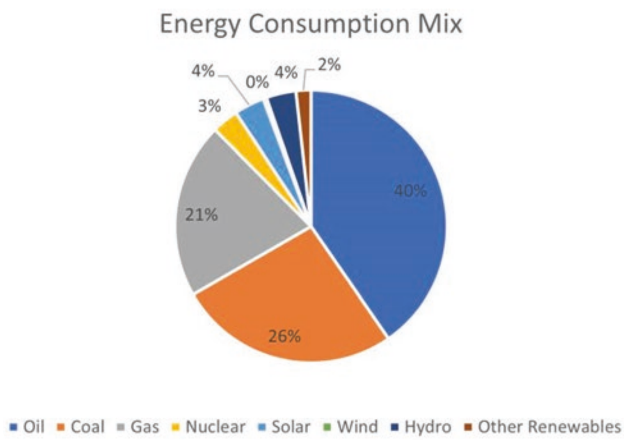

Fig. 2 The energy consumption mix of Japan [2]

producer. In 2017, Japan produced 3200 bbl/day, exported 0 bbl/day, and imported 3.208 million bbl/day [5]. Japan receives most of their oil imports from the Middle East. In 2019 36% came from Saudi Arabia, 29% from the United Arab Emirates, 9% from Qatar, 8% from Kuwait, 5% from Russia, 2% from the United States, 2% from Oman, and 9% from other countries [2]. As of 2020, Japan has 44 million barrels of proven oil reserves [5].

Coal

Japan is a large coal consumer, as coal is still one of the top fuels for electricity generation. Japan has around 48,000 MW of coal powered generation capacity, which produced 273,970 GWh in 2020 [6, 7]. In 2019, Japan consumed 200 million short tons (MMst). Sixty percent of the coal consumed was for power generation, the rest was for the steel and iron industry [2]. Due to Japan's lack of natural resources, they do not produce any coal, and everything must be imported. In 2019, Japan imported 202 million short tons of coal. Sixty percent of their coal comes from Australia, 15% from Indonesia, 11% from Russia, and 14% from others [2]. Japan does not have any notable coal reserves.

Natural Gas

Japan is one of the largest natural gas consumers in the world, reaching number one in 2019. In 2019, they consumed 3.6 trillion cubic feet of natural gas. The majority of this was for power generation, where 308,900 GWh of electricity were generated [7]. As of 2017, Japan produced 3.058 billion cubic meters, imported 116.6 billion cubic meters, and exported 169.9 million cubic meters of natural gas [5]. Domestic production only made up 2% of their natural gas consumption [2]. Japan imports their natural gas from many sources. Region wise 67% comes from Asia and Oceana with the majority being from Australia, 18% from the Middle East, 9% from Russia, 5% from the United States, and 2% from others [2]. Like coal and oil, Japan lacks significant reserves of natural gas. As of 2018, they had 20.9 billion cubic meters of natural gas [5].

Nuclear Energy

In 2011, Japan was struck by the Tohoku earthquake, which resulted in the Fukushima Daiichi nuclear disaster, where the Fukushima Daiichi nuclear power plant underwent nuclear meltdowns, hydrogen explosions, and radioactive contamination. Following this, all but two of Japan's nuclear power plants were shut down. In 2014, the Japanese government enacted the Strategic Energy Plan for 2030, which aimed to reduce dependency on nuclear power and fossil fuels and increase the usage of renewable energy. The goal for nuclear is to supply around 20% of Japan's electricity needs [1]. To meet this goal, more reactors will need to be restarted, and new reactors may have to be built. In 2015, the first two nuclear reactors were brought back online after being shutdown in 2011. There are currently 39 functioning nuclear reactors with a total capacity of around 38,000 MW, which generated around 65,680 GWh of electricity [1, 7, 8]. Japan has received nuclear fuel from the United Kingdom and France [9].

Renewable Energy Generation

Photovoltaics (PV)

Japan currently has around 62,000 MW of photovoltaics installed [10]. From this 84,450 GWh of electricity were generated [7]. As of 2020, the largest plant in operation is an 82 MW PV power plant located in Oita City, Japan. The plant began operation in 2014 and was built by Hitachi [11]. Japan has an average solar potential, with an average irradiance of between 3.2 and 4.2 kWh/m^2 [12] (Fig. 3).

Japan has seen a rise in solar power in the past few years, with a consistent 10,000 MW increase in capacity per year for the past 5 years [10]. Due to the feed-in tariffs, it is likely that this trend will continue into the foreseeable future, to meet the Strategic Energy Plan of 2014 [13].

Fig. 3 The average global horizontal irradiance of Japan [12]

Wind

As of 2020, Japan has 4370 MW of operational wind power capacity, spread among 2531 facilities [14]. From this 10,620 GWh of electricity were generated [7]. Currently the largest wind farm in Japan is the Tsugaru wind farm in the Aomori Prefecture. The 122 MW facility was constructed by Pattern Energy and began operation in 2020 [15, 16]. Japan has good potential for wind energy both onshore and offshore. Onshore it is estimated that Japan has 144,000 MW of wind potential [17]. Offshore it is estimated that Japan has 128,000 MW of potential xed-bottom, and 424,000 MW of floating wind potential [18]. Currently Japan is aiming to have 10,000 MW of offshore wind power capacity by 2030 and between 30,000 and 45,000 MW by 2045 [14]. Additionally, there are 55 projects totaling 14,400 MW in the Environmental Impact Assessment (EIA) process in 2021 [14].

Hydro

As of 2020, Japan has 50,000 MW of installed hydropower [10]. From this 84,950 GWh of electricity were generated [7]. This includes both conventional hydropower and pumped storage hydropower [19]. The largest conventional hydropower facility is the Okutadami Dam in Uonuma, Japan, which is owned by J-Power [20]. Japan's conventional hydropower is considered to be fully developed. Current and future efforts are going toward small-scale hydropower and pumped hydro storage [19]. Small hydro power is being promoted as part of the Strategic Energy Plan of 2014. Small rivers and agricultural waters are the primary target for these small hydro installations [13].

Ocean

Currently Japan does not benefit from any form of ocean energy. It is estimated that Japan has a total oceanic current potential of 10,000 GWh/year, tidal current potential of 6000 GWh/year and wave power potential of 18,800 GWh/year [21]. Currently Japan's plans for ocean energy are largely theoretical. Currently the largest practical plan is a deal between the British companies Xodus and Atlantis Resources to develop a tidal facility in Japan. Additionally, Simec Atlantis Energy has been commissioned by Kyuden Mirai energy to produce a tidal demonstration project which will generate 500 kW of energy in 2021 [22].

Geothermal

As of 2019, Japan has 525 MW of installed geothermal capacity [10]. From this 2400 GWh of electricity were generated [2]. Japan is home to the largest geothermal energy plant in the world, the Hatchobaru Geothermal Power Plant, a 112 MW power plant owned by Kyushu Electric Power [23]. Japan is estimated to have around 23,000 MW of geothermal potential, which is the third largest in the world [24]. The problem behind Japan's vast geothermal potential is that most of it is located in national parks. Regulations have been changed since 2012 to allow for more of the area to be used for geothermal energy. The amount of eligible area has increased from 25% of the country to 60% of the country [24].

Biomass

As of 2019, Japan had 4400 MW of operating biomass power generating capacity [25]. From this 41,000 GWh of electricity were generated [2]. The largest biomass power plant in Japan is the 75 MW Handa Biomass Power Plant located in Handa City, Aichi Prefecture owned by Summit Energy [26]. In 2020, Japan produced 10.2 million bone-dry metric tons (BDt) of wood biomass, mostly wood chips [27]. It is expected that biomass has the potential to meet 4% of Japan's total energy mix [28].

Biofuels

In 2019, Japan consumed 791 million liters of bioethanol fuel and 15 million liters of biodiesel [29]. There is one bioethanol producing facility in Japan, a JA Zen-noh owned refinery in the Niigata prefecture. This refinery produces around 0.15 million liters of bioethanol. The refinery does not operate all year and is not self-sustaining. Biodiesel is produced at a small scale around the nation, often using used cooking oil as a base. In 2019, 23 million liters of biodiesel were produced [29].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

Japan has a significant amount of energy storage facilities. The majority of these are pumped hydro storage, with a total capacity of 26,000 MW [30]. As of 2017, Japan also had around 175 MW of batter storage installed [31].

Country's Future Storage Direction

Because Japan's conventional hydropower potential is almost fully developed, future hydropower projects will be pumped hydro facilities. Additionally, Japan is promoting the installation of batter storage around the country. Due to an already large number of rooftop solar installations, the Ministry of Economy, Trade and Industry has been encouraging residents to invest in storage systems which could work as a backup electricity network during major service interruptions like typhoons [13, 32].

Carbon Footprint

Most Recent Carbon Output

In 2019, Japan had an annual CO2 emission of 1.11 billion tonnes [33].

Historical Trends of Carbon Footprint

Japan has a peak carbon footprint in 2013 with an annual output of 1.31 billion tonnes. Since 1946, the CO2 emissions have increased steadily until 2013. Since 2013, the annual emissions have steadily decreased due to the Strategic Energy Plan of 2014 [13, 33] (Fig. 4).

Types and Main Sources of Pollutants

Based on 2016 data, industry was the largest contributor to greenhouse gases (GHG) with a 46.9% contribution, followed by transportation at 19.4%, commercial sources at 12.2%, residential at 12.2%, and energy industry at 9.3% [34]. The largest category of GHG is non-CO2 gases. These include fluorinated GHAGs, nitrous oxide, and methane. Following these are CO2 [35].

Air Quality

According to the World Health Organization, Japan's air quality is considered moderately unsafe. The average level of PM2.5 (particulate matter with a diameter less than 2.5 microns) is 12 μg/m^3 [36].

Energy Resiliency

Electrical Grid

Japan's electricity grid is split into two, the western and eastern grids. The eastern grid runs at 50 Hz, while the western grid runs at 60 Hz. This is because when the grids were being built, the builders for the eastern grid used generators from Germany, while the western builders used generators from the United States. This makes it so the grids cannot directly exchange power [37]. Japan has a total of 178,665 km of transmission lines and 4,095,978 km of overhead and underground distribution lines [38]. According to TEPCO (Tokyo Electric Power Company), Japanese households average 0.13 power outages per year [39]. Following the 2011 Tohoku earthquake, many municipalities have begun incorporating distribution energy systems to reduce the impact natural disasters have on electricity availability. These distributed energy systems reduce the reliance on the main grid [40]. Japan does not have any geographic limitation to their electricity grid.

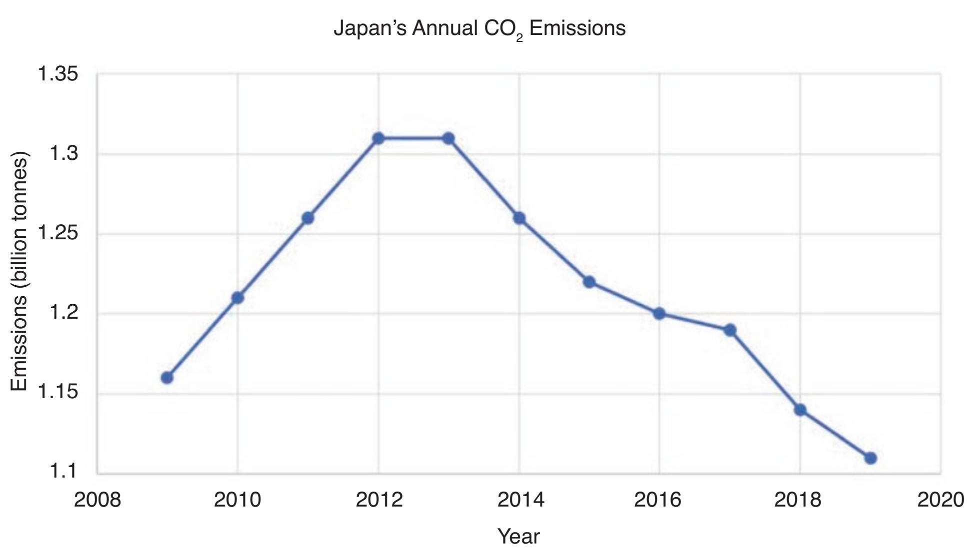

Fig. 4 Annual emissions in Japan for the past 10 years

Climate and Natural Disasters

Japan is frequented by natural disasters. Due to the geographic location, Japan is subject to disasters such as earthquakes, typhoons, tsunamis, and volcanic eruptions [41].

Grid Resiliency

Japan currently has a high reliance on fossil fuels, a large amount of industrial production, and a large amount of transportation vehicles. These are the three highest contributors to pollution [42].

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

Japan has a strong reliance on foreign resources and relationships as Japan's lack of natural resources means they must import most of their fossil fuels. Most of their oil comes from the Middle East, most of their coal comes from Australia, and most of their natural gas comes from Australia [2].

Relations with Global Community/ Socioeconomic Influence

The Paris Agreement is an international treaty established in 2015 with the intent of limiting global warming to below 1.5 °C. The primary target of Japan's Paris Agreement is to reduce emission to 26% below 2013 levels by 2030 [43]. Japan joined the United Nations in 1956 and has maintained that cooperation with the UN is a basic foreign policy principle. While Japan generally has good relationships with other countries, the primary exception is with North Korea. In 2020, North Korea turned to a more forceful foreign policy approach, specifically by deciding to no longer abstain from missile testing. These missile tests have put a strain on the Japan-North Korea relationship, as a submarine launched missile landed in Japanese territory [44]. Japan hopes that renewable energy will account for 50% of their energy supply by 2050 [45].

Education

Energy education is an important factor in a country's willingness to adopt renewable energy technology. A populace educated in the types of renewables will be in a better position to push for policy changes that benefit renewable adoption. Japan has a few schools that offer higher education in energy related fields. Kyoto University has Master's and doctorate programs in multiple energy science disciplines such as Socio-Environmental Energy Science, Fundamental Energy Science, Energy Conversion Science, and Energy Science and Technology [46]. The Tokyo Institute of Technology also offers a Master's degree in Energy Science and Engineering [47].

Summary

Current Energy Situation

Currently Japan's energy system is dominated by fossil fuels, with oil, coal, and natural gas making up over 50% of both energy generation and consumption. However, Japan has had in increasing renewable presence. Solar power in particular has seen a steady increase in the past few years.

Future Energy Situation

Being an island nation, Japan has a large offshore energy potential. Japan is aiming to have 10,000 MW of offshore wind power by 2030 and between 30,000 and 45,000 MW by 2045 [14]. Harnessing more renewable sources will require both private and government involvement, with both being key to the future.

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Lebanon

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National Energy Introduction

Energy Policies

Three renewable energy action plans have been released since 2010 [1]. The latest National Energy Efficiency Action Plan updates the initial goal of having 12% of the nation's electricity delivered by renewables by 2020 to now aiming for 30% by 2030 [1].

Lebanon's primary renewable energy generation comes from hydropower, which contributed 348 GWh in 2018 (Fig. 1), accompanied by smaller shares by photovoltaics at 68 GWh and rapidly growing, and wind at a mere 6 GWh, a yearly breakdown of which is shown in Fig. 2 [2]. The National Energy Efficiency Action Plan for Lebanon has ambitious goals to ramp up other renewables with US$1.7 billion of funding to make an energy mix of that in Fig. 3, for a total installed capacity breakdown described in Fig. 2 [1].

The International Renewable Energy Agency, or IRENA group, has further mapped Lebanon's renewable energy targets with an accelerated model called REmap (Renewable Energy Roadmap) projecting into 2030 [1]. This model asserts that Lebanon is capable of supplying 30% of its electricity demand and 10% of total energy from renewable sources by this 2030 target, with potential savings of up to US$249 million [1]. This savings would undoubtedly bolster national security by reducing the nation's debt from oil imports and increasing overall generation capacity.

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Breakdown of Energy Generation "Mix"

Energy Generation Mix (Figs. 3 and 4)

Fossil Fuels

Oil

Imported oil products account for 96% of Lebanese energy and almost a quarter of the national debt [1]. Liquid petroleum gasoline (LPG) is used to meet the needs of the transportation sector and fuel oil is used for electricity generation. Gas oil provides electricity to both the grid and private generators; it is also used for heating and as fuel for large vehicles.

Natural Gas

Liquid gas is used for cooking, and kerosene is used as airline fuel [1].

Renewable Energy Generation

Less than 4% of Lebanon's energy originates from within the country itself via hydro, solar water heaters, and PV installations [1]. Private investment into renewable generation technology is widely considered to be the best option to bolster national security by mitigating Lebanon's dependence on oil imports as well as by filling the gaps in the nation's public electric company, Electricite du Liban, or EDL's generating capacity.

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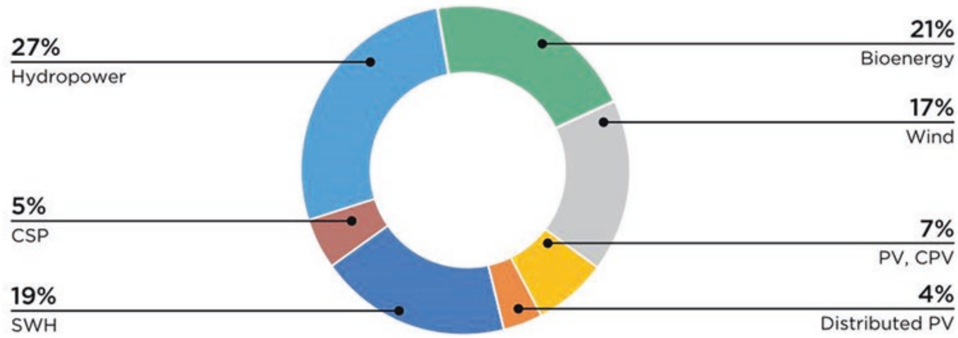

Fig. 1 NREAP 2020 target energy mix (CSP stands for concentrating solar power; SWH stands for solar water heating; CPV stands for concentrator photovoltaics; and PV stands for photovoltaics) [1]

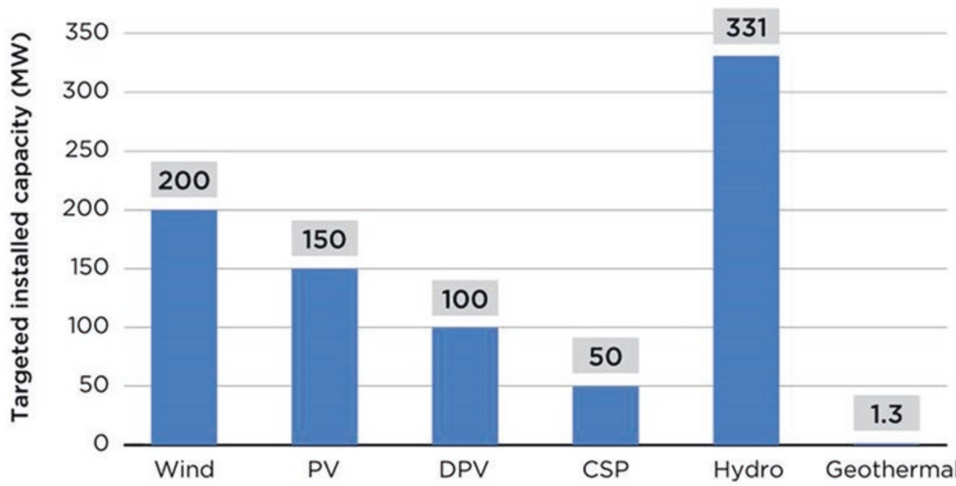

Fig. 2 NREAP 2020 target installed capacities (DPV stands for distributed photovoltaics) [1]

Photovoltaics (PV)

The solar resource potential of Lebanon is even higher, with an estimated 5558 km^2 of land deemed suitable for large-scale solar installations estimated to be capable of 182,615 MW capacity [1]. Lebanon's installed solar PV capacity amounted to a fraction of this potential in 2018, merely 56.37 MW [1]. The first large-scale PV project in Lebanon completed its first 1 MW phase in 2013 and is called the Beirut River Solar Snake project [1], shown in Fig. 5. There are to be ten total phases as the installation snakes along the Beirut River, 1 MW at a time, aiming to deliver power to 10,000 households upon completion [3]. The project is still accepting bidding offers from both local and international companies at the time of writing. Rooftop solar also has considerable potential, as much as 80% of total rooftop area in Beirut may be suitable for such installations that could supply nearly a third of the city's electricity demand [1].

Financing for Lebanon's renewable sector is obtained by either having a private investor responsible for the engineering, procurement, and construction of a project (EPC) to then be operated by the EDL or to have a private company bid on a contract in order to sell power to the EDL upon the project's completion via a power purchasing agreement (PPA) [1]. The Beirut River Solar Snake project was financed via EPC in 2013 to invite further investment into the nation's solar sector. Since the first stage of that project's completion over a hundred companies from 26 countries have bid on future Lebanese solar projects [1].

Wind

The evaluated potential wind resource in Lebanon spans 1558 km^2 of land capable of large-scale wind farms for an estimated 6223 MW capacity [1]. The first wind farms in Lebanon were erected in Akkar to deliver 200–220 MW capacity. The country is intent to capitalize on this readily available resource and is awaiting project proposals from numerous companies that have already pledged interest [1].

Hydro

Lebanon has historically had 282 MW generating capacity from the hydroelectric power plants erected between the 1930s and the 1960s [4]. Considerable focus of the nation's renewable plan is on rehabilitation of these existing plants, estimated to increase output by at least 1000 GWh annually [1]. Construction of new hydro plants as well as run of the river plants is estimated to increase generating capacity to 473 MW by 2030 [1].

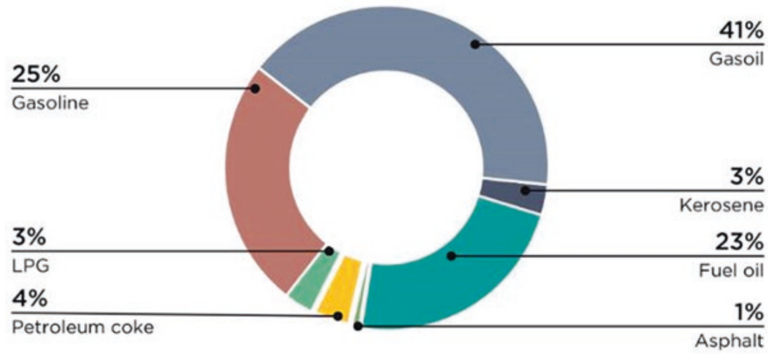

Fig. 3 Breakdown of Lebanese energy [1]

Fig. 4 Renewable electricity generation [2]

Energy Storage Technologies

Country's Future Storage Direction

One of the recommendations of the REmap study, in conjunction with goals for increased grid stability, is to potentially locate future energy storage systems adjacent to renewable energy generation systems [1]. There are many proposed projects, in various stages of funding, for large-scale PV farms with accompanying energy storage systems, though none are yet completed [1].

Carbon Footprint

Historical Trends of Carbon Footprint

Lebanon's CO_2 emissions reflect the fact that the nation is heavily reliant on oil imports for the majority of its energy demand. The breakdown of emissions by sector, shown in Fig. 6, reflects this dependence but also shows a reduction in emissions over the last few years corresponding to a decline in overall oil consumption [2].

Energy Resiliency

Electrical Grid

Lebanon's overburdened electricity grid was a common target during the Lebanese Civil War from 1975 to 1990, considered the onset of Lebanon's electricity crisis [5]. As a result of these attacks to the grid and subsequent political instability, the country's electricity demand exceeds its generating capacity by a growing margin each year—most residents only receive between 3 and 12 h of electricity a day [6]. These extended blackout periods have necessitated that private generator owners weave an intricate web of wires connecting various generators to consumers to kick in when required. Multiple generators supply power to each building, and the chaotic wire system makes it nearly

Fig. 5 Beirut River Solar Snake PV installation [3]

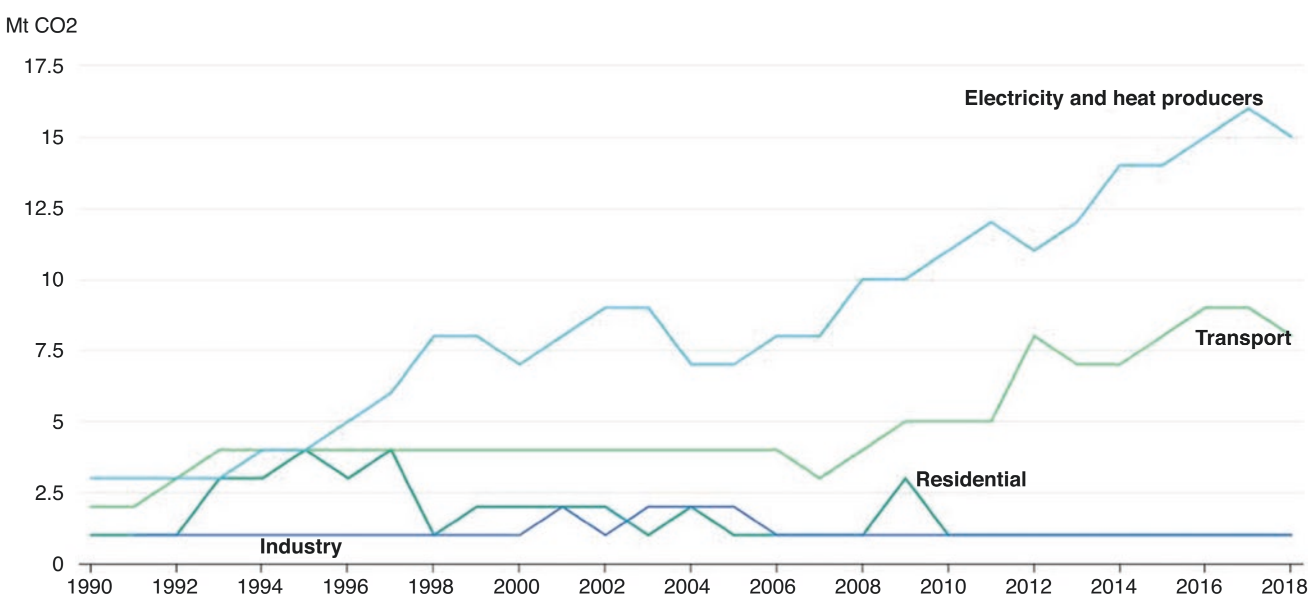

Fig. 6 CO_2 emissions by sector [2]

impossible to accurately account for individual usage—as such the generator owners set the prices as they see fit, earning them the title of the "Generator Mafia" [7]. The Lebanese people are therefore responsible for two electricity bills, one to the EDL and the second much higher one to the Generator Mafia [5].

The EDL is incapable of meeting the nation's energy demands not only due to the aftermath of the Lebanese Civil War, but as a result of years of governmental mismanagement and corruption. As mandated in 1964, the EDL is solely responsible for electricity generation, transmission, and distribution in Lebanon, save for the few hydroelectric power plants (public and private) [5]. Efforts to rehabilitate the electricity grid following the war have been wholly insufficient; attempts such as the Power Sector Master Plan seemed ambitious. However the Lebanese government failed to prioritize these infrastructure improvements, in part due to a failure of any one party to accept accountability [5], and therefore inefficient generating capacity as well as substantial grid losses continue to plague the nation.

The economic hardships facing Lebanon are inextricably linked to the country's inability to provide constant electricity to its residents. Years of protesting in Beirut and the worsening economic crisis in Lebanon seem to have finally brought the electricity grid's state of disrepair to the forefront of the Lebanese government's concerns. Lebanon's government is presently hoping to receive a US$10 billion loan from the International Monetary Fund, contingent upon comprehensive electricity reform [8]. Many similar agencies have pledged to assist Lebanon under the condition that political, economic, and infrastructure reforms are adequately prioritized [8].

The 2019 Electricity Plan, ratified last April to this end, is intent upon a fourfold reform of the EDL. First, the plan aims to reduce grid losses by improving the distribution grid infrastructure and by installing meters to accurately measure consumption [9]. The plan also intends to increase generation capacity through the construction of additional power plants in the long term while meeting the immediate demands via additional power barges, financing the two in tandem with a PPA [8]. Additionally, the plan hopes to reduce production costs by converting to natural gas rather than liquid fuel using three Floating Storage Regasification Units connected to the shore via underwater pipeline to be constructed (est. 2022) [8]. The final aspect of this plan is to eventually increase tariffs to 14.4 ¢/kWh once 24/7 access to electricity is maintained to begin to tackle the EDL's US$2 billion operating deficit [8].

The promises of the 2019 Electricity Plan must be tempered by the Lebanese government's history of attempted regulatory action without adequate enforcement or accountability. The existence of private generator operators has been illegal since the 1960s, yet the government considers their service essential, though unregulated and as such has not prioritized enforcing this law [9]. Despite numerous years of legislation without follow through, in 2018 the Ministry of Economy and Trade mandated that all private generator consumption be accurately metered to allow for accurate billing based on consumption rather than according to hours of blackout [9]. Seemingly breaking the cycle of empty promises, the MOET mandate has been enforced via numerous inspections, fines for noncompliance, confiscation of unregulated generators and arrests and boasts that 60% of all consumers in Lebanon are now billed according to meters and pay almost half the prices previously charged [9] (Fig. 7).

Climate and Natural Disasters

On August 4, 2020, an industrial building in the Port of Beirut, storing 2750 tonnes of contaminated ammonium nitrate as agricultural fertilizer, was ignited by an earlier explosion of 23 tonnes of fireworks [10], the cause of which has yet to be determined. The death toll is over 200 with at least 6500 injured [10]. Damages to the city are estimated at

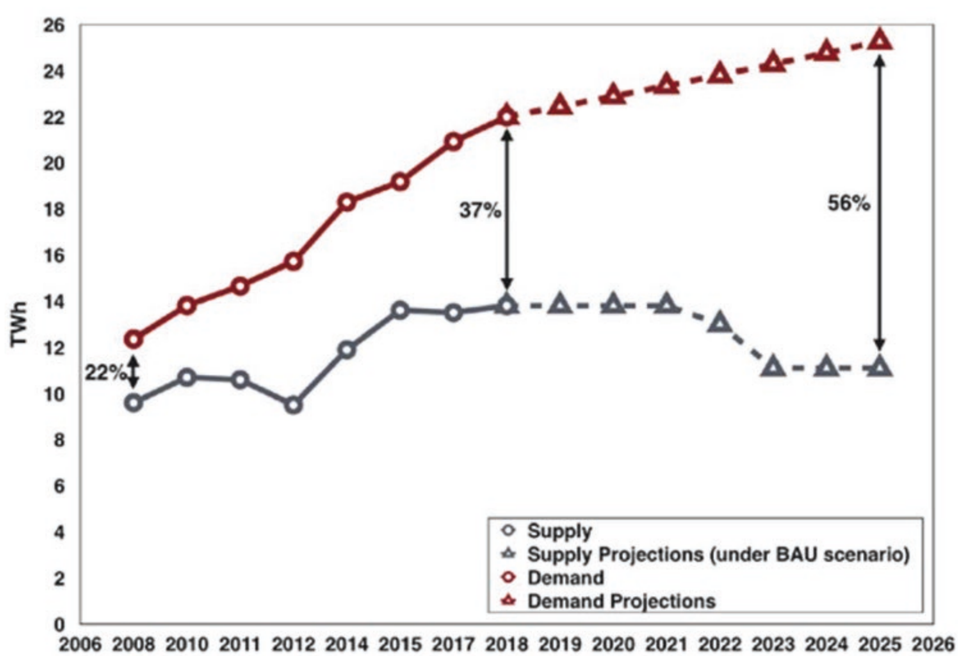

Fig. 7 Electricity supply versus demand, historical and projected [9]

15 billion dollars, and losses from the grain silos adjacent to the warehouse and disruptions to port operations impacted food supply to the city [11]. An estimated 300,000 people were rendered homeless by the resulting destruction [11]. In the days that followed, protestors in Beirut have called for the corrupt politicians responsible for the deadly oversight to step down and Prime Minister Hassan Diam has called for early elections in response [12].

Future Energy Situation

Resource potential and financial investments have enabled Lebanon's renewable energy sector to slowly grow under only temporary legislation and legal loopholes. The Electricity Regulatory Authority was established in 2002 to allow such private investments; however, additional and conflicting laws have since negated the ERA and prevented a clear definition of the role of renewables in Lebanon's energy future [1]. The target of 30% renewables by 2030 has been quoted as planned since 2018 [1], but the legal framework to meet those goals does not exist to facilitate it. The Lebanese government has pledged for years to reform the EDL and to rebuild the nation's grid infrastructure, with very little follow-through or accountability. The renewable energy goals of the nation are vulnerable to these same tendencies if politics as usual prevails.

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Nepal

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National Energy Introduction

Energy Policies

One of Nepal's most important energy policies is for the maximum utilization of hydroelectric power generation [1]. With the rising concerns of climate change, and the preexisting large renewable energy potential found within its borders, increase of renewable energy systems for energy generation is paramount for this small nation.

To help grow the energy and electricity sectors of the nation, Nepal is planning on expanding their energy portfolio to increase usage by both commercial and industrial sectors; Nepal is additionally planning to make the electrical grid accessible to all residents by 2022 [2]. This would expand energy consumption to a larger demographic than primarily the residential sector. Logic would lead to the assumption that if this were to occur, Nepal would be able to improve their infrastructure or increase exports to improve their per year GDP (Fig. 1).

Trends in Generation Technologies

Electricity generation has primarily been done with the usage of hydroelectric power generation. Nepal is known for its large usage of hydroelectric generation for the last century, and as of 2021, hydro is still the primary source of generation for the nation. There have been small applications of fossil fuel generating plants throughout the country, but this small amount of generation only accounts for roughly 5% of the national grid capacity as of 2016 (Fig. 2) [3].

As a result of the poor electrification and stability of the Nepali electrical grid, stand-alone and grid integrated photovoltaic projects have slowly been implemented as an alternative source of generation. This allows for electricity distribution to communities that are strongly affected by the rolling blackouts caused by load shedding and low distribution capacity. Any additional grid generation will likely occur in the form of renewable energy generation systems. Nepal has a high potential for increased hydroelectric generation and photovoltaic solar potential. It is anticipated that within the next 5–10 years, there will be a larger increase of these generation types nationally [4].

Domestic Resources

Energy and electricity usage comes from two primary categories in Nepal: biomass and hydroelectric. Hydroelectric is the primary form of electricity generation for the country while biomass, namely, wood, is used for heating, cooking, and other miscellaneous needs not pertaining to electricity generation. These resources are plentiful within Nepal and currently require no importing. Fuels such as petroleum cannot be found domestically and therefore are imported from countries such as India.

History of Energy

Before the usage of electricity in Nepal, like many nations in their technological and industrial infancy, biomass was the main form of energy consumption. This remained the norm until 1911 when the 500 KW Pharping hydroelectric power plant was installed [5]. Since 1911, several other hydroelectric power plants and two thermal generating plants have been integrated into Nepal's young electrical grid. Energy consumption has grown drastically, with hydroelectric dominating the electricity generation category (supplying 93% of the population) [3] with bioenergy dominating the overall nonelectrical energy consumption of the country.

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Breakdown of Energy Generation "Mix"

Energy Consumption Mix (Fig. 3)

Fossil Fuels

Oil

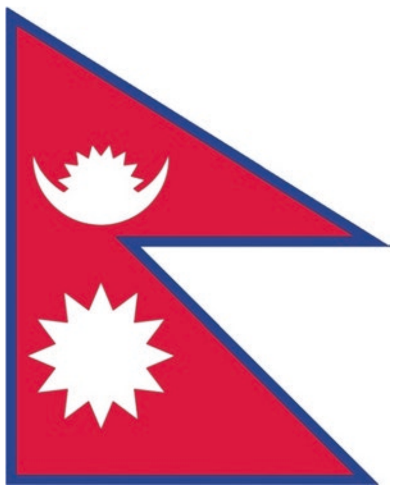

Fig. 1 Nepali flag [3]

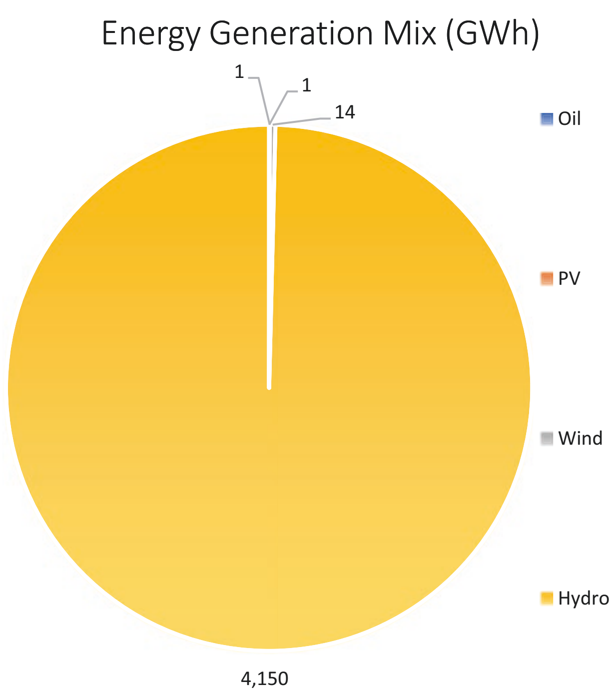

Fig. 2 Nepali energy generation

Oil and oil derivatives are primarily used as combustible fuels in the country of Nepal. In 2018, Nepal imported 30,028 GWh (2582 ktoe) worth of oil into the nation [6]. The importance of these combustible fuels can be seen that during the 2014–2015 fiscal year, oil and petroleum products amounted to roughly 20% of Nepal's import budget at an amount of roughly US$1068.5 million [7]. Although oil imports are a large cost for the nation, there have been reports indicating that there are crude oil reserves in the Upper Mustang region; volumetric reserves in this region are currently unknown [8, 9].

Although Nepal is primarily a green energy generation country, there still exist nonrenewable electricity generation plants. As of 2008, there are two plants in operation; one located in Hetauda and one located near Britanagar. Hetauda can generate up to 14.4 MW of power with the potential to deliver up to 0.92224 GWh of energy to the grid per year [10, 11]. The second generator is a multifuel thermal generator used in Nepal at the Duhabi Multifuel Center with a maximum capacity of 39 MW [11]. This generator can be found in the Morang district in south-easter Nepal in the Biratnagar province [12] (Tables 1 and 2).

Coal

Coal is imported to Nepal [13] primarily for usage in the industrial sector where large furnaces for trades such as metallurgy is done. In 2018, it was reported that 9804 GWh (843 ktoe), 9781 GWh (841 ktoe) was used for industrial purposes with the remaining 23.26 GWh (2 ktoe) used for residential purposes [6]. There currently is no coal usage for electricity generation and there are no plans to construct such facilities in the future.

According to a geological study conducted by the Nepali Department of Mines and Geology under the Ministry of Industry, Nepal has produced between 2900.3 and 10,499.26 metric tons of coal from domestic mines between 2009/2010 and 2016/2017 fiscal years, with the shortest production year occurring in the 2015/2016 fiscal year [14]. Although Nepal may produce as much as 10,500 metric tons of coal on the best year, this equates to only 85.48 GWh (7.35 ktoe), which is virtually negligible compared to the imported 9804 GWh (843 ktoe) [13].

Natural Gas

Natural gas has very little to no useable applications in Nepal, and any small amount of usage may be considered negligible [3, 6]. Natural gas would likely be used for residential or personal applications for heating but would not be economically feasible to import from neighboring coun-

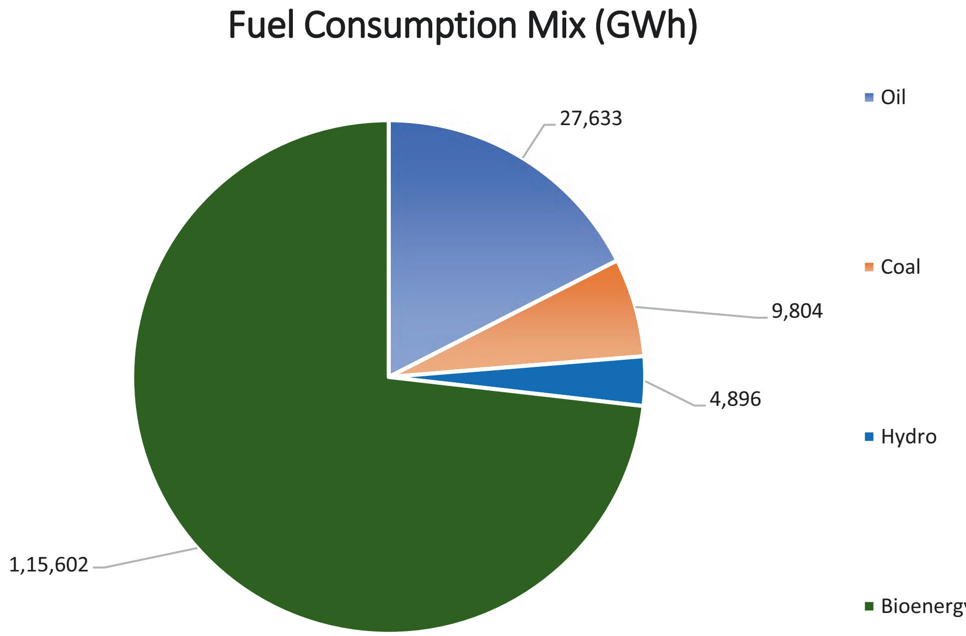

Fig. 3 Nepali energy consumption

Table 1 Oil derivative consumption breakdown [6]

Fuel consumption type	Kilotons of oil used	GWh of oil used
Gasoline/diesel	1428	16,608
Liquid petroleum gas/ ethane	480	5582
Jet kerosene	31	360.53
Motor gasoline	399	4640
Miscellaneous kerosene	26	302
Miscellaneous oil	12	139.56

Table 2 Nepal thermal generators

Generation plant	Capacity (MW)
Hetauda	14.4
Britanagar	39

tries as biomass is already used to such a large extent for these applications. Additionally, there have been reports confirming that natural gas does exist in Nepal [8, 9], but the volume of these reserves is unknown [3]. Further studies can be done to determine the volumetric reserves in the country, but this may only be done if external investors were to help with supplying the necessary capital.

Nuclear Energy

It has been recently discovered that, in 2015, a large deposit of uranium resides in the Upper Mustang region of the country [8]. This deposit is projected to be of high quality which would be ideal for nuclear energy generation, but there has been no known work for extraction.

Nuclear power generation currently does not exist in Nepal [6]. A likely cause of this is the financial and political constraints associated with the installation and operation of nuclear power plants. With the large hydroelectric and photovoltaic potentials in Nepal, paired with a small population, the financial comparison for nuclear energy would be considered irresponsible.

Renewable Energy Generation

Photovoltaics (PV)

Nepal has a suitable solar irradiance for the application of large level solar power generation. Roughly 73% of the country has a global horizontal irradiance between 4.2 and 5 kWh/m^2/day [15], with the entirety of the country having a global horizontal irradiance of 3.9–5.1 kWh/m^2/day [16]. This shows that Nepal has a good potential for increasing the level of solar power generation for both grid-tied systems and for stand-alone microgrids. In 2013, it was reported that roughly 12 MW of solar capacity was used, in 2016, only 0.1 MW of solar capacity was used [11, 17], and in 2018, total energy generated from solar was only 1 GWh [6]. This shows that there is ample opportunity for the introduction of governmentally owned, subsidized, or privatized solar field integration in Nepal; with no solar thermal in the country, therein lies additional opportunities for further solar expansion.

Wind

Wind power generation currently is not highly utilized within Nepal. In 2013, only a 20 kW capacity was generated using wind [17], but in 2018, 14 GWh was generated [6]. Wind generation can produce 170.3 MWh/year (0.1703 GWh/year) [18] in the Tila village of Jumla. Although regions vary, this shows promise that similar areas around the nation can use wind as a generation source. Despite there not being much research conducted on wind energy for Nepal, it is possible that it is capable of being implemented for similar microgrid or grid-tied systems like that of solar.

Hydro

Hydroelectric power is the primary source of electricity generation for the nation. With Nepal existing within part of the Himalayan mountain range, water runoff from seasonal glacial melt provides a large resource. With roughly 6000 rivers throughout the country, a potential of 83,000–90,000 MW of generation is available for the Nepali Energy Agency or independent generators to harness rivers [9, 19, 20]. Although there is a large potential for usage, only 42,000–50,000 MW is considered economically feasible for installation and grid integration [20].

In 2017, it was determined that 92% of the total grid capacity came from the usage of hydroelectric generation [3] and in 2018, there was 4896.26 GWh (421 ktoe) of energy consumed [6]. The benefit of this generating form is that it can be used for more rural communities and can be used to electrify these regions as microgrids. As of 2019, there is an installed capacity of 1127 MW of hydroelectric with 4150 GWh of energy generation from Nepali hydro power [21], which indicates that hydroelectric power generation has steadily been growing throughout the nation.

One of the larger projects under construction is the 3000 MW hydroelectric dam which is to be placed on one of Nepal's largest waterways, the Saptokshi River [22], but there still remain concerns of hydropower supply during the dry seasons [23] (Table 3).

Table 3 Five largest hydroelectric plants currently in operation [20]

Generation plant	Capacity (MW)	River location
Kaligandaki A	144	Gandaki
Middle Marsyangdi	70	Marsyangdi
Marsyangdi	69	Marsyangdi
Kulekhani I	60	Kulekhani
Kulekhani II	32	Kulekhani

Biomass

In a recent report from the International Energy Agency, it was found that Nepal consumes 115,602 GWh (9940 ktoe) of energy between all biomass, biofuel, and biological waste combined [6].

Biomass accounts for most of the nation's energy consumption. With the difficulty continual and reliable electrification, biomass is used largely for heating, cooking, and other residential purposes throughout Nepal. A study conducted on cooking electrification in Nepal found that in the fiscal year of 2014–2015, firewood was used in approximately 59.3% of Nepali households for a multitude of applications and can be seen as a cooking fuel for 85% of rural areas that have poor electrical grid attachment [7]. Although firewood is a stable energy source, there are several different forms of biomass used in Nepal such as agricultural waste and livestock waste which equates to roughly 8.983 GWh (32,338 GJ) of energy for just the residential sector of Nepal [7].

Biofuels

There currently is no import of biofuels in Nepal. To help reach carbon emission goals and integrate cleaner burning technologies, Nepal's Alternative Energy Promotion Centre will begin working with two private organizations (currently unknown) to develop biofuel processing plants soon [24]. Biogas is another biofuel that has become popular in Nepal for cooking energy. Many villages (2800 out of 3915) utilize biogas with installed distribution [25].

Energy Storage Technologies

Country's Future Storage Direction

Peak load times in Nepal have frequently led to power outages and remain a consistent nuisance to the population. To aid during peak load times, Nepal has considered the application of solar battery storage to compensate for what current and conventional generating methods fail to produce [23]. Lead, nickel, cobalt, and cadmium have been found in many locations throughout the country [8]. Although not as desirable as lithium for battery production and energy storage applications, it is possible for Nepal to increase battery manufacturing with the materials to begin nonimported battery storage sites and small microgrid applications.

Pumped hydroelectric has also been considered as a potential energy storage technique [26]. With the already high hydroelectric generation potential, the creation of reservoirs from preexisting rivers for load compensation during peak hours is a viable and potential cheaper option compared to large battery storage.

Carbon Footprint

Most Recent Carbon Output

In the global context, Nepal has a small influence level of emissions. In 2015, it was reported that Nepal only contributed to 0.027% of the global emissions. Compared to developed, or more industrialized nations, most emissions produced are derived from the energy sector as the low-level industrialization of Nepal has a near negligible contribution [1]. In 2018, it was determined that Nepal produces 11.2 megatons of CO2 from energy consumption [6].

On a per capita basis, the carbon emissions for Nepal have been on an increasing trend starting form 0.008 metric tons of CO2eq in 1960 up to 0.334 metric tons in 2016. This has additionally resulted in air pollution of 94.33 mg/c^3 of particulate matter, 9.11 megatons of CO2, and 41.15 megatons of methane carbon [27].

Historical Trends of Carbon Footprint (Fig. 4)

Types and Main Sources of Pollutants

No information was provided by the author.

Energy Resiliency

Electrical Grid

The electrical grid of Nepal has previously experienced frequent blackouts because of low generation levels and low transmission capacity. To prevent system failures, the NEA and IPPs would conduct load shedding to prevent issues with generation or transmission. As of 2016, there only exist two different transmission level voltages for transmission. These are 66 and 132 kV which currently have 511.2 and 2416.7 ckm[1] lengths, respectively, between both the NEA and Independent Power Producers. There is the additional implementation of an increased installation of more 132, 220, and 400 kV transmission throughout the nation in attempts to increase power delivery to all residents [17]. With the implementation of these new transmission systems, the NEA has stopped load shedding for residents (2017) and industrial (2018) sectors [28]. With the new transmission systems implemented and maintained, 93% of the 2020 population has access to electricity [3].

Climate and Natural Disasters

As a result of climate change, Nepal has experienced variations in temperature and rainfall throughout the nation. These changes will have significant effects on hydroelectric generation which relies on the heavy rainfall monsoon seasons and glacial melt, and the agricultural sector will experience lower crop yields because of increased temperatures and reduce precipitation. Additionally, climate change induced earth-

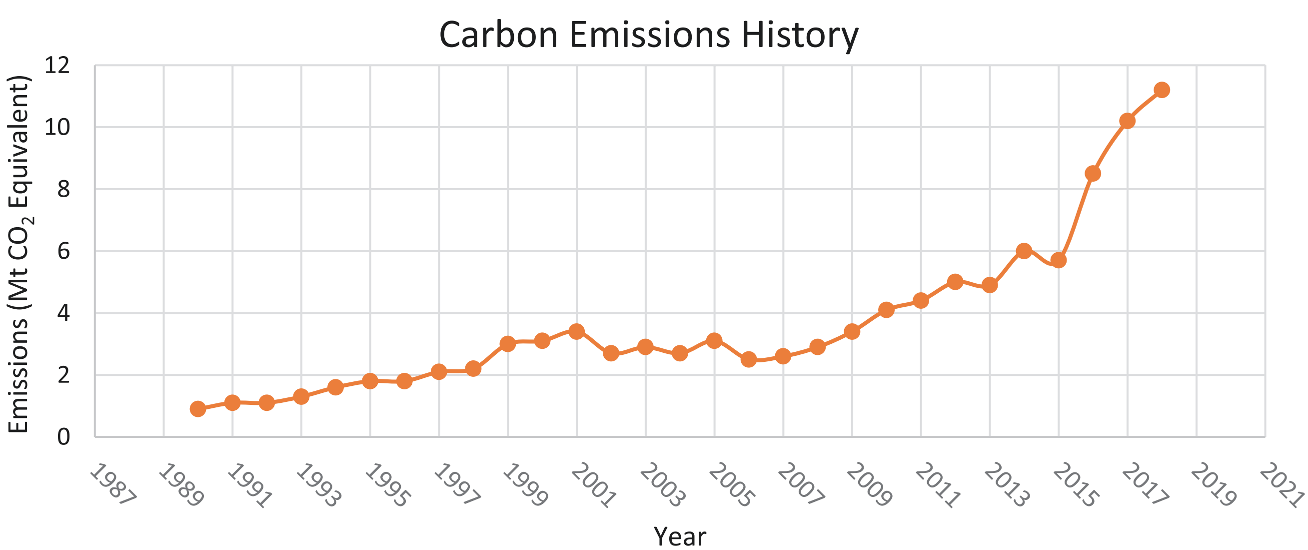

Fig. 4 Nepali carbon emission history [6]

[1]ckm = circuit kilometer.

quakes are of major concern to the Nepali government. The geographical location of Nepal has resulted the nation to be the 11th most earthquake prone location globally. As a developing country, major earthquakes can wreak havoc on the nation's economy and residents [1].

Grid Resiliency

Despite Nepal being able to provide power to a large portion of the population, electricity is still being imported from India to compensate for generation capacity deficits [17]. The specific quantities are dependent on season and general load requirements, but an interconnect between the two nations is critical in supplying ample power to the people of Nepal, especially during the dry season where hydroelectric generation capacity is reduced. Since the grid requires the aid of another nation for stability, and much of the primary generation source decreases during half of the year, additional methods for energy storage of additional generating sites for compensation should be included for proper resiliency.

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

India is the primary exporter of oil and petroleum products to Nepal [17]. This forces Nepal to be extremely reliant on India for combustible fuel needs, and any governmental strain between the two may lead to a significantly reduced, or completely ceased, trade of fuels. Additionally, India supplies electricity to Nepal when generation cannot maintain loading. This creates a regional dependency for power supply which could be stopped by India given international tensions between the two countries.

Relations with Global Community/ Socioeconomic Influence

There has been interest from both China and India to invest in Nepal's electricity market. With the large hydroelectric potential that has not been fully tapped by the NEA and Nepali IPPs, it has been discussed that Nepal could become a green energy power for South Asia and the drastically growing energy and electricity demands [29]. This has been seen on several occasions where China and India have discussed with the Nepali government about large hydroelectric power plant investments [30].

Education

There are currently a few masters level programs for renewable energy and sustainability. At Tribhuvan University, there is a Masters of Science in Renewable Energy Engineering and a Masters of Science in Energy for Sustainable Social Development [31, 32]. With the development and implementation of more renewable sources in Nepal, it is likely that these programs will increase and potentially have an outreach to undergraduate and community level.

Summary

Current Energy Situation

Nepal is a country full of renewable energy generation consumption and generation. The first electrical generating plant was hydroelectric which has become the dominate source of generation accounting for 92% of the grid. With gravity fed rivers fed from mountain runoff and seasonal monsoons, Nepal is expected to focus most of their generating efforts on hydroelectric power with additional integration of solar and wind, while still maintaining the two thermal plants for additional capacity. It is also expected that biomass will continue to be a primary energy source for the small nation as usage of electrical appliances for heating and cooking is not economically feasible for most of the population.

Future Energy Situation

In the near and far future, it is expected that the Nepali government will continue to implement hydroelectric sources and will receive international financial backing from countries such as China and India to produce and sell power as an export [29]. This, including solar and wind potentials therefore leave access to an open and largely untouched energy market for private business ventures which will not only benefit the investor(s) but will likely increase the economic growth of Nepal and improve the life of the population.

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Pakistan

Slobodan Petrovic and Kyle Buchanan

National Energy Introduction

Energy Policies

Pakistan is a part of the Paris Climate Agreement [1].
Targeting 30% renewable energy generation by 2030 [2].

Trends in Generation Technologies

Pakistan's energy generation mix is shown in Fig. 1. Energy consumption mix is shown if Fig. 2. The difference between the two reflects ratio between domestic resources and imported. Pakistan has a history of utilizing hydroelectricity and in recent years has made additional investments in hydroelectric dams.

Domestic Resources

Pakistan has a large amount of biomass that can be used to generate energy, as well as moderate amounts of oil and natural gas, although not enough to supply the country's energy demand.

History of Energy

Pakistan has been a country mostly reliant on fossil fuels for their energy supply. They also get a large portion of their energy from biomass, but that is generally through residential cooking. Pakistan leans heavily on imports from China, Qatar, and South Africa to meet their energy needs.

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Breakdown of Energy Generation "Mix"

Fossil Fuels

Oil

Current Usage: 255,116 GWh/year [3].
Production: 48,939 GWh/year [3]. The majority of oil is imported from China, the United Emirates, and Saudi Arabia. This oil comes mostly in the form of petroleum products and palm oil [4].

Oil usage has been a large part of Pakistan's infrastructure for decades.

Coal

Current Usage: 132,303 GWh/year [3].
Production: 23,667 GWh/year [3]. The majority of coal is imported, primarily from South Africa, Indonesia, and Afghanistan [5].

Natural Gas

Current Usage: 329,210 GWh/year [3].
Production: 235,797 GWh/year [3]. Pakistan imports their natural gas primarily from Qatar [6].

Nuclear Energy

Policy: Pakistan is not part of the Nuclear Non-Proliferation Treaty, meaning it is limited in how it can trade in nuclear materials, which significantly impedes on the nation's

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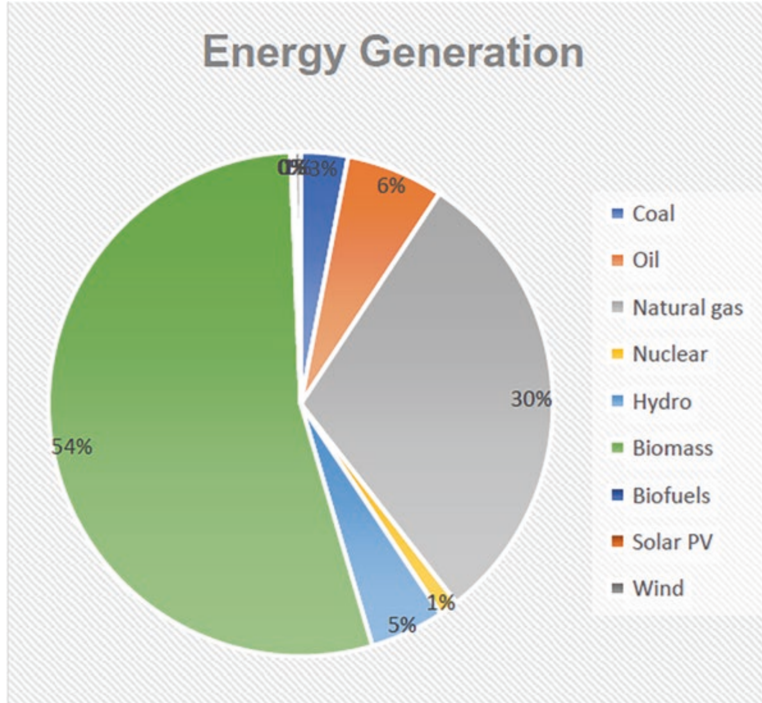

Fig. 1 Pakistan's energy generation mix

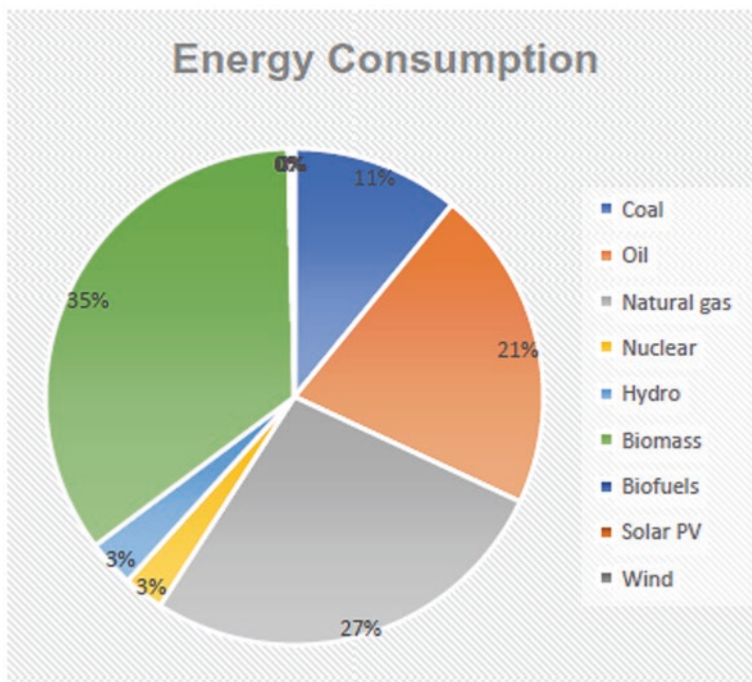

Fig. 2 Pakistan's energy consumption mix

nuclear energy growth [7]. China has been a partner of Pakistan however and is aiding Pakistan in Nuclear energy developments.

Current Usage and Future Plans: Pakistan consumes 31,680.12 GWh/year from nuclear energy, however only 9507 GWh/year is generated domestically [3]. There is also an additional 2300 MW of nuclear capacity under construction in Pakistan, which should increase the generation capacity by over 150% [7].

Renewable Energy Generation

Photovoltaics (PV)

Current Usage: Pakistan generates and consumes 882 GWh/year from solar PV [3]. Pakistan has had steady growth since 2015, growing over four times in terms of energy capacity. One of the benchmark projects was the Quaid-e-

Azam Solar Power Park, located in the Cholistan Desert, which was built in 2015 and is the largest solar plant in the country [8]. This solar power plant has a 100+ MW peak power output and houses 392,158 solar panels [8].

Potential: Pakistan is one of the sunniest regions on the planet, receiving around 6–7 peak sun hours on average year-round [9]. With the abundance of solar energy they receive, they have significant potential for future solar PV development.

Future Plans: The Pakistani government has received $105 million in financing from the World Bank to invest in solar energy projects. In order to meet their 30% renewable energy goal by 2030, Pakistan needs to continue to invest in solar energy.

Wind

Current Usage: Pakistan generates and consumes 3157 GWh/year from wind energy [3]. Wind energy has grown almost eight times as much since 2013 [3].

Potential: Parts of Pakistan are very windy, especially near the coastlines. Due to certain areas having high wind speeds and low land value, there is significant potential for additional wind energy development.

Future Plans: There are several wind power plants either recently contracted or in construction in Pakistan. A few of the notable plants in the works are Jhimpir Corridor (150 MW), Three Gorges Second (50 MW), and the Three Gorges Third (50 MW) power plants [10, 11].

Hydro

Current Usage: Pakistan generates and consumes 37,380 GWh/year from hydroelectric dams [3]. Hydroelectric energy production in Pakistan is second only to biomass in terms of renewable energy generation. In recent years, there have been several large-scale hydroelectric power plants completed in the Khyber Pakhtunkhwa province, which lies in the North [12]. A few of the most notable being Daral Khwar (36.6 MW, completed 2018), Ranolia (17 MW, completed 2016), and Machai (2.6 MW, completed 2017) [13–15].

Potential: Pakistan has many rivers that flow through it, including the Indus River that connects to the Arabian Sea. Pakistan has had high rates of hydroelectric energy generation for decades, generating up to 45% of their total power generation in 1991 [12].

Future Plans: Through the China Pakistan Economic Corridor (CPEC), China is investing in the Karot (720 MW) and Suki Kinari (870 MW) power stations [11].

Ocean

Current Usage: Pakistan has no installed ocean or tidal power plants.

Potential: Pakistan has a 1050 km coast on the Arabian Sea, so it has potential to harness tidal energy from that source.

Future Plans: There have been various groups and organizations that have shown interest in investing in tidal energy; however, no financing or contracting has been completed yet.

Geothermal

Current Usage: There is no substantial geothermal energy generation in Pakistan.

Potential: There is significant potential for geothermal energy development, from the use of hot dry rock, hydrothermal sources, and shallow direct use in various terrains [16].

Future Plans: There are no contracted large-scale geothermal projects in Pakistan.

Biomass

Current Usage: Pakistan consumes roughly 423,018 GWh/year from biomass, although a large portion of this energy is not generated through commercial means [17]. Biomass makes up roughly a third of Pakistan's energy consumption since many of the residential areas of the country do not have reliable access to electricity from the grid [17]. About 80% of this biomass energy is used for cooking [17].

Production: All biomass consumed is produced domestically.

Potential: Even with the amount of energy being generated from biomass, Pakistan has a large supply of untapped bioenergy crops which they will likely need to utilize in order to close the energy gap in the country [17]. Pakistan must be able to source and convert reliable indigenous bioenergy crops in order to meet the nation's energy requirements, especially until a more reliable energy solution is presented for all regions of the country [17].

Biofuels

Current Usage: Pakistan consumes 1046 GWh/year from biofuels.

Production: All biofuels consumed is produced domestically. Most of the biofuel production is in the form of ethanol [17].

Potential: Pakistan has a significant supply of biofuel crops and sugarcane production, which can be used to create biofuels [17].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

Pakistan currently has no significant grid-tied energy storage systems.

Country's Future Storage Direction

Pakistan recently accepted a $27.9 million pilot project with the Asian Development Bank to set up their first large-scale grid-tied energy storage system by the end of 2023 [18]. In order for Pakistan to meet all of their energy needs from renewable energy, they will need to significantly develop their energy storage capabilities.

Carbon Footprint

Most Recent Carbon Output

Pakistan released 194 megatons of CO_2 in 2018 [3].

Historical Trends of Carbon Footprint

Pakistan has had a steady increase in CO_2 emissions over the past 30 years [3].

Types and Main Sources of Pollutants

The primary source of CO_2 emissions are coming from fossil fuels. The top sources are oil (86 Mt), natural gas (66 Mt), and coal (42 Mt).

Air Quality

Pakistan has high air pollution, being classified as "unhealthy" with an average US AQI score average of 156 over the course of 2019. Pakistan's PM2.5 concentration for 2019 was six times above the World Health Organization's recommendation [19].

Energy Resiliency

Electrical Grid

Age/Historical Improvements: Pakistan is in the midst of an energy crisis, in large part due to insufficient transmission and distribution lines and an underfunded energy sector [20]. Transmission line losses are around 17% and distribution losses are approximately 50% [21]. These losses are well above normal levels and are being driven by a number of factors including inadequate grid conductors and lengthy distribution lines [21].

Maintenance Costs and Is It Being Completed (Workforce): The energy sector has been historically underfunded, which has led to many issues with grid maintenance. Pakistan loses an estimated 2% of their GDP from power shortages each year, which some researchers have suggested is a low estimate [20].

Stability: Compounding generation and distribution issues has led to a shortage of an estimated 5 GW/day [21]. This underdeveloped energy infrastructure frequently leads to grid outages, which makes the grid unreliable. In 2011, many areas of Pakistan, including some urban areas, experienced around 14–18 h of complete power loss each day [14]. Many of these same instability issues persist today.

The World Bank is financing a $425 million project to increase capacity and reliability of parts of Pakistan's transmission systems as part of the National Transmission Modernization Project [22].

Comparison with other countries electrical grid: Pakistan is a developing country and has a similar grid development issues such as lack of funding. Losses from transmission and distribution lines are well below grid averages in first world countries [21].

Geographical Limitations: Parts of Pakistan are mountainous, which can be problematic for connecting them to the grid. Due to poor electrical infrastructure and geographical limitations, roughly 30% of Pakistanis do not have access to the grid at all [20].

Climate and Natural Disasters

Natural Disasters: Pakistan is subject to a range of natural disasters due to its varying climate. It can be exposed to floods, earthquakes, cyclones, landslides, and drought.

Resources: Pakistan has a variety of climates depending on the region, mostly composed of tropical, subtropical, semi-arid, or desert. The coastal portions of the country near the Arabian Sea are quite tropical; however, some of the northern mountain ranges near the Himalayas are frigidly cold year-round. This climate yields a range of biomass resources as well as fossil fuels.

Pollution and Other Contributing Factors Exacerbating a Country's Climate: Pakistan is the fifth largest country in the world by population with over 222 million people and growing faster than any of the countries above it [11]. Having such a large population leads to high population density and heavy air pollution issues.

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

Imports/exports: Pakistan is heavily reliant on fossil fuel imports. They import the majority of their oil and coal and are still not able to meet their full energy demand [3].

Energy sales: Pakistan exports some fossil fuels, but due to their gap in energy demand, the vast majority of energy sources are used domestically.

Relations with Global Community/ Socioeconomic Influence

Pakistan signed Paris climate agreement in 2016.

Pakistan is in the United Nations.

Pakistan has had some political conflicts with India, leading to Pakistan's refusal to give up their nuclear weapons until India does. Their nuclear weapons program has led to them being excluded from the Nuclear Non-Proliferation Treaty [23].

China Pakistan Economic Corridor (CPEC): The CPEC is an organization set up between the Pakistani and Chinese governments to promoting bilateral investment between the two nations. There have been dozens of large-scale projects through this organization, and it is a large driving factor for Pakistan's energy development.

Current Renewable Energy Goals: Pakistan has committed to reaching 30% of all generation to come from renewable energy by 2030 [2].

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Qatar

Slobodan Petrovic and Morgan Lanen

National Energy Introduction

Energy Policies

Qatar is a desert country located in the Middle East as a peninsula in the Persian (or Arabian) Gulf. In 1977, a decree law was enacted to preserve oil resources by setting technology norms and industry standards for production [1]. This law was set out to protect the environment and reduce the risk to human life [1]. Law No. 30 of 2002 was set in motion by 2003 to maintain the environmental quality, avoid damaging effects from man-made error, sustainable developments moving forward, and protection of public health as well as wildlife [1]. The country is subject to extreme heat, and therefore many energy policies center around air conditioning. Policies enacted in 2009 and 2013 set standards and parameters for energy production for the purposes of air conditioning [1].

Trends in Generation Technologies (Fig. 1)

Domestic Resources

The country of Qatar is abundant in oil and natural gas both onshore and offshore. The countries resources are so vast that they have little purpose to depend on other countries for energy production.

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History of Energy

Before oil was developed in Qatar, the country's economy was largely based on underdeveloped agriculture [2]. In 1931, Anglo-Persian Oil Co. did a geological survey and discovered oil potential [2]. By 1935, that same company was granted a concession for development [2]. The license for the concession was transferred to Qatar's Petroleum Development in association with Iraq's Petroleum Co; however, Anglo-Persian was still a shareholder [2]. Dukhan No. 1 was the first to strike oil on one of the first well explorations in 1938 [2]. Two other wells were erected in the area, however, World War II forced all three wells to stop resulting a production drop-off of 40,000 barrels per day at the time [2].

At the end of 1947, oil production was restarted, and by 1949 the country opened up to further exploration including offshore ventures [2]. The third offshore field, Bul Hanine, was discovered in 1970 and was producing by 1972 [2]. By Decree No. 72 of 1980, Qatar General Petroleum Corporation (QGPC), created in 1974, was merged with the Qatar Petroleum Producing Authority and took over all the counties shareholdings across the various oil companies in operation within their borders [2]. Most of Qatar's natural gas production is in conjunction with their oil wells [2]. Qatar's oil and natural gas sectors are overseen by the state-owned organization Qatar Petroleum (QP) [3].

In December 2003, Qatar climbed the ranks to one of the key players of the global economy in oil and natural gas revenue [4]. In 2013, Qatar was the fourth largest dry natural gas producer in the world [3]. Much of the country's economy relies on their energy sector with 49% of government revenue coming from hydrocarbon sales in 2014 [3]. A discussion lecture given in February 2014 informed the public that Qatar's unique ability to supply 100% of its power from natural gas has allowed the country to use the oil production as a way to drive revenue [5]. The same session observed the necessity for renewables due to the fact that reserves will eventually deplete and as they do the countries revenue will also causing financial hardship [2].

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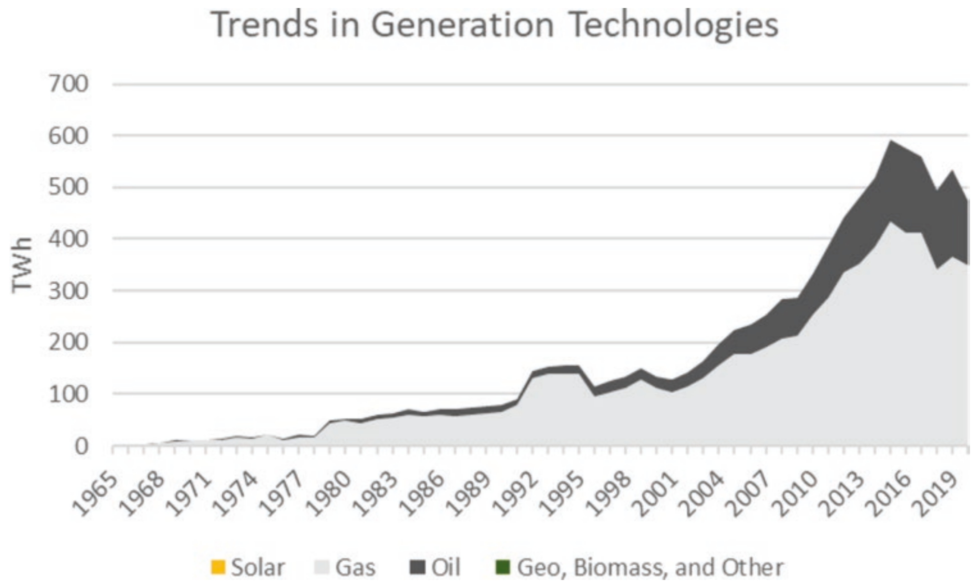

Fig. 1 Qatar trends in generation technologies [2]

Breakdown of Energy Generation "Mix"

Energy Generation Mix

Electricity production in 2016 was up to 39.78 billion kWh with country consumption at 37.24 billion kWh [6]. The total installed capacity of Qatar as of 2016 was 8.796 million kW where 100% was generated from fossil fuels [6]. Figure 2 is the combination of energy generation within Qatar in the units of gigawatt-hours (GWh).

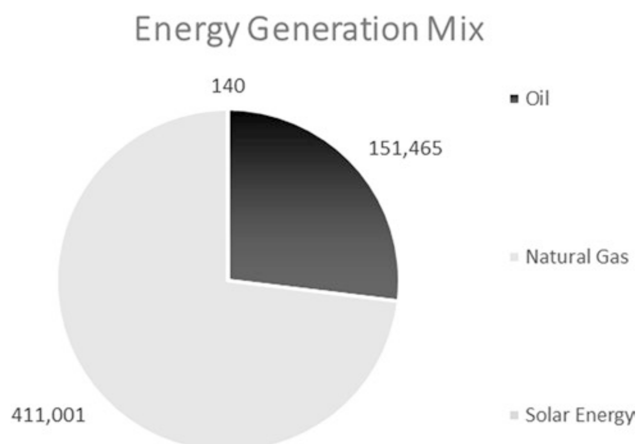

Fig. 2 Energy generation mix

Energy Consumption Mix

Figure 3 is the consumption distribution of fuel within Qatar rated in GWh.

Table 1 is the numerical summary of the generation and fuel data to be described in detail below.

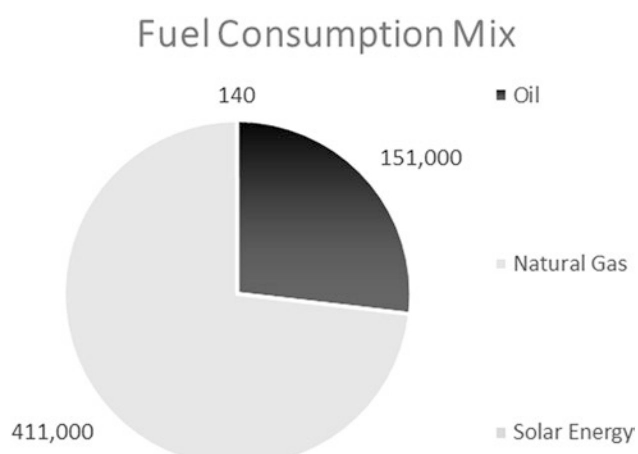

Fig. 3 Fuel consumption mix

Fossil Fuels

Oil

Being a large producer of oil, Qatar only uses approximately 277,000 bbl/day (as of 2016) generating about 151 TWh from oil in 2019 [6, 7]. Current production of crude oil is around 1.464 million bbl/day with 1.15 million bbl/day being exported [6]. Refined oil production was at 273,800 bbl/day as of 2015 with exports at 485,00 bbl/day and imports of 12,300 bbl/day [6].

Qatar has nine major oil fields: Al Shaheen, Dukhan, Idd al-Shargi, Bul Hanine, Maydan Mahzam, AlKaheleej, Al Rayyan, Al-Karkara, and El-Bunduq [3]. The fields consist

Table 1 Fuel breakdown

Fuel	Quantity	Installed capacity (MW)	Energy production (GWh)	Energy consumption (GWh)	Imports (GWh)	Exports (GWh)
Oil	9	2661.68	151,465.1862	151,000	20.8977	465.1862
Coal	NA	NA	NA	NA	NA	NA
Natural gas	28 (lines)	2716	411,001.3055	411,000	0	1.30548
Nuclear	NA	NA	NA	NA	NA	NA
Solar energy	1	7.39	140	140	NA	NA
Wind	NA	NA	NA	NA	NA	NA
Hydro	NA	NA	NA	NA	NA	NA
Ocean	NA	NA	NA	NA	NA	NA
Geothermal	NA	NA	NA	NA	NA	NA
Bio-energy	NA	NA	NA	NA	NA	NA

Table 2 Oil fields of Qatar [3]

Field	Capacity (thousand barrels per day)	Primary operator	Comments
Al Shaheen	300	Maersk	Maersk began work on $2.5 billion drilling program in 2013 to maintain output at 300,000 bbl/day
Dukhan	225	Qatar Petroleum	ExxonMobil-led development plan likely to conclude in 2014
Idd al-Shargi	100	Occidental	Occidental Petroleum investing $3 billion to maintain production of 100,000 bbl/day through use of enhanced oil recovery techniques
Bul Hanine	45	Qatar Petroleum	Total to invest $6 billion to double capacity to 90,000 bbl/day by 2017
Maydan Mahzam	22	Qatar Petroleum	–
Al-Kahaleej	19	Total	–
Al Rayyan	8	Occidental	–
Al-Karkara	7	Qatar Petroleum Development Company	–
El-Bunduq	6.5	Bunduq Oil Company	Operated jointly with United Arab Emirates
total	732.5		

of both onshore and offshore wells producing up to 300,000 bbl/day [3] (Table 2).

As of a January 2018 survey, there were 25.24 billion bbl of proven crude oil reserves [6].

Coal

As of a 2019 report, Qatar did not have any coal production or generation [7]. Coal has not been as abundant or accessible in Qatar as oil and natural gas, so there is little to no incentive to develop in this sector.

Natural Gas

Qatar's consumption of natural gas in 2017 was 39.9 billion cubic meter producing 411 TWh of electricity by 2019 [6, 7]. The country has no need to import natural gas due to their abundance of it, however they did export about 126.5 billion cubic meter in 2017 [6].

On- and off-shore fields typically in conjunction with their oil production facilities.

As of a 2018 survey, Qatar had 24.07 trillion cubic meter of natural gas proven reserves [6].

Nuclear Energy

There are no current plans for Qatar to develop nuclear power plants.

Renewable Energy Generation

Approximately 1% of Qatar's installed energy generating capacity is from renewable resources [6].

Photovoltaics (PV)

Currently, Qatar has a small amount of solar power installed but not of a substantial capacity as of yet.

Qatar's new solar production goals for 2030 are broken down into two phases: 2021 will be the launch of 350 MW of capacity to be completed in 2022 with a grand total of 700 MW of capacity [8].

Wind

As of this writing, Qatar has no installed wind generator fields.

While the country does not have wind farms at this time, there is huge potential for such generation. Given a mean wind speed of 5.06 m/s, Qatar could save 6.813 tons of CO_2 with the addition of a 17 MW capacity wind farm [9].

Hydro

Qatar currently does not have any notable hydroelectric plants and no plans of one have been found.

Ocean

Qatar currently does not have any notable ocean power plants and no plans of one have been found.

Geothermal

Qatar currently does not have any notable geothermal plants and no plans of one have been found.

Biomass

Qatar currently does not have any notable biomass plants and no plans of one have been found.

Biofuels

Qatar currently does not have any notable biofuel plants and no plans of one have been found.

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

As of a report in August of 2020, Qatar General Electricity and Water Corporation commissioned their first ever large-scale battery storage system [10]. A 1 MW and 4 MWh Tesla battery storage system is to be grid connected mainly to meet growing energy demands for the summer months, a US$2.75 million investment [10].

Country's Future Storage Direction

Qatar has good global relations and has access to growing technologies of today.

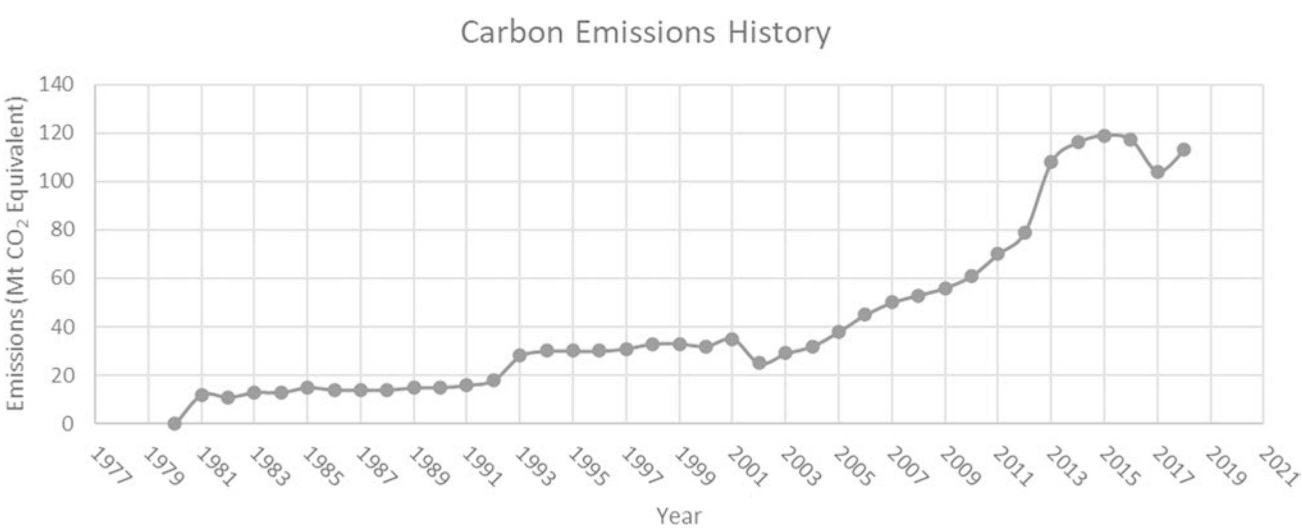

Fig. 4 Carbon emissions history: EIA CO_2 emissions data from 1980 to 2018 [11]

Carbon Footprint

Most Recent Carbon Output

The most recent record of carbon emissions was at 105 Mt of CO2 equivalent [11].

Historical Trends of Carbon Footprint

Figure 4 is Qatar's carbon emissions history from 1980 to 2018 from EIA data. The emissions data includes coal, coke, consumed natural gas, petroleum, and other liquids [11]. It is worth noting that while coal and coke are included, the record shows no carbon emissions from these sources, this is due to coal not being mined or used in Qatar according to current records [11].

Types and Main Sources of Pollutants

The main source of pollutants is from the oil and natural gas fields and their production. Natural gas has a greater impact on pollutants due to its use for power generation throughout the country. Aside from CO2 pollutants, dust storms also wreak havoc on the country which leads into air quality.

Air Quality

Due to the abovementioned pollutants and according to the International Association for Medical Assistance to Travellers (IAMAT), Qatar's air quality is dubbed unsafe with an average concentration of PM2.5 of 91 μg/m^3 [12]. For perspective, PM2.5 are inhalable pollutants of approximately 2.5 μm or smaller, and the recommended levels are within 10 μg/m^3 [12].

Energy Resiliency

Climate and Natural Disasters

As stated in the Pollutants section earlier, Qatar is plagued with dust storms. This could pose a problem with the implementation of renewables and especially with their solar farm plans. For solar fields to work with the best efficiency, they should be clear of debris, however, a dust storm would cover the panels with dust at least in part and would therefore require regular maintenance.

Due to Qatar's geographical location and terrain, heat is a constant hindrance on electrical demand. With the increase of temperatures and change in weather patterns, the temperature is ever increasing the demand on power for air conditioning and water desalination [13]. Typically, 80% of energy production goes toward cooling through the year [13]. Energy consumption is foreseen to increase up to 30% resulting in an increase of carbon emissions, which could worsen the situation [13].

Grid Resiliency

The abundance of natural gas and crude oil allows generating units to be highly resilient, there are few blackouts since the release of 1000 MW to the grid in 2009 [14].

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

Due to Qatar's abundance of oil and natural gas, the country does not require dependency on other countries for fuel resources. However, the county does acquire technological support from other well- developed countries to create energy diversity [8].

A large portion of Qatar's revenue is acquired though their energy sector, mainly in the export of crude oil. The country is endowed with an abundant supply of crude oil and ships it across the globe making Qatar a friend to most of the world. Nevertheless, the country is looking to diversify their energy production and revenue so as not to become dependent upon a diminishing resource.

Relations with Global Community/ Socioeconomic Influence

Qatar is working in pace with the United Nations sustainability goals and is making such strides as to diversify their energy profile to include solar energy and other natural, environmentally-friendly resources [15]. The country is committed to being the first host to prepare a carbon-free World Cup Championship for 2022 [15].

Qatar is focused on meeting the world energy and sustainability goals and to meet the needs of their people.

Education

Qatar has extensive higher education curriculums for environmental and energy research such as contained within its infamous Education City, a campus spanning 12 km^2 and the College of the North Atlantic-Qatar [16]. Qatar is currently growing their energy education system as they start their efforts toward their sustainability and energy diversity goals. Specifics are dependent on the specific institution [17]. The Qatar Environment and Energy Research Institute (QEERI) started a student reachout program in 2019 to educate young children about the environment and energy as well as sustainability [18].

Summary

Current Energy Situation

Qatar is currently a giant in the fossil fuels industry. Producing crude oil for the world and sustaining its own generation needs from natural gas, with a large proportion of governmental revenue coming from their energy and fuel production sector.

Future Energy Situation

The country has access to ever growing technologies as well as doing their own research and development. Being associated with many of the world's leading countries allows Qatar the ability to follow suit with global sustainability goals and quotas. Not without its own challenges, Qatar is maintaining its status as a top energy-producing country in the world by diversifying its energy profile to reflect that. The new implementation of solar energy and the possible future for wind farms have headed Qatar toward their sustainability goals head on. This will not only positively impact the influence of climate change, but strengthen the governmental revenue and solidify energy supply in the coming future.

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Thailand

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National Energy Introduction

Thailand is a country in Southeastern Asia encompassing most of the land between the Andaman Sea and the Gulf of Thailand, and it shares borders with Malaysia, Cambodia, Laos, and Myanmar (Burma) [1]. Thailand was never colonized but was influenced by other nations throughout its history. Nearly 69,481,000 people live in Thailand with the capital city Bangkok containing the highest density of population [1]. All inhabitants of the country have access to electricity with an estimated yearly consumption of 192 TWh [2].

Energy Policies

Beginning in 1971, the government began to enforce the Petroleum Act which states that all petroleum produced in Thailand is subject to government inspection and regulation [3]. Thailand has policies in place that are intended to increase efficiency by 30%, increase the total share of renewables to 30%, and increase to have 1.2 million electric vehicles and 690 charging stations all by 2036, as well as reduce greenhouse gas emissions by 20% by 2030 [4]. The 2015 Power Development Plan (PDP 2015) is an energy policy detailing Thailand's approach to energy security, economy, and ecology in the coming years. Specifically, the plan deals with the expected increase in power demand and calls for more fuel diversification to lessen the dependency on one particular fuel, as well as defines goals to maintain an appropriate cost for power generation and implementing energy efficiency measures, and finally the plan intends to reduce environmental and social impacts of energy generation by reducing carbon dioxide emissions [5].

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The Association of Southeast Asian Nations (ASEAN) have developed a power grid plan that will allow for regional power trading through interconnected grids [4]. As of 2019, Thailand was connected to the grids of Cambodia, Lao PDR, Malaysia, and Myanmar [4]. This trade has boosted the development of some renewables such as hydro which would have been uneconomic if not for the trade agreement [4]. This is due to the fact that trading with neighbors takes advantage of supply and demand imbalances while at the same time reducing grid variability caused by localized wind and solar generation [4].

Trends in Generation Technologies

In 2020, Thailand generated 147.5 TWh of electricity from natural gas and coal, 13 TWh from renewables, 0.9 TWh was generated from oil, and they purchased the remaining 29.5 TWh from neighboring countries [2]. Thailand consumed less electricity in 2020 than in preceding years due to the pandemic and its vast effects on the economy and tourism [2] (Figs. 1 and 2).

Domestic Resources

Thailand has access to natural gas and oil within their borders, but they are relying on imports of hydrocarbons to meet the demand for fuel [7]. In 2016, Thailand had to import a large portion of petroleum liquids (crude oil) to satisfy the demand, but they have eight operating refineries and are a net exporter of petroleum products [7]. In 2014, Petroleum and other liquid fuels accounted for 40% of the country's electricity generation with natural gas providing 28% and another 19% provided by biomass and solid waste, 12% from coal, and 1% from other renewables [7]. The first hydropower dam was operational beginning in

S. Petrovic (ed.), *World Energy Handbook*, https://doi.org/10.1007/978-3-031-31625-8_25

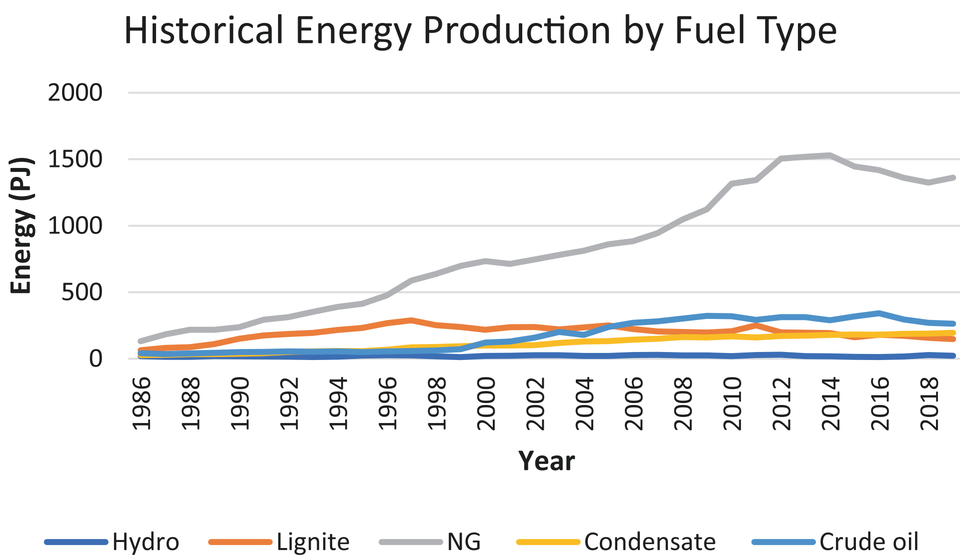

Fig. 1 Historical energy production by fuel type. (Data from EPPO [6])

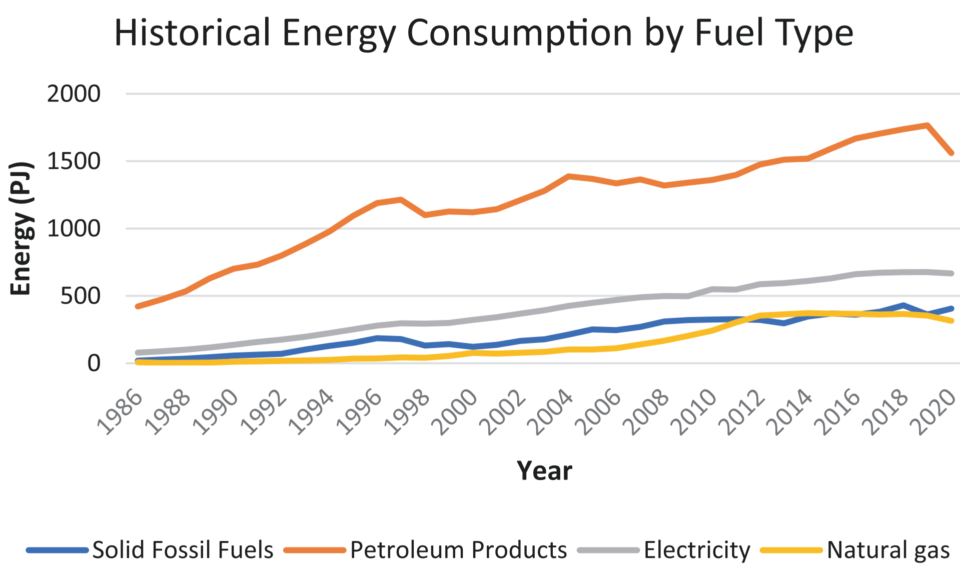

Fig. 2 Historical energy consumption by fuel type. (Data from EPPO [6])

1964, and at the time the power system was comprised of a few large thermal and gas turbine power plants and many small diesel power plants [8]. Through the next several decades generation of all types increased and the combined cycle and other renewables were introduced in 1983 and 1990 respectively [9]. Between 2000 and 2017, Thailand saw a marked increase in hydroelectric, bioenergy in the form of bagasse, solar, wind, and geothermal generation [4]. Additionally and despite public opposition, the government plans to build more coal-fired generation plants in order to reduce dependency on imports to meet demand [7].

History of Energy

Thailand has never been colonized.

Breakdown of Energy Generation "Mix"

Energy Generation Mix (Fig. 3)

Energy Consumption Mix (Fig. 4)

Fossil Fuels

Oil

Thailand generates a small portion of its electricity from oils. In 2020, they used oil to generate 0.9 TWh of electricity

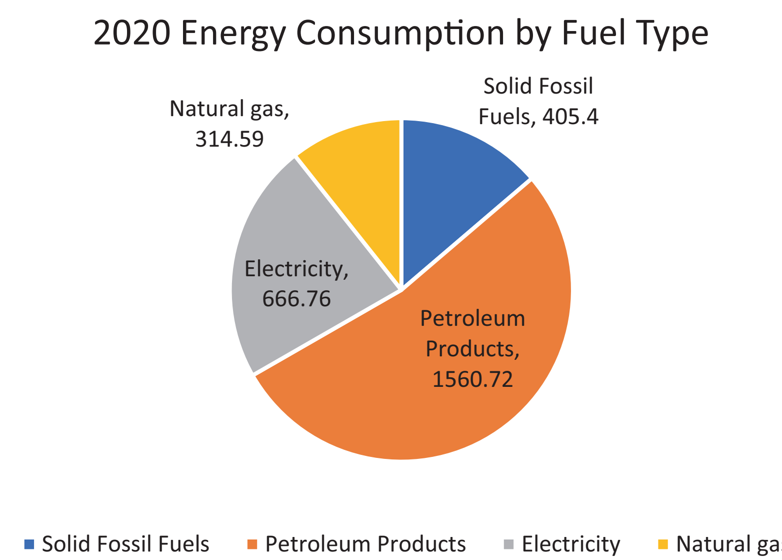

Fig. 3 2020 Energy consumption by fuel type. (Data from EPPO [6])

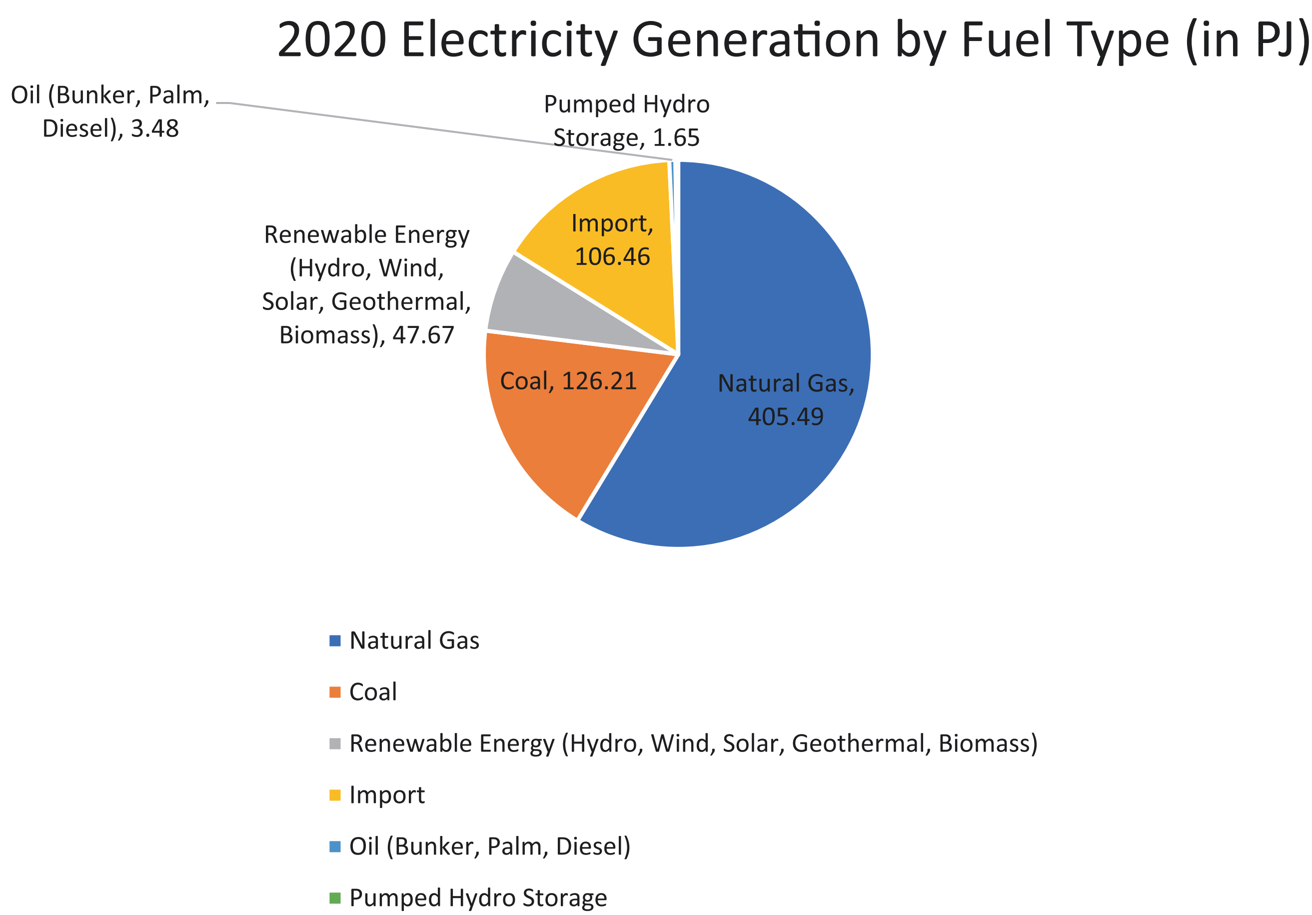

Fig. 4 2020 Electricity production by fuel type. (Data from EPPO [2])

which accounts for only 0.5% of the total electricity consumption [2].

Thailand extracts crude oil and refines it as well as imports crude oil for use and refining from other countries [10]. In 2019, the Department of Energy Business reported that Thailand was producing crude oil at a rate of 6.43 million metric tons (125,889 bbl/day) on a downward trend and importing another 50,000 metric tons (932 bbl/day) from other countries (57% from the Middle East, 15% from Malaysia, Indonesia, and Brunei, and 28% from Russia and

Australia) [10, 11]. Thailand consumes crude oil and oil products at a rate of 65.5 million metric tons (1,282,819 bbl/day) [6].

Thailand has eight operating refineries which is the second largest capacity in Southeast Asia, with Singapore having the largest capacity for oil refining. The total refinery capacity in 2019 was reported to be 63 million metric tons (1,234,500 bbl/day) of which Thailand consumed 53 million metric tons (1,050,795 bbl/day) and exported the rest [6]. The exported products are primarily in the form of diesel, fuel oil, and jet fuel [7].

A majority of the crude oil produced in Thailand comes from offshore fields in the Gulf of Thailand [7]. The Petroleum Authority of Thailand Exploration and Production (PTTEP) is the state-run producer, and Chevron operates many fields in the Gulf [12]. As noted above, these mining operations are diminishing the oil reserves resulting in declining production numbers. When an offshore mining platform's production declines to uneconomical levels, it is abandoned so the Ministry of Energy is developing in depth decommissioning plans [13]. The Gulf of Thailand is a major fishing area and tourist destination so decommissioning plans focus on the impact of the marine environment and preserving or restoring as necessary [12].

Coal

Thailand is a natural producer of coal in the form of lignite. In 2020, the country produced and consumed 13 million tons of lignite and imported 24 million tons of coal, generating 35.1 TWh of electricity, which accounts for 18.27% of the country's total electricity consumption [2, 6]. A vast majority, 98%, of this lignite is produced by the plant in Mae Moh, Lampang, run by the Electricity Generating Authority of Thailand (EGAT) [10]. Lignite is a poor-grade form of coal that is high in sulfur content and low in calorific (heating) value, but this is the only coal resource that Thailand has [14]. The demand for coal goes beyond the domestic production capabilities, resulting in the import of high-grade coal from overseas [10]. Thailand imports coal in various forms such as briquettes, anthracite, bituminous, lignite, and coking coal [6]. In Thailand, 60% of the coal consumption is used for electricity production with the rest being utilized in the industrial sector [10].

Thailand has four major thermal power plants with a combined capacity of 5239 MW [15]. In 2015, the Ministry of Energy and the Electricity Generating Authority of Thailand published The Power Development Plan in which they state intentions to increase the share of coal powered generation through clean coal technologies. For example, the Mae Moh power plant is the largest in the region with the ability to supply 50% of the required electricity to the northern area, 30% to the central area and 20% to the northeastern area, and it now uses ultra-supercritical technology which makes combustion more efficient, requires 20% less fuel, and results in less carbon dioxide emissions [15]. Additionally, the plant utilizes other modern technologies to scrub harmful pollutants from the emissions [15].

Natural Gas

Thailand is a producer and importer of natural gas. In 2020, Thailand generated 112.6 TWh of electricity from natural gas, accounting for 58.68% of the total generated and purchased power for the year [2].

In 2019, domestic production reached 3623 mmscfd which is a slight increase from 2018, but prior to that the domestic production numbers had been steadily decreasing (from 4073 mmscfd in 2014) [6]. While the domestic production has decreased the imports have increased to maintain a steady supply [6]. In 2019, Thailand imported 1394 mmscfd, and they consume about 5000 mmscfd of natural gas per year [6].

Thailand's natural gas reserves peaked in 2006 and have generally declined since then [7]. In 2016, it was reported that they had 7.3 trillion cubic feet in reserve, and they have natural gas fields in the Gulf of Thailand whose output has been decreasing recently [7]. Thailand's consumption of natural gas has outmatched their production since 1999 when a natural gas pipeline was installed to import the fuel from Burma [7]. Thailand has an extensive natural gas infrastructure and pipelines that connect the on- and offshore fields to gas separation plants, power plants, and many industrial users [7]. They also plan to be a local (ASEAN) hub for liquefied natural gas; they have signed purchase contracts with several companies and are building receiving terminals in preparation [10].

In 2019, Thailand's use of natural gas was broken down as follows: 58% (roughly 2800 mmscfd) was used for electricity, 21% (1000 mmscfd) was sent to gas separation plants, another 16% (760 mmscfd) was used for industry, and the last 4% (190 mmscfd) was used as natural gas for vehicles [10]. It is expected that the demand for liquefied natural gas will continue to increase, and Thailand plans to replace some coal-fired power plants with plants fueled by liquefied natural gas [10].

Nuclear Energy

Thailand does not currently have any nuclear energy power plants. But they have signed two memorandum of understandings (in 2009 and 2018) with the China General Nuclear Power Corporation [16]. The memorandum of understanding is a partnership between the Chinese nuclear power plant and the EGAT, which allows them to exchange technical information and supports the eventual development of nuclear power in Thailand [16]. Additionally, the PDP 2015 describes plans for two nuclear power plants to be built in 2035 and 2036 with each to provide 1000 MW [17]. These power plants are expected to provide less than 5% of the installed capacity for the country [17].

Thailand does not have any known Uranium deposits; hence, nuclear fuel will need to be imported when the time comes [18]. The Thailand Institute of Nuclear Technology may play a role in developing and managing the nuclear power plants, but no information has been disseminated about this, and it's possible EGAT will continue to manage all aspects of the projects [18]. In 2016, the Nuclear Energy for Peace Act established the Thai Nuclear Energy Commission for Peace which is the regulatory authority for Thailand and is responsible for licensing and regulating radiation from nuclear facilities and activities [18].

Renewable Energy Generation

Photovoltaics (PV)

Thailand has abundant solar resources due to high irradiance throughout most of the country [19]. In 2016, they had a cumulative installed solar capacity of 2753 MW, most of which had been installed in the previous 6 years [19]. By 2018, the installed capacity had already increased to 3437 MW as more solar panels were installed throughout the country, amounting to 538 solar power plants in 2019 [20, 21]. Most of the installed solar capacity in Thailand is in the form of grid-connected centralized solar farms and they account for 2827 MW [20]. Almost 600 MW of the installed capacity are grid connected and distributed solar farms and 11 MW are off-grid installations [20]. It has been estimated that in 2018 the total PV electricity production was close to 5.23 TWh and accounted for 2.78% of the country's electricity consumption [20]. The PDP 2015 has set a target to have an installed solar capacity of 6000 MW by the year 2036, and they are well on their way to that goal [17].

Thailand has several grid-connected solar power plants managed by EGAT, and they are in the process of commencing operations on a 45 MW floating solar farm (the largest in the world) located in Ubon Ratchathani, as of June 2021 [22]. EGAT partnered with B. Grimm Power Plc which served as the engineering, procurement, and construction firm for the power plant which is designed to be a hybrid system with 36 MW of hydropower [22]. The Thap Sakae Solar Power Plant has an installed capacity of 5 MW and serves as a research center for solar panel efficiency [15]. EGAT has installed four types of solar cells in order to collect data and compare how efficient each different type is within the coastal climate [15].

The 2018 National Power Development Plan details a commitment by EGAT to build more floating solar farms on all nine of its operating dams over the next 20 years for a total combined capacity of 2725 MW [22]. By 2036, Thailand plans to have an installed solar capacity of 6000 MW and expects to produce 8.4 TWh of electricity from solar panels [19].

Wind

Thailand began using wind energy in 1983 and by 2019 had 36 wind power plants, amounting to an installed capacity of 1506 MW [21]. The PDP 2015 has set targets to have an installed capacity of 3000 MW and an expected generation of 6.3 TWh from wind turbines by the year 2036 [19]. According to the Global Wind Energy Council, the number of new wind projects in Thailand will decrease for a few years due to expiring subsidy schemes without new incentives in place, however their wind market is one of the strongest in the region and will come back stronger in a few years [23].

Thailand has an average wind speed of 6 m/s at a height of 90 m, giving it a technical potential of 13 GW in 21 different areas across the country onshore and another 7 GW of offshore potential in the Bay of Bangkok [20]. This is a comparatively low wind speed and accounts for the modest growth rate of wind capacity in the country [19]. And studies have shown that if modern low-speed wind turbines are used, Thailand's wind potential jumps up to 17 GW [19]. Additionally, if the offshore potential is built, the estimated electricity production from those wind turbines would reach 15 TWh/year [19].

The largest wind farm in Thailand is the Hanuman Wind Farm, located in the northeastern province of Chaiyaphum, with a capacity of 260 MW that commenced operations in 2019 [24]. The project is built by Energy Absolute with technology from Siemens Gamesa in Spain. The wind farm consists of 103 sets of wind turbine generators rated for 2.4 MW each, at a height of 163 m and a blade length of 67 m [24]. The complex is operated and maintained by Siemens Gamesa, and the electricity generated is sold to EGAT for distribution [25].

In December 2019, the Global Wind Energy Council called for a revision to Thailand's PDP to increase the wind energy capacity goal from 6 to 7 MW by 2037 [26]. A meeting was held, called the Thailand Wind Energy Roundtable, in which they discussed implementing new policy frameworks that would support developing wind projects such as streamlining, permitting, and offering new incentives [26].

Hydro

As of 2021, Thailand has many hydropower plants at dams around the country with a combined capacity of 3000 MW [15]. The Alternative Energy Development plan does not call for an increase in installed hydro capacity due to environmental concerns, and thus hydroelectric production has been declining since 2012 when it peaked at 8000 GWh (for reference, in 2016 electricity from hydropower was only 3000 GWh) [19]. Thailand plans to have an installed capacity of 3300 MW of hydropower and expects to produce 5.7 TWh of electricity from hydro by the year 2036 [19].

Some of the environmental concerns of hydropower include the impacts dam placements have on fish migrations, river hydrology, and sediment transfers [27]. These negative complications of hydropower can affect riparian ecology up to 1000 km away from the rivers [27]. Additionally, many communities rely on nearby rivers for food and livelihood so negative impacts on the river can result in loss of food and economic security for the country's population [27].

The largest dam is the Bhumibol dam in Sam Ngao District in the Tak Province with a capacity of 780 MW [28]. The dam was built after the Second World War for fast and steady electricity supply [28]. The location for the dam was chosen after a survey and feasibility study deemed Yanhee valley in Ping River to be the most suitable area, and construction of the dam was completed in 1964 [28]. Yanhee Electricity Authority is responsible for the dam [28].

A new hydropower plant is under construction at Pha Juk dam and is expected to commence operations by the end of 2022 [29]. It will have two generators with capacities of 7 MW each for a total capacity of 14 MW [29].

Ocean

Thailand does not currently utilize ocean power, nor does it have plans to implement ocean power into the energy generation mix [19]. However, there is ocean energy potential from the two bodies of water bordering Thailand, the Gulf of Thailand and the Andaman Sea. Kompor et al. performed a study to determine feasible locations for tidal and wave projects near Thailand and found several promising locations for wave power with a maximum energy density of 0.52 kW/m [30]. Ocean wave power may become an energy option for Thailand in the future, if the cost of wave energy conversion technologies declines to reasonable rates that will make the endeavor worth the cost.

Geothermal

Thailand does not have any geothermal power plants or plans to build any in the future [19]. There are several hot springs in Thailand and studies have been performed to identify the potential from such geothermal sources [31]. It was found that there are 12 hot springs with high enough temperatures to produce electricity on a scale that justifies the cost and process of installing equipment [31]. The results of the study indicate that Thailand has a geothermal energy potential around 6.6 MW if four different technologies are used [31].

Biomass

In 2016, Thailand had an installed biomass capacity of 2812 MW, including on- and off-grid installations [32]. Of that number, only 930 MW were selling power [32]. Most of the installed biomass power plants are located in the northwestern and central provinces due to the supply of fuel from local agriculture as well as existing grid connections [32]. In 2014, it was estimated by DEDE that there is the potential for another 4000 MW from unused biomass fuels and by 2036, Thailand plans to have 5.6 GW of installed biomass capacity [32].

The main biomass resources are woody biomass residues, agricultural residues (rice husk, bagasse, corn cobs, etc.), biomass for ethanol and biodiesel production, industrial wastewater, livestock manure, and municipal solid wastes and sewage [32]. The industrial sector of Thailand relies on biomass to produce heat and electricity mostly for their own use [19].

In 2019, DP CleanTech announced plans to build a 9.5 MW biomass power plant in Uttaradit Province [33]. The plant would be owned by Uttaradit Green Power Co. Ltd and operated by Phichit Biopower [33]. The fuel for the plant will be rice husks, woodchips, or a mixture of each [33]. In 2018, Poyry was awarded the engineering contract for a 20.6 MW biomass power plant in the Chana district, and all electricity is supposed to be sold to the grid [34]. Also in 2018 the Asian Development Bank agreed to pay for a 25 MW biomass power project in the Chana district, using rubber trees as fuel [35].

Biofuels

Thailand utilizes biofuels for power generation and has a capacity estimated around 892 ktoe in 2021 [19]. That number is planned to increase up to 2104 ktoe by 2036 [19]. Ethanol and biodiesel are the two main types of biofuels used [19]. Ethanol consumption was estimated to be 4.79 million liters per day in 2021 and is expected to increase up to 11 million liters per day by 2036 [19]. Biodiesel consumption was estimated to be 3.58 million liters per day in 2021 and is expected to increase up to 14 million liters per day by 2036 [19]. The two other types of biofuels that are not as common but are expected to become more prevalent are pyrolysis oil, which has an expected consumption of 171 ktoe or 0.53 million liters per day by 2036 [19]. The last fuel is compressed biogas, and it is expected that by 2036 Thailand will consume 2023 ktoe or 4800 tonnes per day [19].

In 2015, Thailand consumed 32.6 billion liters of ethanol but the government has made plans to reduce consumption due to uncertainty over the availability of molasses and cassava supplies which are the main feedstocks for ethanol production [36]. Additionally, there are negative impacts of increasing the supply such as displacing land for food crops and the fertilizers and open field burning utilized in the cultivation of bioethanol feedstocks [37]. There is potential to utilize more postharvest and residual biomass from agricultural production if the agricultural and ethanol industries are decentralized and work as local small-scale plants to reduce current issues of transportation, material management, and the seasonal dependence of feedstocks [37].

In 2017, it was reported that Thailand had over 1700 biogas plants and more than 150 plants of industrial waste [38]. The government is sponsoring projects to use biogas to produce compressed bio-methane gas to replace natural gas for vehicles and liquefied petroleum gas used in ceramic kilns [38]. In the alternative energy plan, the Thai government has set a goal to replace 5% of the current consumption of natural gas for vehicles with compressed bio-methane gas [38]. Thailand started subsidizing biogas in the 1990s by supporting biogas projects on livestock farms and later in 2008 they encouraged industrial factories to use biogas by providing design consultants and investment funds [38]. More recently, they have been producing biogas from wastewater from food processes [38].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

Thailand does not have any notable energy storage installed, but they are working toward implementing more storage in the near future.

Country's Future Storage Direction

In 2016, the EPPO provided grants to research and develop battery energy storage in Thailand, an amount of US$23 million was provided, and so far 32 projects have been approved [19].

Thailand is also working on wind and solar-powered hydrogen energy storage systems that will utilize surplus electricity from wind and solar during off-peak hours and convert it to hydrogen [19]. Then the hydrogen fuel cell will provide electricity during peak hours [19]. The Lam Takhong Wind Turbine Generation Project is one of many such endeavors [19].

The Clean Technology Fund has helped fund the Southern Thailand Wind power and Battery Energy Storage Project in which a 10 MW wind power plant will be combined with a 1.88 MWh battery energy storage system [39]. It is expected that the plant will generate almost 15,000 MWh of electricity and reduce carbon dioxide emissions by over 6000 tons [39].

Hitachi ABB Power Grids is building a large private microgrid in which 214 MW of a combination of cogeneration gas turbines, rooftop and floating solar PV, and battery energy storage will power a "smart industrial park" [40]. The smart grid will manage and optimize power output from the different sources in real time to ensure power quality and reliability [40].

Small islands of Thailand have been testing new technologies for renewables and hybrid storage systems [19]. Due to their power grid isolation, islands are the ideal place to implement renewables, especially when paired with storage for off-peak hours [19].

In order for the energy storage of Thailand to continue to expand, the government needs to establish policies to promote their use and outline stakeholder responsibilities [41].

Carbon Footprint

Most Recent Carbon Output

In 2018, the carbon dioxide emissions of Thailand were estimated to be around 430 Mt, the highest number to date but also a slower yearly increase (up from 428 Mt in 2017) than the previous 2 years (410 Mt in 2016 and 396 Mt in 2015) [42]. The government has established a national target to reduce these emissions to 115 Mt by the year 2029 [43].

Historical Trends of Carbon Footprint

The most rapid increases in emissions happened between the years 2010 and 2011 in which emissions rose from 329 to 364 Mt [42].

In 2018, a predictive model was published which showed that current trends will cause emissions in Thailand to steadily increase if no policy action is taken [43]. The factors that affect emissions rates are found to be per capita GDP, urbanization rate, industrial structure, and total exports and imports [43]. Some unnecessary factors that are sometimes used in predictive models are population growth and total coal consumption, but this particular study has determined these factors to be the least related to emissions [43]. Previous models that included those factors led to poor policy making that has in turn resulted in the continual increase of carbon emissions in Thailand [43].

Types and Main Sources of Pollutants

The main greenhouse gas pollutant of Thailand is carbon dioxide which is primarily produced from fuel combustion activities to supply energy and industrial mining processes [44]. Other pollutants are nitrogen dioxides, carbon monoxide, ozone, and sulfur dioxide which come from the same sources as carbon dioxide and also from the chemical production industry, construction, transport, and oil and natural gas fuels [44].

Air Quality

In 2015, the overall air quality of Thailand had improved from previous years [44]. There was a 2% decrease in PM10 down to 42 μg/m^3 and a 3% decrease in PM2.5 down to 28 μg/m^3. In particular, ozone was measured at 125 ppb which was a 4% decrease, sulfur dioxide was measured at 2 ppb and nitrous dioxide was measured at 14 ppb [44]. Most particulate matter comes from motor vehicles, dust from construction, petrochemical industries, and open-burning agricultural practices within the country and from neighboring territories [44].

Energy Resiliency

Electrical Grid

Electricity was first introduced to Thailand in 1884 when Chakri Maha Prasat Hall was electrified for the first time in honor of King Rama V's birthday [45]. In 1887, the Bangkok Electric Light Syndicate began generating and selling electricity to customers within the city and was joined by Wat Lieb Power Plant in 1889 and Sam Sen Power Plant in 1912 [45]. In the 1920s and 1930s, the public health department established power plants to supply electricity to provincial areas [45]. During the Second World War, the Wat Lieb and Sam Sen power plants were badly damaged by bombs, and it took the Thai Electric Corporation 2 months to restore Wat Lieb and nearly 4 years to get Sam Sen supplying electricity again [45]. After the war, the government established many electricity-related organizations to help mitigate the electricity shortage and find ways to provide enough electricity for all residents of the country [45]. The first high voltage line was built in 1959 in Lampang Province, and it was later extended to Lamphun and Chiang Mai [45]. The northeastern provinces began utilizing hydropower power in 1962, and the Krabi power plant used lignite to provide electricity between 1964 and 1995 [45].

As of June 2021, Thailand has over 38,000 circuit-km of transmission lines ranging in voltage level from 69 to 500 kV [46]. There are 232 substations and the country's transformer capacity is almost 130,000 MVA [46].

The Electricity Generating Authority of Thailand is responsible for the power system transmission lines and their maintenance, and they have ongoing projects in five different categories [47]. The first category encompasses development projects to accommodate for increasing demand for electricity in the industrial and private sectors as well as for general use [47]. The second category includes projects to reinforce power security, continuity, and sufficiency [47]. One project in this category is a submarine cable to Ko Samui District in the Surat Thani Province [47]. The third category of projects is for standard improvements and expansions to the transmission system to replace old equipment and add more equipment to ensure the stability of the power supply [47]. The fourth category focuses on developing the transmission system for connection to new power plants including the purchase of power from local cogeneration and hydro power plants [47]. The last category is for development projects to facilitate grid to grid interconnection with neighboring countries [47]. Thailand already has five grid-connected points at 115 kV along the Lao PDR border and a 300 kV HVDC connection with Malaysia [47].

Thailand gets a high share of electricity from combined-cycle gas turbines, a reasonable share of electricity from hydropower and has a high reserve margin resulting in overall system stability and flexibility [48]. But as more renewable energies are added to the mix and as supply and demand change, they will need to adapt to keep that flexibility and stability through technological investments and a reworking of their contractual obligations to purchase power and fuel [48]. There are very few reports of unplanned power outages in Thailand in the last several years and those that were unexpected were caused by accidents or storms unrelated to the state of the transmission lines.

Thailand's electric grid reaches every corner of the country. There are no major geographical limitations to the transmission system.

Climate and Natural Disasters

The climate in Thailand is tropical, and they have seasonal monsoon winds that cause abundant rain, especially in the mountains [49]. In the year 2015, there was an annual mean temperature of 27.9 °C, which is a little warmer than past average temperatures making it the second warmest year in a 65-year period [49].

Thailand is prone to natural disasters such as earthquakes and resulting tsunamis, floods, and storms or cyclones [50]. There are four distinct regions of Thailand each with their own separate risks of disaster [50]. In the north the hills, mountains and jungles are prone to floods, landslides, wildfires, and severe winter weather [50, 51]. A flat region around the Chao Phraya River in central Thailand puts millions of people at risk of flooding [50]. The northeast region is affected by droughts that damage rice farms and instigate wildfires [50, 51]. Finally the southern region is surrounded by seas and active volcanoes and so is subject to the earthquakes and monsoons that cause floods, landslides, and storms [50, 51]. While the geography of these areas increases the potential for these types of disasters, it is important to note that for a long time, Thailand did not suffer many effects of such disasters. It was not until the tsunami in 2004 that resulted from the earthquake on Sumatra Island in Indonesia which caused over 5000 deaths and affected a great number of people that the Thai government began to take a closer look at and overhaul their disaster emergency plans [51]. In 2010, major floods in the northeast and southern regions of the country were considered the most destructive disaster Thailand had yet to face [51]. Another flood in 2011 in the southern region affected almost two million people and was extremely costly [51]. The increase in extreme weather events is a direct result of global climate change and while some studies have researched the effects of climate change and specific implications regarding sea level rise, there is much more work that needs to be done in this area to develop a full understanding [52].

Grid Resiliency

Part of Thailand's energy policy is the smart grid initiative which incentivizes state-owned enterprises to invest in smart grids by 2036 to enhance energy supply, efficiency, and resilience while reducing carbon emissions [53]. Additionally, the Electricity Generating Authority of Thailand has several projects under way to maintain and improve the grid including preparing for connections to neighboring countries through the ASEAN (Association of Southeast Asian Nations) Power Grid initiative [47]. These over-the-border connections that allow for electricity sale and purchase as opposed to simple fuel sales will increase the resiliency of the grid in each country. Having those connections in place will better allow the system to meet electricity demand while improving overall access to electricity across Southeast Asia [54].

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

Thailand imports around 20 TWh of electricity from Laos and Malaysia along with many fuels [7]. They import 50,000 metric tons of crude oil from the Middle East and Asia, and they export about ten million metric tons of oil products from their refineries in the form of diesel, fuel oil, and jet fuel [7]. Since Thailand only has lignite as a natural coal resource, they must import higher grade coal from Indonesia, Australia, and Russia for electricity production and heat in the industrial sector [10, 55]. Thailand imports around 1400 mmscfd of natural gas annually from Qatar and Myanmar [7, 6]. Thailand sells energy to neighboring countries, and this year it was reported that they sold almost 20 million kWh, mostly to Laos (19.41 million kWh) but also to Malaysia (0.14 million kWh) and Cambodia (1.21 million kWh) [56].

Relations with Global Community/ Socioeconomic Influence

Thailand signed and ratified the Paris Agreement in 2016, and even before that they had signed the Kyoto Protocol. Thailand published an updated Nationally Determined Contribution in 2020, outlining their commitment to reducing greenhouse gas emissions by 20% by 2030 [57].

Thailand joined the United Nations in 1946 as the 55th member [58]. After the Korean War in 1950, Thailand was the first to offer ground troops to the UN force [58]. Over 27,000 Thai peacekeepers have been deployed as of 2020 with significant support going to UN efforts in South Sudan including military engineers [58]. In 2016, Thailand was selected as chairman of the Group of 77 focused on the realization of the Sustainable Development Goals [58].

Thailand announced plans to strengthen relations with the Middle East by expanding partnerships and cooperation through the ASEAN and TAC (Treaty of Amity and Cooperation in Southeast Asia) [59]. Thailand gets a lot of tourism, specifically medical tourism, from the Middle East [59]. In 2018, the UN put a stop to budding trade relationships between Thailand and North Korea, but this year, in 2021, officials from both countries met to discuss how they can strengthen relations [60]. For the past few years, Thailand has been a destination for defectors of the communist state of North Korea, but Thailand has not signed the Geneva Convention on Refugees so defectors are arrested for illegal entry and deported to South Korea [61]. Thailand has a positive relationship with China, and the two countries are working together on coronavirus prevention and vaccination as well as the Belt and Road Initiative and China-ASEAN relations [62]. Thailand interacts with Russia through the Russia-ASEAN relationship, which involves the cooperation of ASEAN and Russia regarding issues of Covid-19, political and security issues, emergency and disaster management, economic issues, and science and technology [63].

Thailand is a constitutional monarchy in which a prime minister heads the government while a monarch is the head of the state [64]. The government has often changed between a dictatorship to an election-based democracy, but throughout all changes the hereditary monarch has been head of the state [64]. The monarch mainly acts as a figurehead without having major sway in the political decisions of the country [64].

Thailand has an Alternative Energy Development Plan (AEDP 2015–2036) with the following targets for installed capacity: 3.3 MW of Hydropower, 3 MW of Wind, 6 MW of Solar, 600 MW of Biogas, 5.6 MW of Biomass, 501 MW of waste, and 680 MW of Energy crops [65]. If these targets are met, renewables will provide 20% of the electricity consumed in Thailand in 2036 [65].

Education

Thailand has several EGAT learning centers at power plants around the country that can be visited [15]. For example, at Chana power plant the exhibits aim to educate visitors on energy saving measures they can implement on a daily basis [15]. The Lamtakong Jolabha Vadhana Power Plant has an education center that contains exhibits on pumped storage, wind power, and storage systems for renewable energy [15]. The Mae Moh Power Plant has a mine museum and botanical garden to raise awareness on coal power and the importance of Mae Moh regarding the power security of the country, in addition to an exhibit focused on reducing impacts of electricity generation on the environment and community [15]. These are just a few examples, and there are many other EGAT learning centers around the country [15].

Summary

Current Energy Situation

Thailand consumes 191.9 TWh of electricity every year [2]. The primary method for generating electricity is the burning of natural gas which generates 112.6 TWh, and this accounts for 58.68% of the total electricity consumption [2]. Coal is the second most consumed fuel in Thailand, generating 35.1 TWh of electricity or 18.27% of the total consumption [2]. Oil accounts for only 0.5% of the total consumption as it is used to produce 0.9 TWh of electricity [2]. Renewable energies all together generate 13.2 TWh of electricity, accounting for 6.9% with an additional 0.5 TWh (0.24%) of electricity generated from pumped-storage hydropower plants [2]. The remaining 29.6 TWh of electricity was imported, and this accounts for 15.41% of the total electricity consumption [2].

Of the renewable energies, the most recent data shows that solar power generated around 5 TWh of electricity (2.6% of the total), and it is expected that by 2036 Thailand will generate 8.4 TWh of electricity from solar [19, 20]. Wind turbines are expected to produce 6.3 TWh of electricity by 2036 which would account for somewhere between 3% and 4% of the total energy consumption, depending on how much consumption changes between now and then [19]. Hydropower dams produce 3 TWh accounting for 1.6% of the total consumption, but this is expected to increase up to 5.7 TWh (2–3%) by 2036 [19]. Thailand has biomass plants for electricity production, but the precise amount of electricity consumed from this source is not reported; however, it is estimated that Thailand has an installed capacity of 3000 MW of biomass power plants [19]. Thailand does not utilize ocean or geothermal energy nor do they have plans to implement those technologies [19]. Thailand does not currently use nuclear power, but they have plans to build two nuclear power plants by 2036 with a combined capacity of 2000 MW [17].

Future Energy Situation

Thailand has ongoing energy projects to strengthen their electric grid and energy security while providing a larger share of electricity from renewable energies. They are following their Alternative Energy Development Plan which has targets set for the installed capacity of renewable energies by the year 2036. Additionally, the World Wildlife Fund has researched the Sustainable Energy Scenario (SES), which demonstrates that it is technically and economically feasible for Thailand to supply the total electricity demand from domestic sources with 85% from renewables by the year 2050 [66].

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Vietnam

Slobodan Petrovic and David Green

National Energy Introduction

Trends in Generation Technologies

Due to their increasing population and industrial sector, Vietnam's energy generation trends have fluctuated tremendously based on what was available. The chart below shows the year-to-year changes in primary energy consumption by sources from 2004 to 2019 [1] (Fig. 1).

As the chart shows, hydropower and coal are the two sources that have experienced the most drastic changes in generation and by effect consumption. There has been an uptick in renewable energy generation recently, with solar and wind power providing 10% of the total electricity production at the beginning of 2020, already meeting the government's 2030 goal [2]. Furthermore, as a member of multiple climate agreements, Vietnam is looking to provide even more of its electricity from renewable sources, while reducing the use liquid natural gas (LNG) coal-fired power plants [3].

Domestic Resources

Vietnam also has a vast quantity of domestic resources in minerals, coal, oil, and hydropower, with each controlled by the state. According to the United States Geological Survey (USGS), Vietnam is ninth largest of antimony and phosphate, the tenth largest of tin, the 11th largest of bauxite (important for Al), the 12th largest of titanium, and the 13th largest of manganese worldwide [4]. Due to the Mekong River delta, Vietnam has a large potential for hydropower as shown by their historical reliance on it. The state-run oil company PetroVietnam (PVN) is one of the largest producers of oil in Southeast Asia due to the large reserves found off the southern shore [5]. Their coal production is found mostly in the hills to the north, and it is mostly anthracite coal [5]. Although it makes up a large part of their energy consumption and generation, Vietnam has been a net coal importer since 2015, due to the increased electricity demands from their industrial sector and population growth [6].

History of Energy

Vietnam is a coastal nation occupying the eastern shore of Southeast Asia with a population of around 103 million people [6]. It has a long, complex history of occupation as a part of ancient Chinese dynasties, French Indochina, and other Western countries up until 1976, but it still maintains relatively strong relations with those countries [5]. As such, their energy sector was heavily influenced historically by those relationships, with oil making up as much over 80% of their energy consumption at one point, until their independence that saw a conversion to coal [1]. Since 1976, the ruling party in the country has been the Communist Party of Vietnam (VCP) that controls a vast majority of the country's energy resources with state-run companies such as Electricity Vietnam (EVN) and PetroVietnam (PVN) [5]. Their electricity is generated mostly by coal-fired power plants and hydroelectricity, which, at various times in its history, comprised 53% and 75% of the total electricity demands, respectively [1]. Historically, the residential sector consumed most of the energy (as Vietnam was a largely agrarian country), until 2008 when the industrial sector began to boom, and its energy use skyrocketed; it was surpassed by transportation in 2015 as the country began to be modernized [7]. They have achieved 100% electrification in all of their provinces, so their energy demand will only continue to rise [1].

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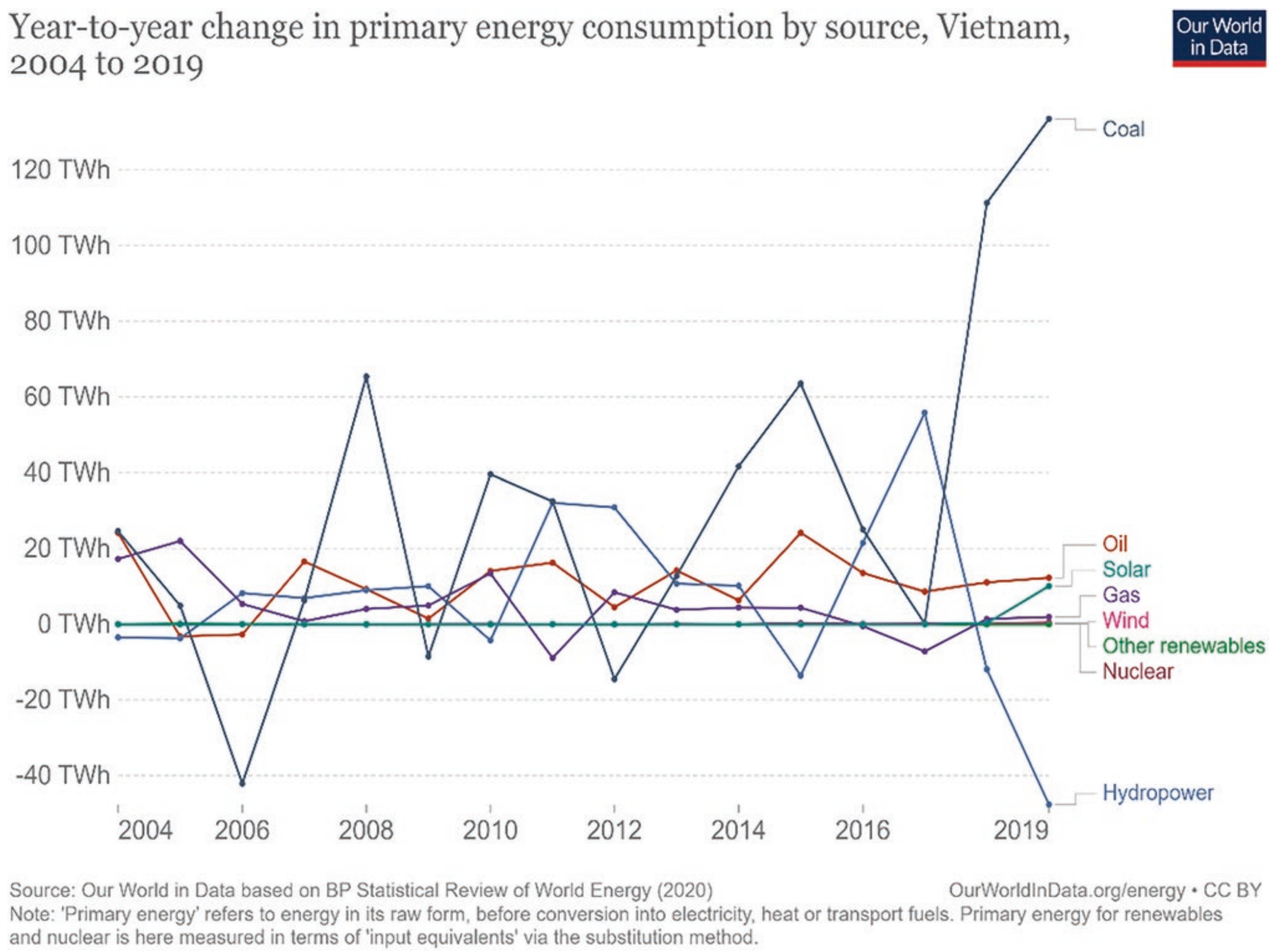


Fig. 1 Yearly change in energy generation with hydropower and coal swapping dominance in the more recent years

Breakdown of Energy Generation "Mix"

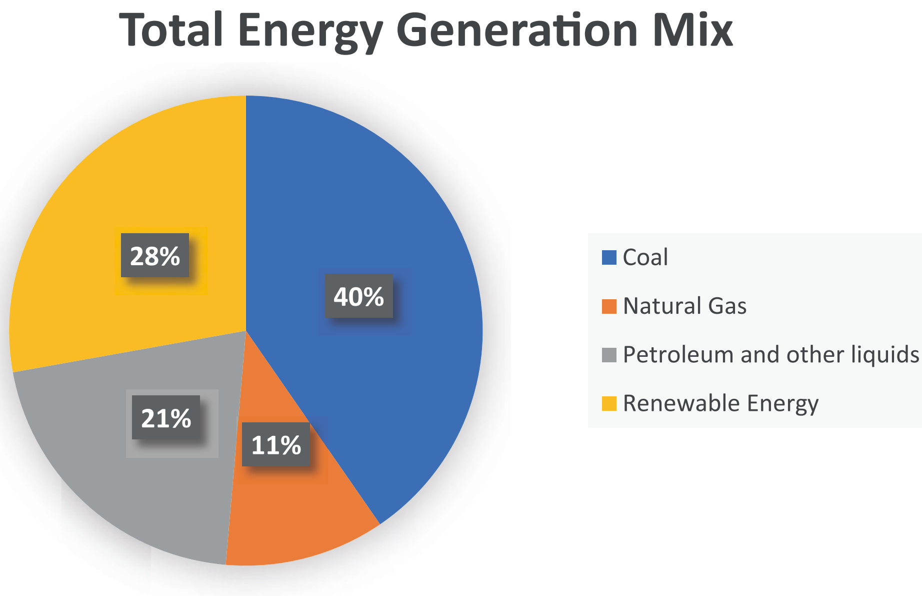
Energy Generation Mix

Vietnam's energy generation mix consists of coal and renewable energy, with most of the renewable energy coming from hydropower. Not all forms of energy are accurately reported as the state controls almost all the information coming in and out of the country. For example, the data shown in the chart below are only accurate as of 2018. Vietnam has a rapidly changing landscape in terms of energy generation since they need to provide energy to their growing population and industries but has to balance that with renewable energy generation. If they were shown to have produced more energy from fossil fuels than desired, the state-controlled sources of information may have prevented worldwide release of that information (Fig. 2).

Energy Consumption Mix

However, their energy consumption is more readily available, and the chart of their consumption over time is included. As stated earlier and can be seen clearly from the chart, oil and coal consist of most of the energy consumption followed by hydropower (Fig. 3). Hydropower's higher percentage of energy consumption and energy generation is mostly derived from the electricity generated, as can be seen in Fig. 4. Furthermore, Vietnam imports energy from Laos and China, whose total values might be included in their respective sources (i.e., the energy they buy from Laos is wind-powered so it might be included in that total) [8].

Fig. 2 Breakdown of energy mix by percentage with 1.115 quad Btu of coal, 0.302 quad Btu of natural gas, 0.574 quad Btu of petroleum and other liquids, and 0.768 quad Btu of renewable energy



Fossil Fuels

Oil

Vietnam is a large producer of oil in Southeast Asia due to the large oil deposits off the southern coast; as a result, almost 26% of their energy consumption in 2019 was oil [1, 5]. They do not import any oil, as their production covers their domestic needs, and they export what they do not use for themselves [6]. Their main sources of exportation are China, Australia, and Singapore, and they were the 34th largest producer of oil in the world in 2019 [9]. However, Vietnam's oil production has declined in the recent years, falling from a height of ~352,000 barrels per day in 2015 to ~207,000 barrels per day in 2020 [9]. PVN stated in July 2020 that crude oil production has peaked at most of its offshore oil fields and that it will stop developing coal-fired power plants in favor of renewable energy [10]. This follows a trend in recent years of de-emphasizing fossil fuel use and switching to cleaner forms of energy generation. PVN has four major refineries: two for fertilizer production, one for oil refinery, and one for petrochemical refinery, and it has four gas-to-power plants: three hydropower plants and one coal-fired power plant [11]. These refineries and power plants have produced 11.47 million tons of crude oil, 1.8 million tons of fertilizer, 11.85 million tons of petroleum products, and 19.2 billion kWh of electricity in 2020 [11].

Coal

Vietnam produces most of its electricity through coal-fired power plants, with 300 TWh (nearly 53%) of its generation in 2020 coming from coal [1]. They have around 3.36 billion tonnes of coal reserves as of 2020 and have over 14 GW of coal-fired capacity [12, 13]. While they produce a lot of coal, Vietnam transitioned from a net coal exporter to a net coal importer around 2015 due to an increase in population and industries with most of their imported coal coming from Australia, Indonesia, and Russia [10]. However, as mentioned earlier, their use of coal currently fluctuates depending on their energy needs but will see a steady decline in the coming years as Vietnam focuses on installing more renewable energy and cleaner-burning LNG [3]. An example of their current predicament involving coal is highlighted by some recent transactions: In the period of January–June in 2020, Vietnam's coal imports increased by 53.8% from the same period a year earlier, which is 25% overall for the entire year compared to 2019 [10, 14]. However, in 2021, coal imports decreased by 33% for the period of January–May, down from 24.9 million tons to 16.6 million tons [14].

This decline is due to a number of factors like greater generation from renewable sources and less strain on the grid from people staying indoors during the coronavirus pandemic. The increased importation of coal (and by effect increased electricity usage) during the height of the coronavirus pandemic, that is, April–May in 2020, is more of an outlier than the 2021 import data, which falls more in line with import statistics of coal from 2016 to 2019 [14]. Thus, when analyzing Vietnam's coal importation and the use of coal for electricity generation, it is important to consider the circumstances surrounding the country in 2020: a large, dense, and growing population that was forced to shelter in place due to a highly contagious virus. This will be detailed later in the sections "Electrical Grid" and "Energy Resiliency" to expain the strain on an already-unreliable grid [15].

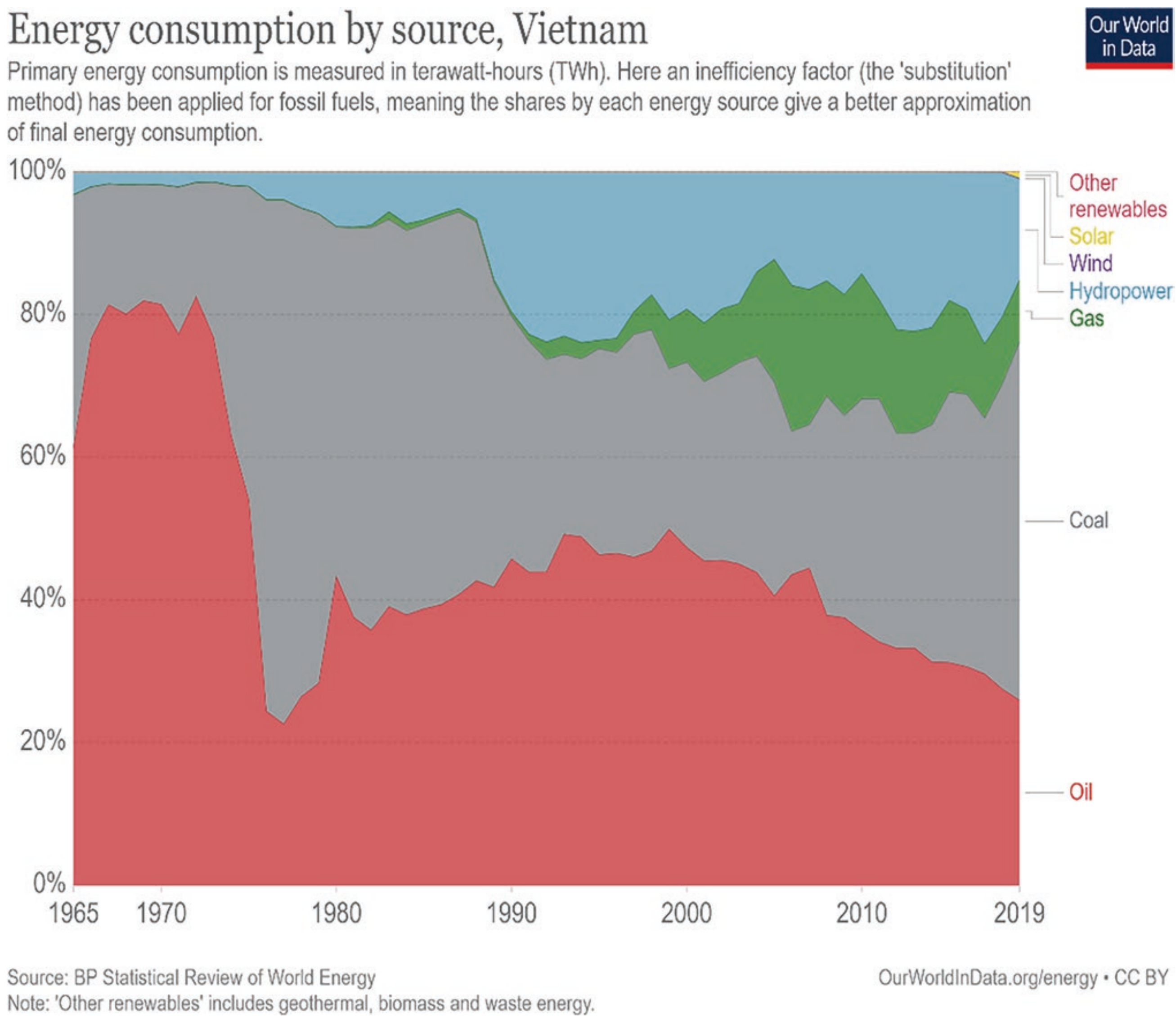


Fig. 3 Relative energy consumption by sources

Natural Gas

Natural gas in Vietnam is similar to the situation regarding oil: They produce enough to cover their own domestic needs and are found in the same areas off the southern shore; however, they do not usually export as their production matches their consumption [1]. For example, in 2019, they produced and consumed 99 TWh of natural gas, which means they did not export any [1, 12]. As of 2019, Vietnam had 22.81 trillion cubic meters of natural gas reserves, but with steadily increasing natural gas usage, they may have to import more in the coming years. Currently, the country only has about 7.1 GW of installed capacity for LNG but has plans to expand the capacity to over 38 GW by 2045 [13].

While it currently does not have a large role in the energy generation and consumption in the country, the current Power Development Plan (PDP 8) heavily leans on the use of natural gas in the future as did all of the versions of the PDP before PDP 8 [3]. It remains to be seen whether Vietnam will install the capacity in time to match their demands or whether there will be a period of importing LNG.

Nuclear Energy

Vietnam does not possess any nuclear energy power plants or does not have any of their electricity produced from nuclear sources [1]. There were plans to build two plants in one of the lesser populated provinces, but plans were delayed in order to ensure safety conditions [16]. The plans to include nuclear energy in their generation mix is almost entirely foreign: The plants were partially funded by Russia and

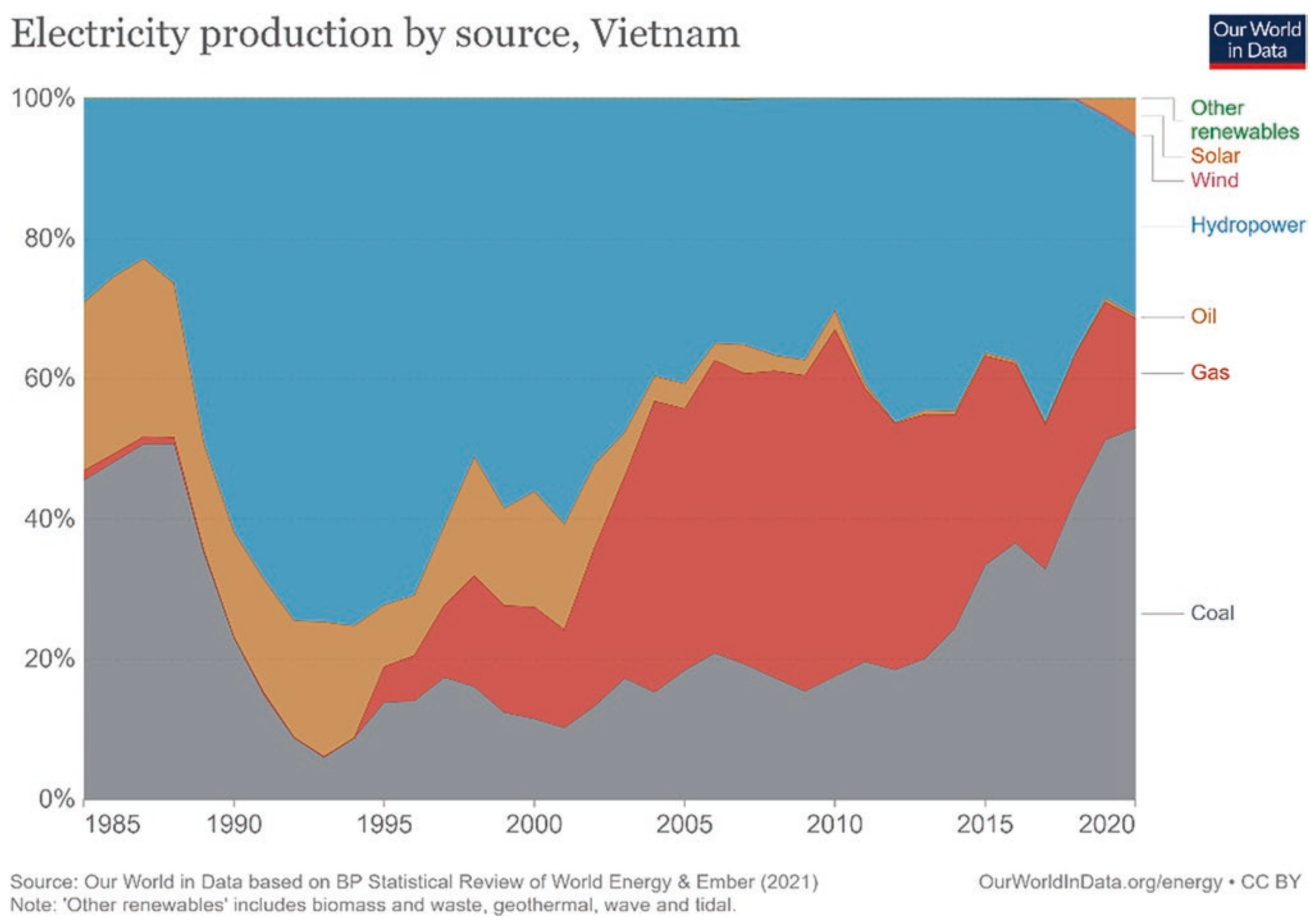


Fig. 4 Relative electricity production by sources from 1985 to 2020

Japan, South Korea and China have been in talks with Vietnam about supplying necessary equipment, and the fuel would be bought from a Canadian company [16]. The PDP 8 removed the future installation of nuclear energy that was in the amended PDP 7, but it remains to be seen whether they will return to this issue as their energy use continues to escalate and their coal usage deescalates [13].

Renewable Energy Generation

Photovoltaics (PV)

The installed capacity of solar PV technology in Vietnam is currently over 16 GW, nearly 25% of its total installed capacity for electricity generation, with plans to more than double it by 2035 [13]. The largest solar power plant in Vietnam is the Trung Nam Thuan Nam Solar Plant built by the Trungnam Group in the southeastern province of Ninh Thuan [17]. It has an installed capacity of 450 MW and became operational in October 2020 [17]. Solar PV provided around 5% of their energy generation in 2020, and even though they added more capacity in 2020, Vietnam plans to reduce its renewable energy output [18]. This is due to their unstable grid and lack of transmission capacity to bring all of the generated energy to households [18].

Rooftop solar is incredibly popular in Vietnam, comprising 13.7 GW of the 16.6 GW of solar PV capacity [19]. This is due to their lucrative feed-in-tariff (FiT) schemes that allow solar projects that are commercially operational by the end of a certain year to receive a fixed rate for each kWh generated and exported to the grid for 20 years [15]. The one in 2020 was the second of its kind, after the first FiT led to 4.5 GW of capacity additions, and 9.3 GW of capacity was added, 6 GW of which was added in the last month of 2020 [19].

Using solar power, under the PDP 8, there are plans to increase the capacity to 17.2 GW by 2025, 18.6 GW by 2030, 30.3 GW by 2035, 42.3 GW by 2040, and 55.1 GW by the year 2045 [13]. The greatest solar potential is in the southern part of the country, whose photovoltaic power potential map can be found in the Appendix [20]. As stated earlier, the only trouble with this increase in capacity is that Vietnam's grid cannot handle that amount of transmission capacity; thus, until it is updated, the effectively third largest solar market in 2020 could go to waste [19].

Wind

As of 2020, Vietnam had only 630 MW of wind capacity, which only generated 0.97 TWh of electricity: good for 0.36% of Vietnam's electricity demand [1, 13]. The Trungnam Group has built the largest wind farm in the country, with a total capacity of 152 MW, combining it with their 204-MW solar power plant in the Ninh Thuan province creating the largest solar–wind combined power plant in Southeast Asia [21]. While currently an exceedingly small portion of their electricity generation in 2020, Vietnam has plans to increase their wind power capacity rapidly and exponentially. According to the PDP 8, they have plans to increase their wind capacity, depending on whether they reach the base-load scenario or high-load scenario, from 630 to 11,320 MW or 12,280 MW, respectively [13]. It is important to note that 1833% to 2000% increase in capacity does not include offshore wind capacity.

There is currently no offshore wind capacity, but there will be at least 2 GW by 2030 under the PDP 8's base-load scenario (3 GW for the high-load scenario) with increases to 9 GW, 15 GW, and 21 GW in the base-load scenario by 2035, 2040, and 2045, respectively (11 GW, 23 GW, and 36 GW in the high-load scenario) [13]. Vietnam's long eastern coastline provides an extremely exploitable offshore wind potential, as shown in the wind potential map in the Appendix [22].

Hydro

As of 2020, Vietnam has a hydropower capacity of over 17 GW installed [13]. Historically, hydropower has generated a large majority of Vietnam's electricity due to the numerous rivers like the Mekong that run throughout the country, at one point consisting of 75% of the total electricity generation [1]. More recently, though, its contribution to the total electricity generation has fluctuated due to increased demand that coincides with droughts or water shortages [18]. The largest of these plants is the Son La Dam, located on the Da River, with a generating capacity of 2400 MW, and was built by EVN with a help from GE; it is also the largest hydropower plant in Southeast Asia [23].

As stated earlier, Vietnam is home to many rivers, so hydropower has the potential to be exploited already more so than it has. However, since it has been a substantial portion of their energy generation thus far, hydropower's future is a limited one. The PDP 8 outlines an increase from 17 GW now to close to 19.8 GW by 2030 and for it to remain at that level through 2045 [13].

Ocean

Vietnam currently has no installed facilities that exploit ocean or wave energy [13]. This is surprising considering their long coastline and that one of their major cities, Da Nang, is a popular surf spot, which would make them an ideal country for utilizing this renewable energy source. However, since the major energy companies in Vietnam are state-controlled interests, the only way for their current policy to change is for the government to act. The PDP 8 is the reference for what energy policies the government will take going forward and it does not include any section for ocean-generated energy [13]. This is likely due to the fact that the size of most ocean-energy projects are smaller scale, and Vietnam, with its growing population and industries, is most likely looking toward larger scale energy generation projects.

Geothermal

Vietnam currently has no installed capacity and generates no energy from geothermal sources [1, 13]. A study conducted in 2005 found that there are 269 geothermal sources in the country with a temperature above 30 °C that could be used [24]. However, the PDP 8, which comes from the government, has no plans for geothermal sources, so it will remain to be seen whether Vietnam ever utilizes its potential [13].

It is worth mentioning that for both geothermal and ocean-generated energy are not explicitly mentioned in the PDP 8 and further research into both the topics yielded very little results [13].

Biomass

As of 2020, Vietnam had 570 MW of installed capacity for biomass and other renewables and produced 0.13 TWh, or about 0.05% of their electricity demand, from it [1, 13]. They currently have no biomass power plants, and any energy derived from biomass is done on a local level [25]. However, under the PDP 8, Vietnam has plans to expand its biomass energy use to 3150 MW by 2030 and 4510 MW by 2040 [13]. It has the potential to produce this energy as a 2021 study showed that the country has the potential to produce 2565 MW just from rice straw where 24 of the 63 provinces have the potential to produce over 30 MW [26]. Vietnam, due to its agricultural sector, also has the potential to exploit bagasse, coffee husks, and wood chips [25].

Biofuels

According to Pham Trung Thuc, Director of the Department of Renewable Energy in the Ministry of Industry and Trade (MOIT), biofuels currently provide 5% of the transportation sector's fuel demand [27]. At present, the only biofuel producer in Vietnam is Tung Lam with two open plants [28]. There were five other plants, some of which were state-owned, that halted production due to inefficiencies and financial losses [28]. Their production relied on locally grown cassava to produce this energy but, due to an increase in population and food demand, lost favor to corn, which is more energy dense [28]. This means that any biofuel energy that needs to be generated has to have some importation to it, thus reducing Vietnam's energy self-sufficiency.

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

Vietnam currently does not have large-scale battery or other types of energy storage, such as pumped hydro storage [13]. While there are numerous high-tech companies in the country, which indicates the use of some battery storage in the form of uninterruptible power supplies (UPSs), there are none that are used as storage for generated power. This, and Vietnam's geography, also further indicates that it has the capacity for energy storage in both pumped hydro and battery storage.

Country's Future Storage Direction

The government recognizes the importance of battery storage going forward, as they have included a rapid expansion of "Pump-storage hydropower + battery energy storage" in the PDP 8, starting with 1.2 GW of capacity by 2030, 5.4 GW by 2035, 9.3 GW by 2040, and achieving 13.8 GW of storage by 2045 [13].

This is a critical development in their energy policy, as Vietnam will see an increasing demand in the future, which can be solved with energy storage. Furthermore, since the emphasis will be shifted toward more offshore wind and solar PV, which become ineffective at times during monsoon season, having energy storage ensures that the country will be able to provide power to its residents in case of emergency.

Carbon Footprint

Most Recent Carbon Output

By the end of 2018, Vietnam emitted 376.53 megatons of CO_2 equivalent emissions excluding land use change and forestry (LUCF) and 364.43 megatons of CO_2 equivalent emissions including LUCF [29]. The Climate Action Tracker has rated Vietnam as "critically insufficient" after the country updated their Paris Agreement Nationally Determined Contribution (NDC) target in 2020 to still have emissions well above the current policy projection [30]. Accurate and recent data on their greenhouse gas emissions are hard to find, as the Vietnamese government controls a majority of the information that is released by the country. As such, if their emissions are well above what they should be, it is entirely plausible that the government suppressed its release to protect itself from criticism. It is intriguing that the majority of data sets that were available do not have data past 2016. This potentially suggests that knock-on political effects (like the election of a United States president who does not care about emissions) affect what data the government will release; if it does not feel pressure to release data about their emissions from outside countries, the government will not release it.

Energy Resiliency

Electrical Grid

Vietnam's largest issue is that its electrical grid is not up-to-date. As stated earlier, the power generated by solar PV is often wasted as the transmission capability and capacity of their electrical grid cannot handle the incoming energy [18]. Some of the country's transmission lines are operating at full load or are overloaded [18]. However, the government is aware of this issue and, since it controls the company that provides more than 95% of the country's electricity, has decided to act. The Ministry of Industry and Trade (MOIT) issued Resolution No. 21, which sets the general priority that inclusion of power grids is prioritized over inclusion of power generation sources [31]. Due to their expanding population and industry, it is the critical issue for the country to solve, and since the government controls the actions that the utilities take, this resolution is a step in the right direction. This resolution is a further expansion on the PDP 7, which covered power sources and power transmission grid development planning for voltage levels of 220 kV or larger which is essential for industry [31].

Climate and Natural Disasters

Vietnam lies in the tropical monsoon area of the northwest Pacific Ocean and has a complex topography with the Annamite Range to its west, the Mekong River basin in the south, and the Red River basin in the north [32]. As a result of this complex topography and its location, the country experiences a wide range of natural disasters ranging from floods, whirlwinds, flash floods, coastline erosion, droughts, and landslides [32]. According to the World Bank, 70% of the population is vulnerable to these natural disasters with storms and floods accounting for 40% of all natural disasters [33]. The island of Phu Quoc, off the southwestern coast of Vietnam and just southeast of Cambodia, experienced the worst flooding in its history in August 2019; many experts believe that climate change and rapid development are to be blamed for it [33].

Since the country relies on hydropower, natural disasters can have a significant impact on their energy generation. As stated earlier, droughts and water shortages can lead to a drop in energy production from hydropower, which is seen in the increase of coal use. The monsoon season, which can bring heavy rains and winds, can also significantly impact their renewable energy generation, especially at the time of writing this. Most of Vietnam's renewable energy generation is in solar PV, which needs clear skies that are not prevalent during the rainy monsoon season. Similarly, in the future as they add more wind power capacity, the high winds during stronger monsoons may force the wind turbines to stop in order to protect them.

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

Vietnam does not rely on foreign countries for its fossil fuel generation, as it produces enough to cover their own needs before exporting what they do not use [6]. However, they do rely on importing some energy from Laos and China to cover their energy needs [13]. EVN has entered a Power Purchase Agreement (PPA) with a Mitsubishi subsidiary and the Thai renewable energy company, Impact Energy Asia Development (IEAD), to buy energy from a wind farm in Laos starting in 2024 and lasting for 25 years [34, 35]. This purchased energy, according to the PDP 8, will consist of over 2800 MW by 2025, then increase to almost 5000 MW by 2030, and stay at that amount until 2045 [13].

Relations with Global Community/Socioeconomic Influence

Vietnam is a member of the United Nations, the Paris Climate Agreement, and the Kyoto Protocol [6]. It is officially known as the Socialist Republic of Vietnam, but the ruling party is the Communist Party of Vietnam (VCP), and their economy is more state influenced than not. The country is not currently embroiled in any militaristic or political conflicts but has a long and complex history of relationships with China, the United States, Russia, and France. In ancient history, China and Vietnam were in conflict with one another, but as Vietnam evolved into a communist country, its relationship with China and Russia improved [5]. Due to the Second Indochina War (commonly known in the United States as the Vietnam War), Vietnam and the United States have a tenuous history, but relations between the two have improved rapidly over the past couple of decades as globalization has increased interactions between the two [5]. A decent portion of the population is highly educated as evidenced by their high-tech industry that comprises a majority of their economy, and they often send their students to universities in other countries to broaden their education.

According to the MOIT, the total percentage of electricity production by sources in 2050 shall be 8.1% biomass, 5.0% wind, and 20.0% solar, accounting for 33.1% of their total generation [27]. However, the same report also states that the MOIT shall determine, on an annual basis, the minimum proportion of renewable energy generated by power generation or distribution entities [27]. This, along with other historical indicators, suggests that if the government feels increased pressure to meet certain goals, they will adjust their proportions of renewable energy generated accordingly. One of the difficulties in predicting what the country's direction is in terms of renewable energy is that the direction can change depending on the government's whim; just as policy in Democratic countries can change on major companies' whims or whoever wins the most votes that election season. While Vietnam's policy might be a little more predictable than that of other major countries, the caution and secrecy that the government exercises in information release means that policy can change internally with little notice.

Summary

Current Energy Situation

Vietnam has a growing population and industries and as a result a growing energy demand [1]. Their main obstacle is the lack of infrastructure to support this growth as their transmission lines need update. As a result, the country's energy demand on a year-to-year basis has fluctuated vastly between hydropower and coal; this suggests that the policy of generation at the moment is to source it from wherever they can to support their population [1]. Historically reliant upon oil, coal, and hydropower for their energy generation, Vietnam has seen a shift toward more renewable energy, becoming effectively the third largest solar market in 2020 due to the popularity of their FiT scheme [19].

Future Energy Situation

The country also has plans to rapidly expand its renewable energy portfolio in areas like onshore wind, offshore wind, biomass, energy storage, and potentially nuclear energy in the coming years under the PDP 8 [13]. With its proximity to large countries like China and Indonesia and a population of 103 million people, Vietnam is poised to become one of the world's leaders in renewable energy generation in the coming years.

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Part IV

Americas

Argentina

Slobodan Petrovic and Ronald Haynes

National Energy Introduction

Located on the southern half of South America, the Argentine Republic (Argentina) is home to a population of approximately 45 million people of Mestizo and European descent. The national language is Spanish, and approximately 80% of the population practices Christianity as a form of religion. The nominal gross domestic product (GDP) for the residents of Argentina is $9887, making it the world's 53rd largest economy and the 3rd in Latin America. The capital, Buenos Aires, is the largest city in Argentina and is located on the northeastern coast, west of the Rio de la Plata estuary [1].

Argentina's economy has become increasingly service-driven upon entering the twenty-first century [2]. The top economic sectors are commerce, tourism, manufacturing, and agriculture. Argentina's main trade partners are Brazil, China, and then the United States. Their main exports are refined petroleum products, vehicles, corn, wheat, soybeans, and related products. Argentina's main import products are petroleum, natural gas (NG), machinery, motor vehicles, organic chemicals, and plastics [3].

Energy Policies

The early twenty-first century saw the Argentina government continues to deliver policies that favored fossil fuel resources. However, the Argentina government is transitioning to policies that now favor renewable resources with the 2016–2025 Renewable Energy Program, The energy generation breakdown is shown in Fig. 4.

During the early twentieth century, the Argentina's electricity sector was vertically integrated and government-owned.

However, during the early 1990s, Argentina experienced a series of energy crises due to the lack of maintenance of nearly half the country's thermal power plants [11]. Since then, Argentina has undergone a process of institutional reform and privatizing the energy sector. These reforms vertically and horizontally unbundled segments of the electricity sector, such as the generation, transmission, and distribution. There was a separation of regulatory functions and policy-making and was the inclusion of the private sector to all segments of the electricity sector [2].

The Ministry of Energy and Mining (MINEM) regulates the electricity sector by means of policies and guidelines. The National Electricity Regulatory Entity (ENRE) supervises the electricity sector and enforces the policies of the MINEM. The management of the wholesale electrical market is carried out by the Argentine Wholesale Electricity Market Administrator Company (CAMMESA). When it comes to the monitoring and investigation of the national and municipal governments, that falls under the jurisdiction of the Federal Electrical Energy Council (CFEE). The commercialization of private concessionaires is carried out by the CAMMESA, and the studies/planning of the energy sector is carried out by the Secretariat of Strategic Energy Planning [9].

In 2015, Argentina launched the 2016–2025 Renewable Energy Program (RenovAr). The purpose of the RenovAr is to increase the penetration of renewable energy in the grid by 20% by 2025. The total energy requirement for the initial contracts is 600 MW of wind energy, 300 MW of solar energy, 65 MW of biomass, 20 MW of small hydroelectric projects, and 15 MW of biogas [9]. Argentina is expected to save US$300 million per year in fuel imports from this initiative [9].

Trends in Generation Technologies

Natural gas represented 52% of total primary energy consumption in 2015 and is used widely in the electrical, industrial, and residential sectors. Petroleum represented 36% of total primary energy consumption and is used in the transportation sector.

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Hydroelectricity is the third largest primary energy resource and is the bulk of renewable energy currently exploited, followed by biofuel and biomass, which are used by the transportation sector and the surplus exported [8].

From Fig. 1, it is apparent that hydrocarbon fuels are the primary fuel source (67%, 2016), followed by renewables (28%, 2016) and nuclear (5%, 2016). The demand for hydrocarbons has had a consistent growth over the decades, aside from a decline during their 2000 recession. Renewables have seen a minimal growth, and most of them were primarily driven by hydroelectricity generation.

Domestic Resources

Argentina has a landmass over a million square miles and an Atlantic coastline that spans approximately 3100 miles north to south. Five countries share a border with Argentina: Chile to the west, Bolivia to the northwest, Paraguay to the north, and Brazil and Uruguay to the northeast. The western border is defined by the Andes Mountains to the west of Argentina. Due to the Andes, most of the western and southwestern regions of Argentina experience levels of the rain shadow effect. The northeastern regions of Argentina are closer to the Tropic of Capricorn and experience temperate climate patterns [4].

Argentina has two main ocean currents, shown in Fig. 2, that impacts the regions' climate. There is the Falkland Current that flows north from West Wind Drift around Cape Horn and brings dense cold subarctic water [5]. Then, there is the Brazil Current that flows south from the Atlantic South Equatorial Current and brings lighter warm subtopic water [6].

The South Atlantic High (SAH) and South Pacific High (SPH), shown in Fig. 3, are the two main air masses that impact the air circulation of Argentina. Due to the Andes position to the west of Argentina, the SPH impacts are limited to the Patagonia region, and so the SAH is the dominating air mass. The SPH brings moist, cold air north from Patagonia, and the SAH brings moist, warm air southwest from the Atlantic Ocean [7].

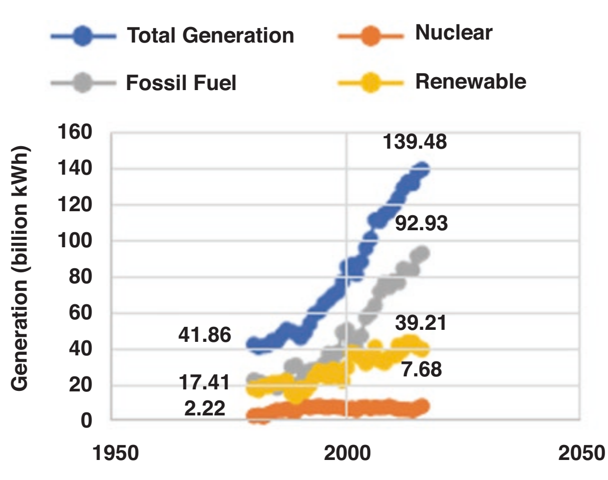


Fig. 1 Argentina's annual power generation [8]

History of Energy

Like other middle-income countries that developed a modern grid in the twentieth century, this growth was powered by fossil fuel and government control of the energy sector. However, the reforms have been made in the early 1990s, and now, the grid is privatized and less centralized.

Breakdown of Energy Generation "Mix"

Fossil Fuels

Oil

As shown in Figs. 5, 6, and 7, Argentina has steadily increased their production, consumption, and imports of petroleum products. This is driven by the growing demand by the middle-class population and industrial and transportation sectors [9].

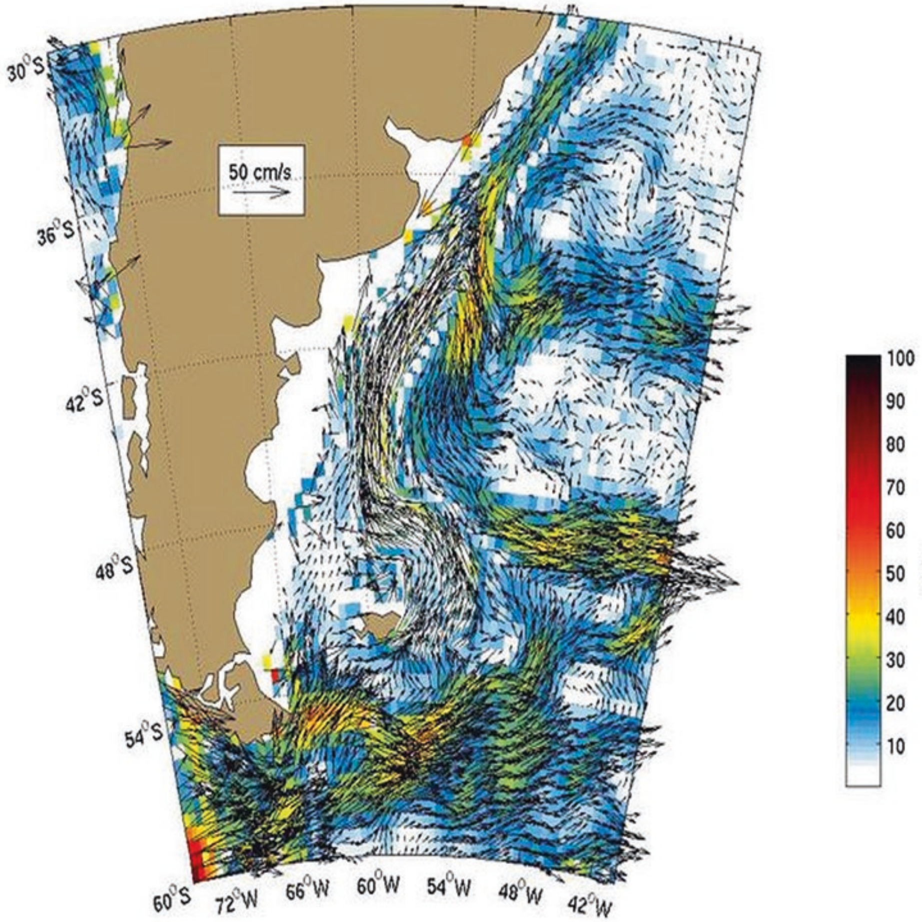
Coal

As shown in Figs. 8, 9, and 10, Argentina has had a steady consumption of coal. However, their production of coal has steadily declined, while their levels of coal imports steadily increased to meet the consistent demand.

Natural Gas

As shown in Fig. 11, Argentina has steadily increased their production of natural gas (NG) until peaking in 2006, and then the production declined until 2015. Figure 12 shows that the consumption of NG has steadily increased over the decades to meet energy needs. The exponential importing of NG from Fig. 13 aligns with the dip of NG production and will be further discussed in the section "Energy Resiliency".

Fig. 2 Falkland and Brazil currents



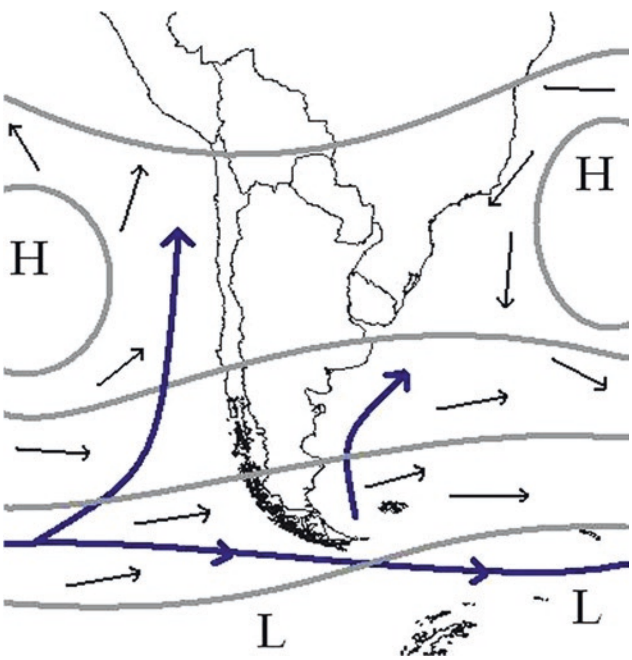


Fig. 3 SPH and SAH air circulations

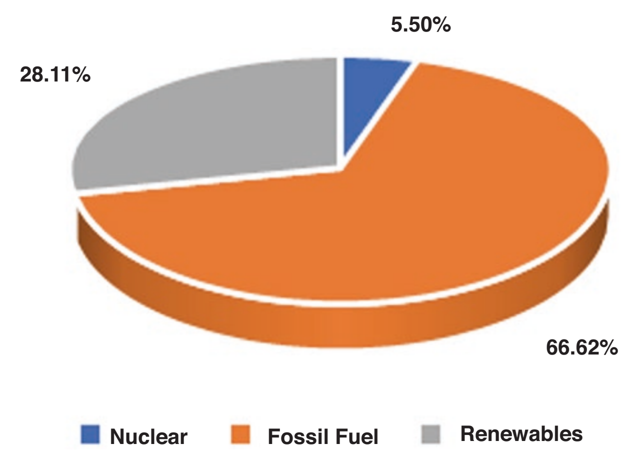


Fig. 4 Argentina's annual energy generation (2016)

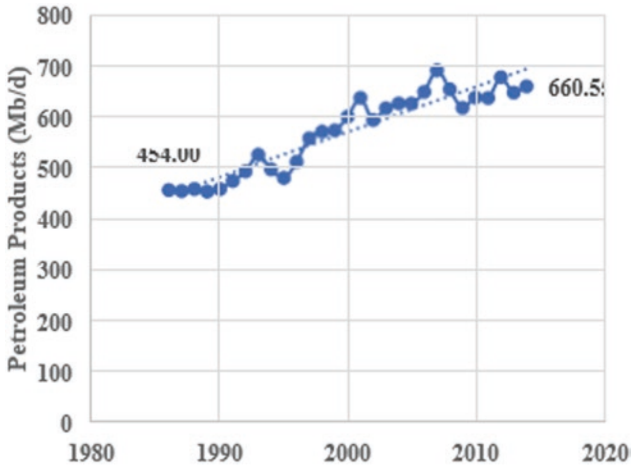


Fig. 5 Argentina's annual petroleum production [8]

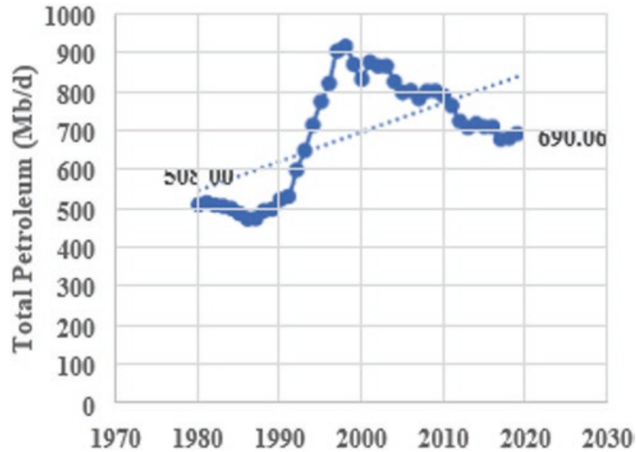


Fig. 7 Argentina's annual petroleum imports [8]

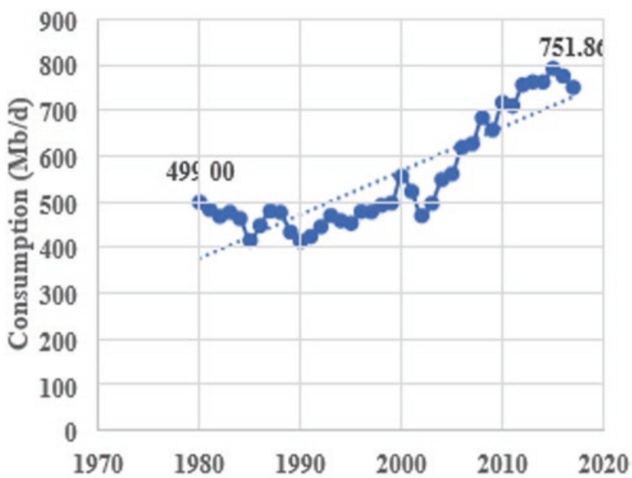


Fig. 6 Argentina's annual petroleum consumption [8]

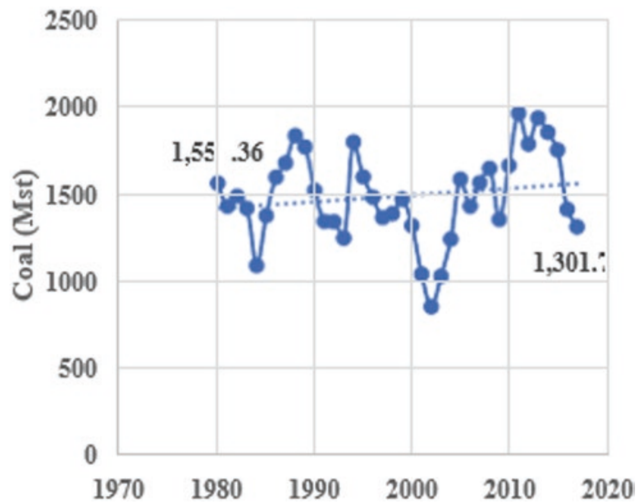


Fig. 9 Argentina's annual coal consumption [8]

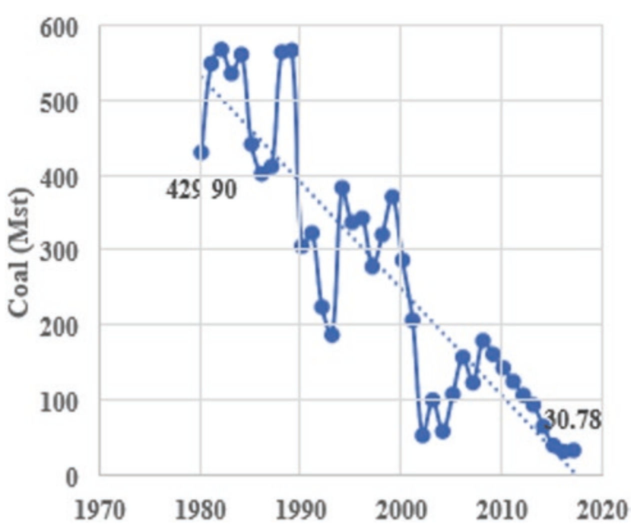


Fig. 8 Argentina's annual coal production [8]

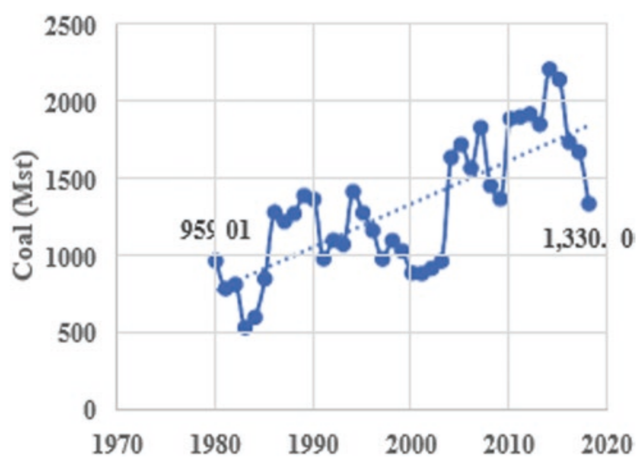


Fig. 10 Argentina's annual coal imports [8]

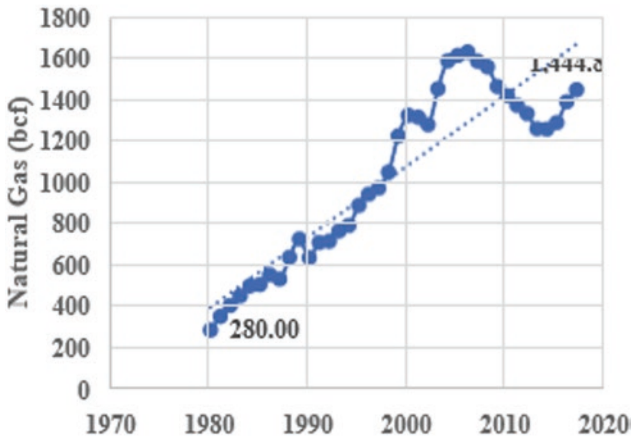


Fig. 11 Argentina's annual NG production [8]

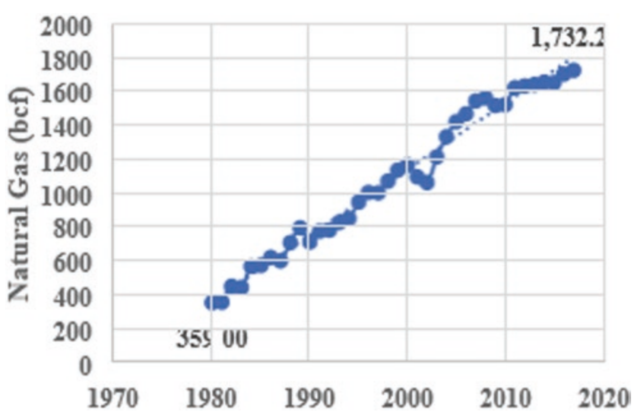


Fig. 12 Argentina's annual NG consumption [8]

Renewable Energy Generation

Photovoltaics (PV)

Solar photovoltaics is an underutilized energy resource in Argentina. Aside the Andes to the west and the plateaus of Patagonia to the south, over half of Argentina consists of plains ideal for gathering solar resources [2]. However, the highest density of solar resources can be found in the northwestern region of Argentina.

Wind

As shown in Figs. 14 and 15, wind generation was nonexistent until the 2000s. There was a gradual growth, but it did not exponentially increase until 2010. However, when compared to the wind resources of Argentina, this is a relatively underutilized resource.

Due to the South Pacific High (SPH) flowing north from around Cape Horn, the Patagonia region is dense in wind energy resources, while the northern half of Argentina is not as wind-dense as the Patagonia region. However, northern Argentina still receives ideal wind resources from the South Atlantic High (SAH).

Hydro

In Fig. 16, we can see that over the past decades Argentina's hydroelectricity generation has more than doubled and is currently the country's largest source of renewable energy.

Fig. 13 Argentina's annual NG imports [8]

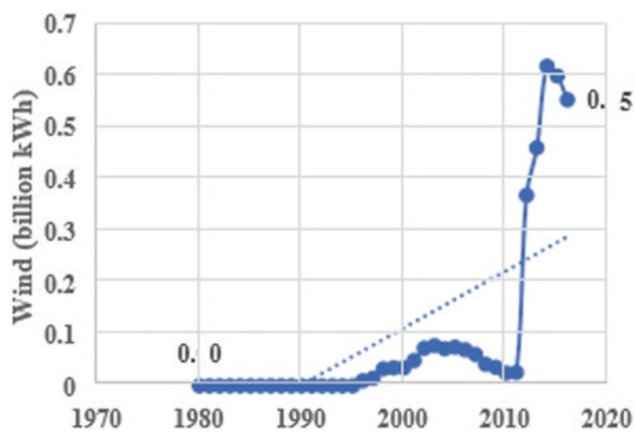


Fig. 14 Argentina's annual wind power generation [8]

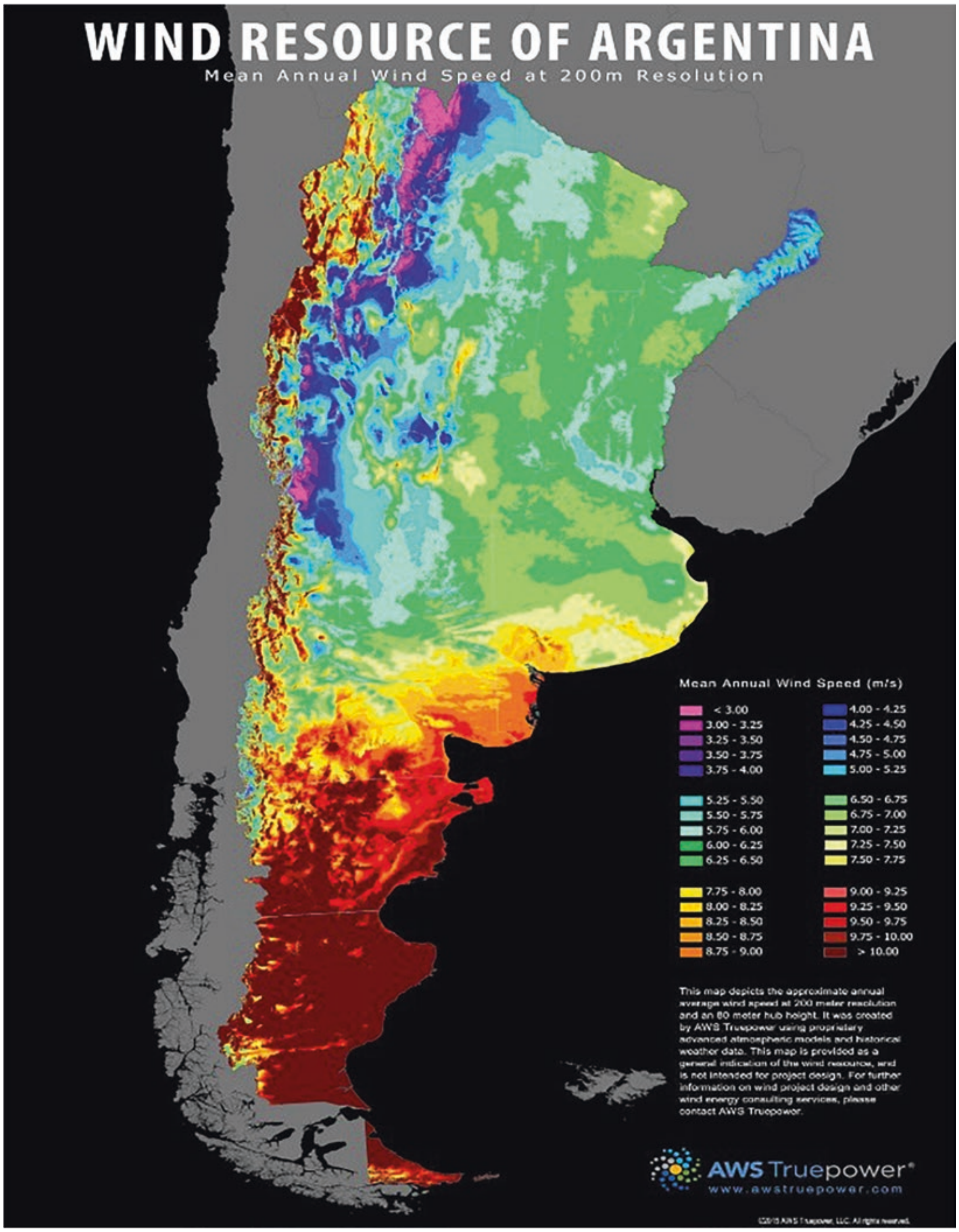


Fig. 15 Argentina's wind resource map

The main drivers of this growth have been the joint binational hydroelectric plant projects Argentina pursued with Paraguay (Yacyretá Binational Entity) and Uruguay (Salto Grande) [9].

Ocean

Based on the information collected from the US Energy Information Administration (EIA), at this time Argentina does not have any form of operating tidal power. However,

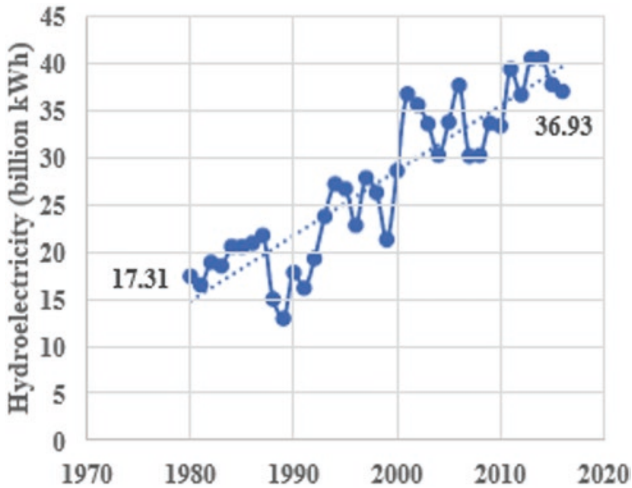


Fig. 16 Argentina's annual hydroelectricity generation [8]

based on the cold reservoir, that is, the Falkland Current, and the hot reservoir, that is, the Brazil Current, it is believed that there is great potential for tidal power, and this is worth further investigation.

Geothermal

Due to Argentina's proximity to the Pacific Ocean and the Andes Mountains, there is a considerable amount of geothermal energy to the west. However, like wind and solar, this is another underutilized resource with great potential. Based on the EIA data, there does not appear to be any measurable levels of geothermal energy consumption in the country (Fig. 17).

Biomass

See section "Biofuels".

Biofuels

Figures 18 and 19 show that from the 1980s until the 2000s biomass and biofuel production was nonexistent. However, by 2007, a biofuel law was put into place, and it mandated that gasoline would be mixed with bioethanol and diesel was to be mixed with biodiesel [2]. This law paired with the large agricultural output of Argentina caused a significant growth in production of both fuel sources. The excess biomass and biofuel are exported to Argentina trade partners.

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

The data from the EIA show that the only energy storage system in Argentina is the Rio Grande Hydroelectric Complex (RGHC) in the Calamuchita providence. The RGHC primarily operates to manage floods and provide municipal water. The RGHC has an installed capacity of 750 MW and an annual average power generation of 977 GWh [10]. Based on the data from Fig. 20, while pumped hydroelectric storage has increased annually, the storage system does not operate near the rated value.

Due to the development of Argentina's hydroelectric infrastructure and a lack of investment toward wind, solar, and geothermal infrastructures, it is understandable that there is also a lack of compressed air, batteries, and fuel cells storage infrastructure to store the excess energy that would be generated by those resources.

Energy Resiliency

Electrical Grid

The Argentina's grid has nearly maximum population coverage with regions in the south still deficient.

Argentina's total electricity coverage for its population was approximately 100% in 2016 [12]. However, there are communities in the rural southern regions of Argentina that still have deficient access to electricity [11].

Akin to the United States, generation plants are a mix of private and state-owned utilities.

The transmission system is named the Argentine Interconnection System (SADI) and covers three quarters of the country's northern region [2]. The SADI consists of two subsystems: the High Voltage Electric Power Transport System (STAT) and the Trunk System (ST). Transener is the company that manages the STAT, while Distrocuyo, Transba, Transpa, Transnoa, Transnea, and Transcomahue are the companies that manage the ST. Distribution at the local level is managed by private concessionaires of a province [9] (Fig. 21).

Climate and Natural Disasters

Over the past decades, precipitation and temperature have increased steadily across Argentina. Precipitation has

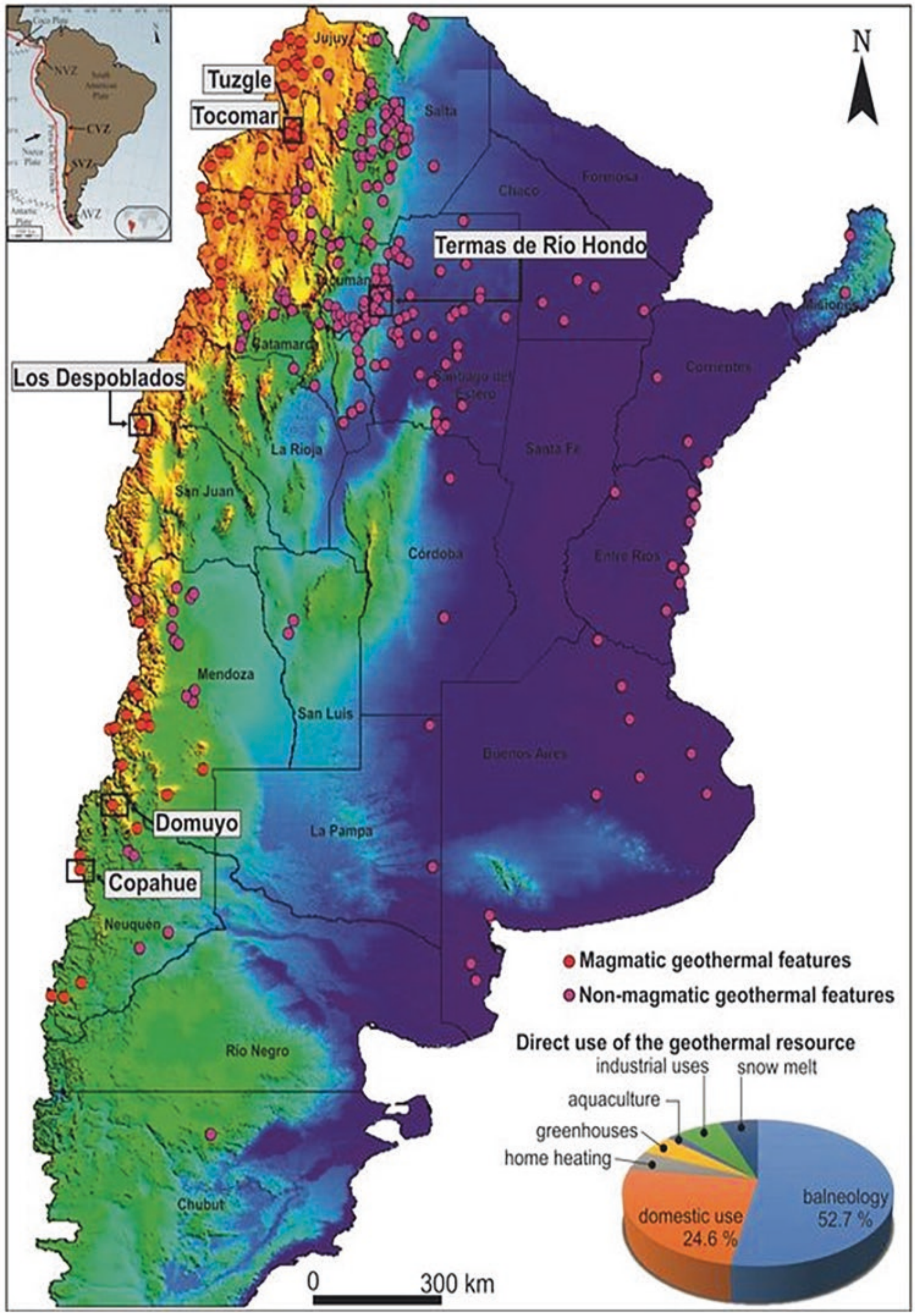


Fig. 17 Argentina's geothermal resource map

increased the most along the northeast region of Argentina at a rate of 10% since the 1970s and 40% in parts of the Buenos Aires province. From 1901 to 2012, the temperature has increased on average by 0.5 °C [14]. The higher temperature has caused a retreat of glacial ice and decreased snowfall in the Patagonia and Andes Mountain regions [14]. The major challenges Argentina is going to face from climate change is the managing of their excess water resources in the northeast region and the decline of water resources in the southern and western regions. The population most sensitive to these challenges is the rural communities dependent on agriculture [15].

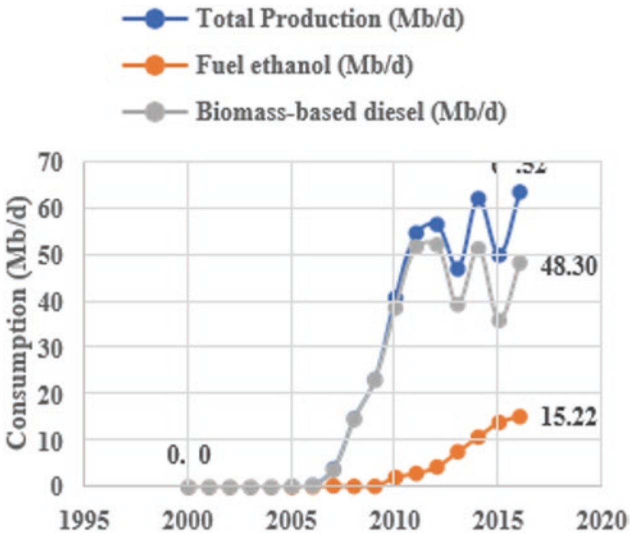


Fig. 18 Argentina's annual biomass/biofuel production [8]

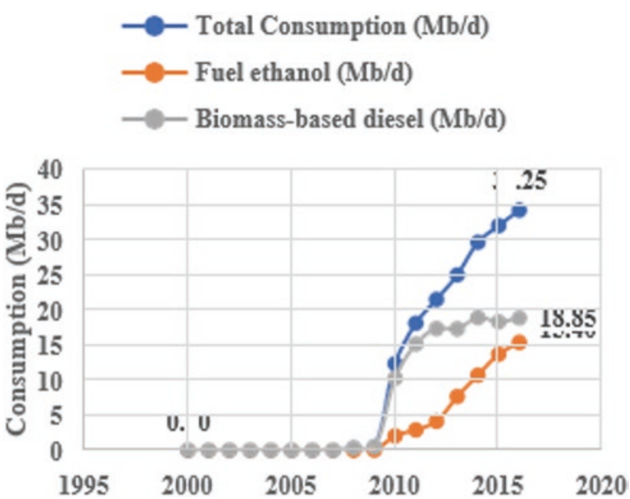


Fig. 19 Argentina's annual biomass/biofuel consumption [8]

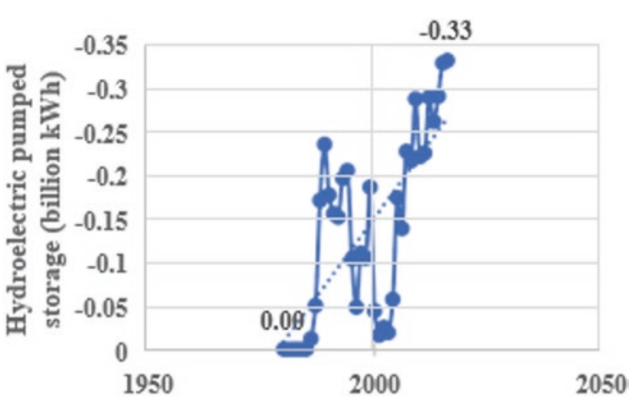


Fig. 20 Argentina's annual hydroelectric pumped storage [8]

Fig. 21 Argentina's interconnection system

Grid Resiliency

Aside from an NG shortage in 2004 and a regional blackout in 2019, the twenty-first century Argentina grid is resilient and transitioning at a rate expected for a country with their GDP size. Argentina is seeking foreign investments to catalyze this transition. However, with America's own aging grid, it is not believed that Argentina could expect direct financing from the United States.

Regarding the 2004 Energy Crisis, Argentina experienced an economic recession in 2000 that caused a decline in natural gas consumption, which decreased natural gas production. However, by the end of 2002, the economy had recovered and the demand rapidly increased. The production could not meet the local demand, and ultimately Argentina had to restrict their NG exports to their trade neighbors like

Chile, Brazil, and Uruguay [13]. While Argentina was able to avoid a power shortage, the relationship with their trade partners soured.

On June 16, 2019, all of Uruguay, most of northern Argentina, and parts of Paraguay experienced a large-scale blackout event. A total of 48 million people went without power for 24 hours. The distribution of potable water was limited, local gubernatorial elections were impacted, and medical patients that depended on home devices were prompted to attend local hospitals. The cause of the blackout is credited to Transener and the failure of communication between a team completing maintenance on a transmission tower and the Automatic Generation Shutdown system (DAG) [14].

Geopolitical Circumstances

Relations with Global Community/ Socioeconomic Influence

Argentina has grid interconnections with Brazil, Uruguay, Chile, and Paraguay. The two Brazilian interconnections go to and from Rincón de Santa María, Argentina (Ar) to Garabí, Brazil (Br) and Paso de los Libres, Ar to Uruguayana, Br. The three Uruguay interconnections go to and from Concepción del Uruguay, Ar to Paysandú, Uruguay (Uy), the Colonia Elía, Ar to San Javier, Uy and the Colonia Elía, Ar to San Javier, Uy. The Chilean interconnection goes to and from Termoandes Cobo, Ar to Atacama, Chile (Ch). Paraguay has two interconnections that go to and from El Dorado, Ar to Carlos López, Paraguay (Py) and Clorinda, Ar to Guarambaré, Py. While Argentina does not currently share an interconnection with Bolivia, both the countries share a mutual interest in future projects [9].

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Canada

Slobodan Petrovic and Melanie Leyson

National Energy Introduction

Canada is the third largest country in the world geographically with a population of 38 million, making it the 38th most populous country [1]. The large land mass within the borders of Canada provides abundant natural resources, and the government is committed to both utilizing and protecting those resources at the same time [1]. In 2018, Canada generated 641 TWh of electricity, 60% from hydroelectric facilities, 15% from nuclear power, 5% from wind, 7% from solar, wind, and biomass, and 11% from conventional fossil fuels [2]. They have a renewable energy capacity of over 2000 PJ from the following sources: hydro, solid biomass, wind, ethanol, municipal waste/landfill gas, solar thermal, biodiesel, solar photovoltaic, and tidal [2].

Energy Policies

Canada has one of the cleanest electricity profiles among members of the International Energy Agency and has pledged to achieve net zero emissions by 2050 [1]. In 2016, Canada adopted the Pan-Canadian Framework on Clean Growth and Climate Change, which is a plan to address climate change by putting a price on carbon pollution, improving energy efficiency codes, preparing infrastructure and communities for climate disasters, and ultimately reducing carbon emissions to 523 Mt by 2030 [3]. In 2017, Canada invested in a clean technology data strategy to measure and analyze economic, environmental, and social impacts of the implemented clean technologies to help inform future decisions [2].

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Oregon Institute of Technology, Klamath Falls, OR, USA

Trends in Generation Technologies (Fig. 1)

Domestic Resources

The rivers in Canada discharge almost 7% of the world's renewable water, and Canada has the third largest proven supply of oil reserves and uranium [2]. They are adding lots of solar and wind to their electricity generation profile such that they produce 82% of their total electricity from renewable, specifically non-carbon-emitting, technologies and they are committed to energy-efficient practices [2].

History of Energy

Canada has maintained domestic control of its natural energy resources since it became an autonomous country in 1867 [5].

Breakdown of Energy Generation "Mix"

Energy Generation Mix (Fig. 2)

Energy Consumption Mix (Fig. 3)

Fossil Fuels

Oil

Canada has the third largest oil reserves in the world proved to be 168 billion barrels at the beginning of 2020, most of which are located in the oil sands [2, 7]. Oil sands are a

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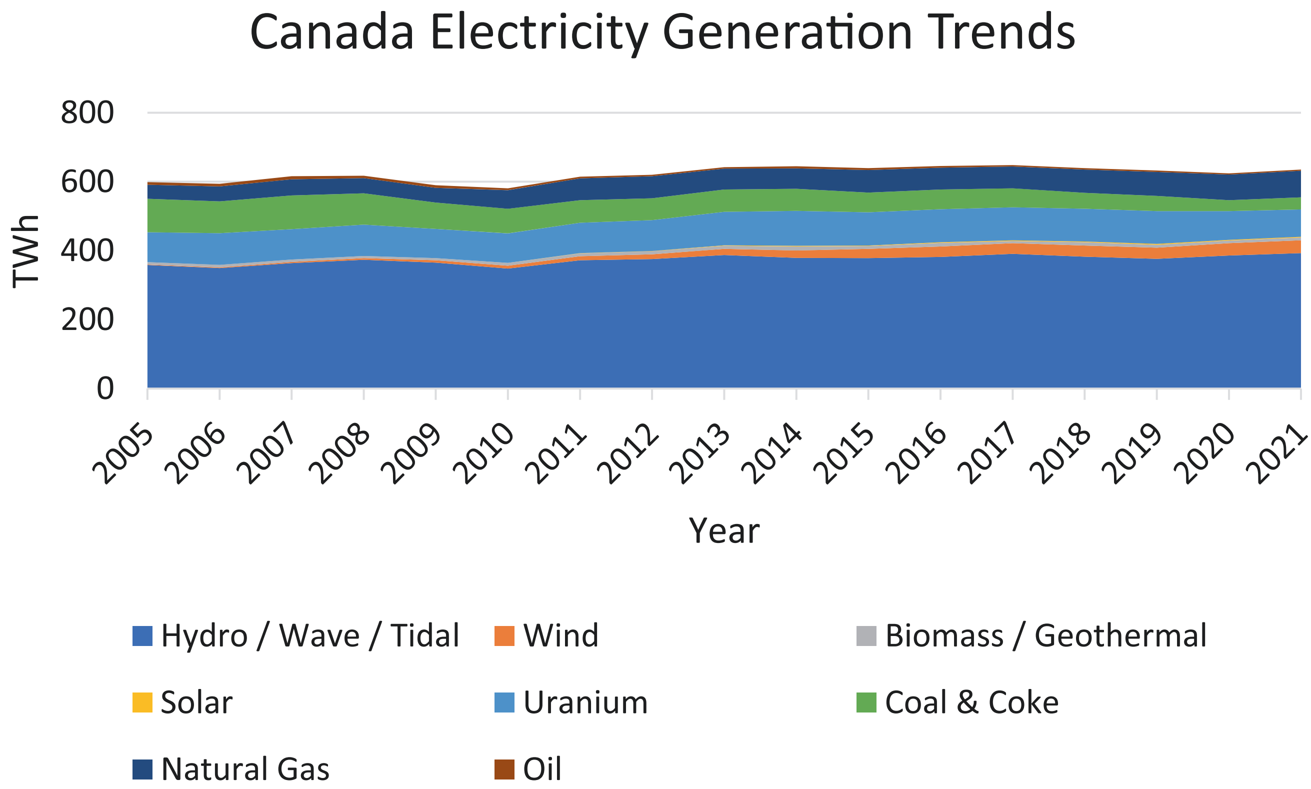

Fig. 1 Canada's electricity generation trends [4]

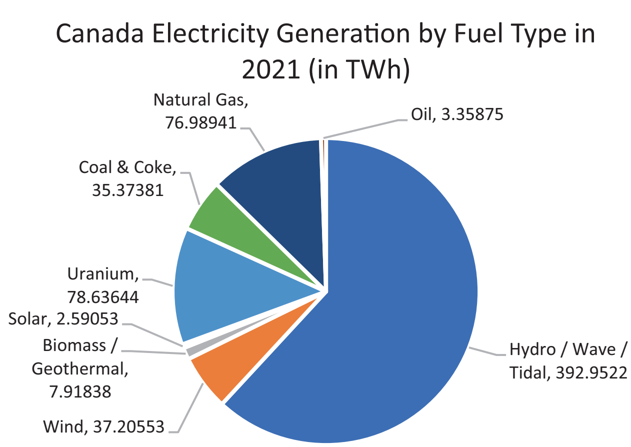

Fig. 2 Canada's 2021 electricity generation by type [6]

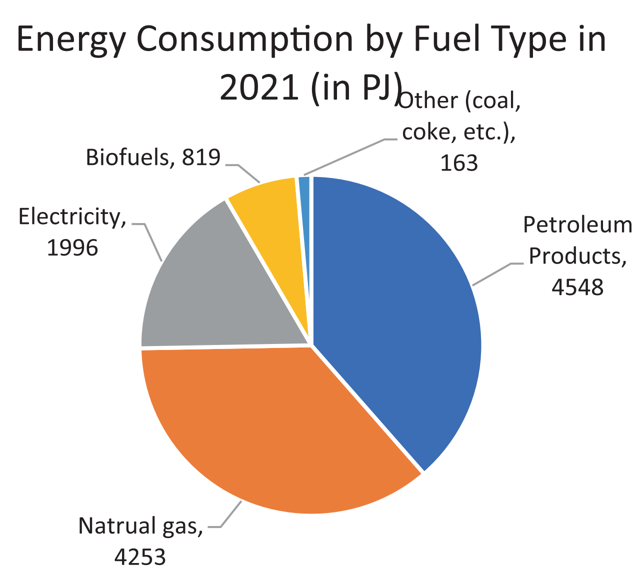

Fig. 3 Canada's 2021 energy consumption by fuel type [6]

mixture of sand, water, and bitumen, which gets extracted by scoops and transported to plants where steam is used to separate the sand from the bitumen [2]. There are some oil reserves in the Atlantic Ocean, which are being extracted and further explored [7].

In 2019, they produced 4.9 MMb/d of crude oil, mostly from reserves in Western Canada [8]. They export 3.8 MMb/day almost exclusively to the United States and import a mere 0.8 MMb/day [2, 7]. Of the imported oil, 79% comes from the United States, 12% from Saudi Arabia, and the rest from Russia, the United Kingdom, and Norway [2].

Canada produces 2.5 MMb/day of refined petroleum products in the form of transportation fuel, fuel oil, and petrochemicals for electronics, textiles, sporting goods, health and beauty products, medical supplies, and other household products [2, 7]. Of these petroleum products, they consume 1.8 MMb/day, export 0.7 MMb/day, and import 0.4 MMb/day [2].

The Canadian Energy Regulator released a document in 2020 that outlines the expected future of energy through 2050. They expect that crude oil production will increase and eventually peak in 2039 around 5.8 MMb/d and then slowly decline [8]. The increase for the next 18 years is due to the expansion of current oil sands projects [8].

Coal

Canada produced 57 Mt of coal in 2019 but has a domestic demand of only 28 Mt to be used evenly for steel manufacturing and thermal electricity production [2]. The rest (37 Mt in 2019) is exported primarily to South Korea, Japan, and India [2]. Canada has a total coal-fired electricity generation capacity of 8801 as of 2019 [2]. They have proved coal reserves of 6.6 billion short tons as of 2018 mostly in the form of anthracite and bituminous coal with some lignite and subbituminous coal [9]. In 2018, the Canadian government implemented the Pan-Canadian Framework on Clean Growth and Climate Change with goals to phase out coal-fired electricity by 2030 [9]. It is expected that by 2050 the demand for thermal coal will be a mere 3 Mt for the industrial sector [8]. At the same time, the demand for metallurgical coal for steel manufacturing will decline from 2.5 Mt in 2018 to 0.7 Mt in 2050 [8]. They will still produce coal for export while domestic demand decreases, and by 2050, they are expected to still produce 24.5 Mt, less than half of the current production [8].

Natural Gas

Canada had 73 Tcf of proved natural gas reserves at the beginning of 2019 [2]. Their natural gas market is tightly integrated with the US market due to the location of supply basins, demand centers, and transportation infrastructure as well as trade agreements [2]. The number of wells for natural gas mining has decreased significantly from over 15,000 in 2004 to less than 2000 in 2019, but the implementation of horizontal drilling and increased well length have maintained the production well [2]. Natural gas accounts for about one-third of Canada's energy needs by providing electricity and heat for appliances and buildings [7]. Additionally, liquefied natural gas (LNG) is used as a transportation fuel for over 20,000 natural gas vehicles in Canada [7]. Other uses of natural gas include fertilizer, energy for irrigation, and heat for greenhouses [7]. Despite all these uses, more natural gas is exported than is used domestically [2]. Most of their natural gas is located in the Western Canadian Sedimentary Basin, but they have some offshore fields in Newfoundland and Nova Scotia, in the Arctic region, and on the Pacific coast [9].

In 2015, Canada's gross natural gas production was 6752 bcf/day [10]. It is expected to increase over the next 20 years to peak in 2040 at 18.4 bcf/day and then slowly decline [8]. The growth is due to increased liquefied natural gas exports, which are expected to reach 4.8 bcf/day in 2039 and will be primarily from British Columbia [8]. Once the production begins to decrease, it should reach 16.8 bcf/day within 10 years by 2050 [8].

Nuclear Energy

Canada has the third largest domestic supply of uranium located in Saskatchewan [2]. They produce 6.9 kt, exporting 75% of it to Asia, the Americas, and Europe [2]. The other 25% of their produced uranium is used domestically at the CANDU reactors [2]. CANDU stands for Canada Deuterium Uranium and is a unique nuclear reactor technology that uses pressurized heavy water (deuterium oxide) [2]. Work is underway to improve the CANDU reactors so that they might use recycled fuel from other nuclear power plants and ultimately reduce the volume of nuclear waste [2]. In addition to the large reactors, Canada has begun discussing the implementation of small modular reactors for utility scale and remote applications [11].

Canada has the world's largest nuclear facility called the Bruce Generation Station [2]. The plant is located in Toronto, Ontario, and began operating in 1977 [12]. It has eight total CANDU reactors, of which only six are operational as of the end of 2021 [12]. With six reactors the plant has a capacity of 4700 MW, while the other two will add 1500 MW when they become operational [12]. Bruce Power began upgrading and enhancing the reactors in 2005 and has plans to continue upgradation work for another 15 years [12].

Renewable Energy Generation

Photovoltaics (PV)

Canada has a solar photovoltaic capacity of 3040 MW, as of 2018, and in 2021, they generated 2.6 TWh of electricity from solar PV, mostly in Ontario [2, 6, 13]. Of the total installed capacity, 1090 MW is distributed, while 2010 MW is centralized [13]. By the end of 2018, there were 43,836 photovoltaic systems in operation in Canada [13]. Of those, 8500 were newly installed in the previous year [13]. Ontario is the host of most of the country's solar generation due to the combination of high potential and government incentives for solar energy [14]. Out of the whole country, Saskatchewan has the greatest amount of sunlight at over 7.0 kWh/m^2, followed by Manitoba, Alberta, Ontario, and Quebec, which get between 5.5 and 6.7 kWh/m^2 [14].

The two largest solar PV facilities in Canada are the Sol-Luce Kingston and the Grand Renewable Energy Park, with capacities of 100 MW each [2]. However, a 465-MW project was approved and commenced operations in 2022 [15, 16]. The so-called Travers Solar project is located in Vulcan County in Alberta and is comprised of 1.3 million monocrystalline bifacial solar panels (provided by Jinko Solar Canada), 153 inverters, an electrical collection system, and a substation [15, 16].

The main barrier for solar installations in Canada is the cost, which is going down as solar panels get cheaper and more efficient [17]. Another issue is space since the locations best suited and available for solar projects are not necessarily near well-populated areas [17]. This subjects projects to transmission losses and economic inefficiencies [17]. It is expected that solar will play a big role in the country's net zero emission goals, and therefore, the government should offer more incentives, introduce stringent building codes to implement rooftop solar, and encourage large-scale solar projects [17].

Wind

Wind power is one of the fastest growing sources of electricity in Canada and in 2018 accounted for 5.1% of their electricity generation [2]. They have a capacity of 13,417 MW, which is more than triple their capacity from 2010, and in 2021, they generated 37 TWh of electricity from wind [2, 6]. Canada has 301 wind farms in operation, with a total of 6771 turbines [18].

The largest wind farm is Henvey Inlet in Ontario with a capacity of 300 MW [19]. The farm has 87 Vestas V136-3.45 MW® turbines and began operation in 2019 [20].

Canada has great wind potential with viable wind speeds at reasonable heights both on and off shore [21]. The country's large land mass and coastal territories further provide ample resources to take advantage of the wind potential [21]. In 2021, there were over 745 MW of wind projects under construction across the country, and since wind is the cheapest and most available resource in the country, it is expected to continue to grow as an energy source for several years [22].

Hydropower

Hydropower provides 60% of Canada's electricity generation, making it the most important resource they have and making Canada the third largest producer of hydroelectricity in the world after China and Brazil [2]. They have a total hydropower capacity of 81,386 MW as of 2019 [2]. In 2021, they generated 392 TWh of electricity from combined hydro and ocean sources, but mostly from hydroelectric dams [6].

The largest hydropower facility in Canada is the Robert-Bourassa plant in North Quebec with a total capacity of 5616 MW [2]. It is located in the La Grande River as part of Quebec Hydro's James Bay project [23]. The generating station has 16 Francis turbines and was built in the late 1970s as the La Grande-2, costing almost $4 billion at that time [23].

It is estimated that the total hydropower potential in Canada is almost 150,000 MW, so they are only using half of what they could [24]. But there are some barriers to realizing the remaining potential and they are mostly due to finances [25]. Three large projects have been under construction for several years and are still behind schedule and over budget; they are located at Muskrat Falls, Keeyask, and BC Hydro's Site C [25]. While potential for more generation is there, the financial responsibility to build the power plants and ancillary transmission infrastructure is massive [25]. However, at the same time, the facilities are expected to last over 100 years and have no re-fueling costs associated with them, so in the end the investment will be worth it [25].

Ocean

The utilization of ocean energy is in early stages in Canada. In 2016, the first grid-connected tidal stream turbine was deployed in Cape Sharp with a capacity of 2 MW [26]. Canada does not have any commercial ocean energy-generating plants, but they have several technologies and institutions undergoing test phases for the implementation and commercialization of ocean energy [26]. It has been estimated that Canada has access to 35,700 MW of tidal energy, and when wave and river capacities are included, that number jumps to a capacity of 340 GW [26]. The Fundy Ocean Research Center for Energy (FORCE) has both on-shore and off-shore facilities to support a transportation network for electricity generated from ocean power that are currently being used for demonstration and research [26]. FORCE is working with five tidal stream developers to implement 22 MW of capacity in Nova Scotia, including grid-connected tidal stream turbines [26]. The Canadian Hydrokinetic Turbine Test Centre (CHTTC) is located on the Winnipeg River and is a global site for testing technology that generates electricity from currents [26]. The West Coast Wave Initiative (WCWI) located at the University of Victoria is performing wave assessments and technology simulation and integration studies with plans to test energy converters in the ocean based on the results of the assessments [26].

One of the main factors in preventing the commercialization of ocean energy is the widely varying market and policy conditions under different jurisdictions [26]. The coming years will be highly formative for the extended future of ocean technologies. Canada recognizes the need to promote innovation and utilize competitive advantages to create the market for ocean energy [26]. Most of the technology developers in Canada are focusing on small-scale community projects, but lots of research and testing are being done to plan for a future of a grid-connected ocean energy market in Canada [26].

Geothermal

Canada has geothermal resources, but it is not utilizing them yet. It is estimated that they have a shallow geothermal capacity of 5000 MW with currently available technology and an additional 10,000 MW more of deep geothermal capacity requiring advanced technology [27]. If just the shallow resources were used, Canada could reduce carbon emissions by 25 Mt per year [27]. There are 18 sites in Canada currently being studied for geothermal potential by different institutions, but they are all in the very early phases, and it will be some time before the geothermal potential in Canada can be used to contribute to their energy mix [27].

Biomass

In 2018, Canada produced 550 PJ of energy from biomass sources such as solid wood waste, liquid wood waste, firewood, and wood pellets [2]. They have 36 operational cogeneration plants at pulp and paper mills with a capacity of 3427 MW for electricity and 1348 MW for heat [2]. Additionally, there are 41 independent power providers who use biomass with a capacity of 794 MW for electricity and 400 MW for heat [2]. There are also many small (less than 1 MW) bioheat projects for schools and hospitals around the country [2].

The largest biomass plant in all of North America is called Atikokan-G1 [28]. It is located in Atikokan, Ontario, owned and operated by Ontario Power Generation, and has a capacity of 215 MW [28, 29]. The plant was originally fueled by coal, but in 2014, it was converted to be able to burn biomass instead [29].

Biofuels

Canada produces both ethanol and biodiesel and have been using advanced biofuels for years [30].

In 2018, they produced 33 MMb/d of ethanol and imported another 21.2 MMb/d to fulfill their domestic demand [2]. The main ethanol feedstock is corn, but they use some wheat [30].

In 2018, Canada produced 6.09 MMb/d of biodiesel, exported 5.2 MMb/d, and imported 9.4 MMb/d to fulfill their domestic demand of 11.2 MMb/d [2]. Canola is the biggest feedstock for biodiesel, but soy, tallow, yellow grease, and corn oil are also used [30].

Canada has plans to increase the production and utilization of biofuels over the next 10 years with goals to increase ethanol production by 62–95% and increase ethanol use by 18–40% [31]. They aim to increase biodiesel production and use by at least 150% over the next 10 years [31].

One of the largest ethanol plants in Canada is the St. Clair Ethanol Plant operated by Suncor in Mooretown, Ontario [32]. The facility opened in 2006 and processes 40 million bushels of corn every year, which accounts for 20% of Canada's corn crop [32]. Since it opened, the plant has produced over 5 billion liters of ethanol [32].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

Industry leaders in Canada have formed an association (Energy Storage Canada [ESC]) to advocate for increasing the number of energy storage solutions through collaboration, policy advocacy, and education [33]. It is clear to members of ESC that energy storage is a necessary step toward phasing out fossil fuels and these systems, and the policy surrounding them, will have a great impact on the trajectory of the industry [34]. Without energy storage, extra electricity that is generated in Ontario is sent and sold to border states of the United States, but the market for energy in these states is very competitive, so selling electricity in this way is not economical [34]. Additionally, by selling energy in this way, Canada is sponsoring jobs in competing markets when they could be generating jobs and income through taxes by implementing energy storage systems in Ontario to store unneeded electricity for a later time [34].

Stantec is working on two projects in Toronto with their Deltro Energy Battery Energy Storage Systems (BESS) [35]. The projects have a 4-MW capacity using lithium ion batteries made by Leclanche and power conversion systems from WS Tech and Greensmith Energy Management Systems (GEMS) [35]. The BESS sites were designed to be connected with the Toronto Hydro substation [35].

Country's Future Storage Direction

Some provinces in Canada have outdated policies that inhibit efficient implementation of energy storage systems, and ESC is encouraging policy changes to adapt to a future with ample energy storage [36]. Ontario has some updated policies including an electricity price structure that reduces electricity costs for customers that have a load over 1 MW if they are able to reduce their demand during peak periods [36]. This policy alone promotes the installation of energy storage systems to stay within the parameters of the lower price structure [36]. In order to continue to promote energy storage systems, special attention needs to be paid toward monitoring new technological advancements to identify new opportunities and applications, as well as monitoring policy developments, regulations, and connection requirements [36].

In April 2021, Canada's Minister of Natural Resources, Seamus O'Regan Jr., announced a $500,000 investment into an advanced compressed air energy storage (A-CAES) technology being developed by Hydrostor Inc. [37]. The technology is for a scalable and emissions-free, long-duration energy storage system [37]. The funds for the project came from Canada's Energy Innovation Program that supports research, development, and demonstration projects that will advance clean energy technologies and help Canada meet its climate goals [11].

Carbon Footprint

The extreme temperatures in the Canadian landscape necessitate the use of a significant amount of energy for building climate control [2]. Additionally, the widely dispersed population requires energy for travel and energy to supply electricity over long-distances in order to reach the entire population [2]. Combined, these factors result in 82% of Canada's total carbon emissions coming from energy use [2]. On a global scale, 78% of greenhouse gas emissions come from the production and consumption of energy, so Canada emits more per capita than other countries on average [2]. That being said, Canada recognizes this fault and has worked hard to improve their economy without increasing carbon emissions, and they have accomplished this with a great success [2]. Between 2000 and 2018, greenhouse gas emissions decreased 31% per dollar of gross domestic product (GDP) and 20% per capita [2]. Emissions from electricity production alone decreased by 50%, in a large part due to the coal phase-out action plan implemented in Ontario beginning in 2001 [2]. However, at the same time, the country increased oil sands production, causing the greenhouse gas emissions from oil and gas production to increase by 23% [2].

Most Recent Carbon Output

In 2019, Canada emitted 730 Mt of carbon dioxide equivalent, which was an increase from the value of 728 Mt in 2018 [38].

Historical Trends of Carbon Footprint

Their emissions have been fluctuating between 694 and 752 Mt over the last 15 years [38]. The most recent low was in 2009, and the high occurred in 2007 [38]. Every year after 2009 it has been between 700 and 730 Mt with a trend showing an average slow increase every year [38]. Canada has a goal to reduce carbon emissions to below their 2005 level which was 739 Mt [38]. It is clear that they have already accomplished this goal.

Types and Main Sources of Pollutants

Canada experiences some air pollution from transportation and electricity generation as well as from the industrial sector [39]. They have a 10-year clean air agenda and pollution-prevention plans that inform individuals and businesses on ways to reduce pollution-causing activities [39]. However, the main way they plan to reduce emissions is by further diversifying their energy portfolio to include an increasing number of low-carbon energy sources [39].

Air Quality

The World Health Organization ranks Canada's air quality among the cleanest in the world. The whole country has made integrated efforts to reduce air pollution from vehicles, power, and other industries. Particulate matter suspended in the air has been decreasing for decades, and in 2008, $PM_{2.5}$ was less than 10 $\mu g/m^3$, which is still higher than the World Health Organization's guideline of 5 $\mu g/m^3$ [39].

Energy Resiliency

Electrical Grid

Canada began utilizing electricity for street lighting in the 1880s, but they began generating electricity from Niagara Falls in 1906, and this is seen as the real beginning of their electric history [40]. Furthermore, in 1910, one of the world's first integrated public utilities, the Hydro-Electric Power Commission of Ontario, completed the first 110-kV bulk power transmission lines to supply power to several municipalities in southwestern Ontario [40]. In addition, by 1920, hydroelectricity accounted for 97% of total production in Canada [40]. The first thermal–electric coal-burning power plant began service in 1951 in Toronto with a capacity of 1 GW [40]. The first nuclear power plant was built in Rolphton, Ontario [40]. It was based on the CANDU and began delivering power to the grid in 1962 [40].

The most recent data from 2014 reported a total installed capacity of 140 GW, and in 2021, they had an annual generation of 639 TWh for the entire country [41]. They have 34 transmission connections with the United States with high-voltage lines (over 100 kV) and 33 major interprovincial connections of high-voltage lines (69 kV) [41]. In 2015, Canada estimated that they had 153,500 km of transmission lines across all provinces [41].

Many systems have been in use since their construction in the mid-twentieth century. As they continue to age and fail, Canada is faced with the task of replacing and improving their equipment. It has been estimated that they will need to spend at least $350 billion over the next 20 years on these upgrades, and in the process, they plan to implement smart grid technology [42]. While they have one of the cleanest systems in the world, their commitment to net zero emissions will necessitate expanding the grid's capacity to account for the electrification of the transportation and industrial sectors [43]. There are several funds to support research and development for implementing and improving green and smart technologies into the electricity industry with a significant focus on electric vehicles [43].

Climate and Natural Disasters

Canada faces many natural disasters and severe climate events. Floods are the most frequent natural hazard occurring throughout the year with causes ranging from severe rain to rapid ice melts to dam failures [44]. The eastern coast of Canada is subject to hurricanes in the months of June through November as the warm waters of the Atlantic Ocean produce tropical cyclones [44]. They experience thousands of avalanches each year that can be triggered by wind, rain, warming temperatures, snow, earthquakes, and recreational activities such as hiking, skiing, and snowmobiling [44]. Additional disasters faced by Canadians include earthquakes, landslides, severe storm weather, tornadoes, tsunamis, wildfires, and volcanic eruptions [44]. It should be clear how each of these events presents a threat and the possibility of severe damage to the transmission system.

Grid Resiliency

In 2003, there was a blackout affecting several northeastern states of the United States and much of southeastern Canada [45]. At least 50 million people were affected, and some lost power for 2 days [45]. In response to this event, Canada and the United States developed an Electric Reliability Organization (ERO) to unify standards and prevent future faults from becoming catastrophic [41]. The ERO and North American Electric Reliability Corporation (NERC) have developed over 100 standards regarding many aspects of the electric grid including transmission operations, demand and resource balancing, facility design and maintenance, system planning, communications, training, security measures, and emergency preparedness [41]. While these standards and regulations are mandatory and enforceable, it is up to provincial governments to write them into law [41]. The federal government of Canada, namely the Canada Energy Regulator, is only responsible for permitting and constructing interprovincial and international power lines and exports; all other regulatory oversight is done by individual provinces [41].

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

Canada primarily exports energy to the United States in the form of oil and natural gas. In 2019, Canada exported more than 3.7 MMb/d of oil to the United States, while less than 1% of Canada's oil exports were to other countries [7]. Despite this incredible oil export, Canada also imports oil to the tune of 660,000 b/d to supply the provinces of Quebec, Ontario, and the other Atlantic provinces [7]. This is primarily due to the fact that Canada's oil reserves are located in the western provinces, and trade with the United States is already well established with pipelines, making it more economically feasible to sell oil to the western United States and import oil to eastern Canadian provinces.

Natural gas exports to the United States have been decreasing as the United States produces more of its own natural gas with advances in horizontal drilling and hydraulic fracking [7]. This is leaving Canada scrambling to find new customers, but nothing will beat the convenience and established infrastructure that facilitates trade with the United States. That being said, demand for liquefied natural gas is growing in Chinese markets and other Southeast Asian markets [7]. Two LNG terminals are under construction on Canada's west coast that will boost trade to demanding markets [7].

Canada is also a net exporter of electricity to the United States. In 2014, more than 58 TWh of electricity was sold to the United States from 64 different companies in Canada [46]. This makes up a whopping 10% of Canada's electricity production and accounts for less than 2% of the United States' electricity consumption [46]. Most of the electricity sold is on the east coast to customers in New England and New York [46]. However, on the other side of the continent, the Pacific northwest states are net exporters to Canada selling extra hydroelectricity to be used during the periods of peak demand [46].

Relations with Global Community/ Socioeconomic Influence

Canada is an active participant in the Paris Agreement and has been from the beginning of 2015 [47]. In 2016, they submitted their long-term low greenhouse gas development strategy that identifies ways to reduce emissions by 2050 [47].

Canada is a member of the United Nations and stands as the ninth-largest financial contributor to the UN peace operations, providing more than $86 million since 2016 [48]. In the past, Canada has been a leader in providing personnel to the UN [49]. However, in 2020, they hit record lows in contributions due to large projects ending and some other internal political reasons [49]. They currently have personnel deployed in several UN peacekeeping missions ranging from Haiti, to Mali, D.R. Congo, Cyprus, South Sudan, and the Middle East [49].

Canada is home to the second largest community of Iranians outside of Iran, but they severed diplomatic ties with the country in 2012 [50]. Canada maintains diplomatic relations with North Korea through a controlled engagement policy due to concerning actions in North Korea related to nuclear weapons [51]. Additionally, Canada has concerns about human rights violations in North Korea and has provided financial support to reduce food shortages in the country [51]. Canada has diplomatic relations with China at federal, provincial, territorial, and municipal levels [52]. Canada has over 1.8 million residents of Chinese origin and over 100,000 Chinese students visiting at any given time, so maintaining the active relationship with China is important for Canada [52]. Canada does not have diplomatic relations with Russia and instead has sanctions and prohibitions regarding the country due to their violation of Ukraine's sovereignty and territorial integrity [53].

By 2050, Canada expects hydroelectricity to provide a majority of electrical power and for fossil fuels to still have some minor contribution to the energy mix [54]. As for fossil fuels, it should be clear that as long as current sources are producing it would be economically detrimental to abandon them [54]. Once the infrastructure is there, it is hard to walk away from it [54]. These are the primary reasons fossil fuels will not be phased out completely, but the plan is to slowly replace them and to expand the country's electrical capacity using renewables. Beginning in 2015, any coal plants more than 50 years old and any new coal plants built were required to emit less than 430 tonnes of carbon dioxide per gigawatt hour or be shut down and replaced [54]. While the plan is to implement more renewables and expand the current capacity, it is hard to predict how this will be done. Many factors affect the expansion of renewables including resource availability and technological advancements and thus funding for the said advances [54]. All that being said, Canada has committed to net zero emissions by 2050 and has implemented the Canadian Net-Zero Emissions Accountability Act in 2021 [55]. As a part of the act, they have an advisory board tasked with identifying 5-year targets for caps on emissions from the oil and gas sectors [55]. Canada has not published any definitive numbers in terms of renewable energy generation or capacity goals.

Education

The government provides many resources with information on energy use, electricity generation, consumption, and their net zero carbon goals. They have tips for reducing energy consumption at a personal level, but it is unclear how they are educating the public about the bigger picture, renewable energy goals.

Summary

Current Energy Situation

Canada has made concerted efforts to build a clean energy profile. As reported, they generated only 11% of their electricity from fossil fuels in 2018 and rely heavily on renewable hydropower. They produce oil and natural gas and are expected to increase the production of both fuels for several years. They also produce coal but do not rely heavily on it for domestic uses and thus will be decreasing production in the coming years. The domestic supply of uranium has driven and will maintain the development of nuclear power plants. As for renewables, Canada has a PV capacity of 3040 MW, a wind capacity of 13,417 MW, a hydropower capacity of 81,386 MW, an ocean capacity of 2 MW, and a biomass capacity of 3427 MW for electricity and 1348 MW for heat, and they produce biofuels in the form of ethanol and biodiesel. Canada does not use geothermal power although sites are being studied for future development. Additionally, every other renewable generation is expected to increase in the coming decades.

Future Energy Situation

Canada is well on their way to reaching carbon neutrality goals by 2050. While they still produce and use fossil fuels, they have advanced policies and guidelines for energy production to facilitate the switch to using mostly renewable energy. Hydropower, wind power, and nuclear power have high installation capacities and the resources are readily available for these technologies, so their contributions to the overall energy mix will only continue to grow. Solar, biomass, biofuel, geothermal, and ocean energy technologies will continue to advance and become more economically feasible to install in different locations in Canada.

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Cuba

Slobodan Petrovic and Melanie Leyson

National Energy Introduction

Cuba is an island in the Caribbean with a land mass of 110,000 km^2 [1]. They have a population of over 11 million spread throughout different towns and cities, the most notable of which is Havana [1]. They produce sugar, nickel, and cobalt and have a tumultuous political and economic history that has greatly affected the energy sector [1].

Energy Policies

In the early 2000s, Cuba began its Revolution Energetica, a five-point plan to reduce energy consumption throughout the country and to increase the amount of energy produced from renewable sources. The first goal of the energy revolution was to increase energy efficiency and conserve energy by replacing millions of appliances with more efficient and upgraded units, along with switching to fluorescent lightbulbs that reduced electricity consumption by 3–4% annually [2]. They also introduced an electricity tariff, which rewarded people who consumed less with a lower tier pricing plan [3]. The second goal was to increase the availability and reliability of the national grid, and they did this by decentralizing the national grid, so that energy was produced closer to the point of consumption [3]. The third goal was to incorporate more renewable energies, which they have done and are still doing, discussed in the sections below [3]. The fourth goal was to increase the exploration and production of local oil and gas, and the fifth goal was to encourage international cooperation, which they have also done by asking for and allowing foreign investors to help with their renewable energy infrastructure [2, 3].

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In 2020, Cuba submitted a nationally determined contribution that outlines their climate change mitigation and adaption policy goals over the next 10 years with a focus on agriculture, forestry, and other land use sectors [4]. The goals include generating 24% of electricity from renewable sources by 2030, further increasing energy efficiency, reducing carbon-intensive ground transportation, increaseing forest coverage, installing 5000 solar pumping systems (by 2030), and treating wastewater from swine [4].

Trends in Generation Technologies

The most recent data from the World Bank report that fossil fuel use in Cuba in 2014 accounted for 85.6% of the country's total energy consumption [5]. The breakdown of electricity output sources in 2014 was as follows: 81% from oil, 14% from natural gas, 4% from biofuel, and 1% from renewables [2]. By 2017, they had already increased electricity from renewables to 4% (from the 1% reported in 2014), and the plan is to have 24% from renewables by 2030 [2]. Figure 1 shows the expected renewable energy mix by 2030.

Domestic Resources

Cuba has offshore oil and natural gas resources [6]. In 2016, they had proven crude oil reserves in the amount of 124 million barrels, but due to geological and technical challenges, exploratory mining has yielded poor results [6]. As for natural gas, they had proved reserves estimated at 2500 bcf in 2016, but they produce less than 40 bcf of natural gas every year [6].

Cuba has significant biomass resources as well as wind, solar, and hydropower resources. Each of these is being utilized but has the potential to expand further to make up a larger portion of the generation mix.

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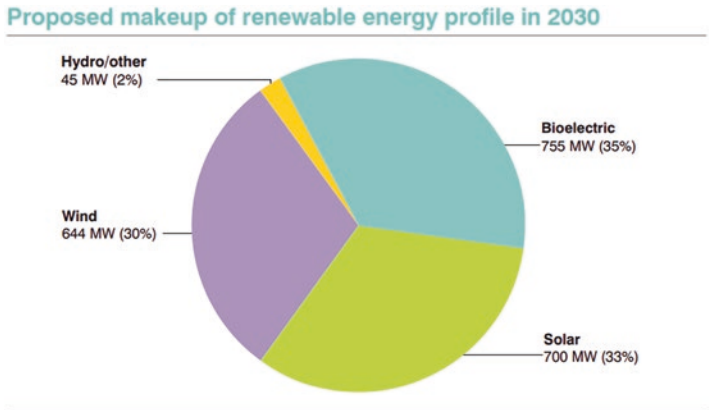

Fig. 1 Renewable Energy mix for 2030 [2]

History of Energy

Cuba's energy industry was built with the help of the Soviet Union, and by the time Fidel Castro took power in 1959, the country was 59% electrified [7]. Over the next 30 years, electricity expanded across the island to provide for 95% of the population [7]. However, due to their large reliance on oil, they suffered from the oil crisis and sanctions in the early 1990s [7]. Since then, they have been working to reduce their reliance on foreign fuels and decentralize their electric grid to better withstand and more quickly recover from hurricanes.

Breakdown of Energy Generation "Mix"

Figure 1 shows the historical electricity generation by source and figure 1 shows Cuba's historical final energy consumption by source [8].

Fossil Fuels

Oil

Oil accounts for 85% of the electricity generated in Cuba [6]. In 2015, they produced 49,000 bbl/day of petroleum and other liquids but consumed a total of 172,000 bbl/day [6]. The deficit is made up of imported oil from Venezuela, but these imports are declining due to political strife in the neighboring country [6]. Additional hindrances in oil production are due to the domestically produced oil being high in sulfur and burning less cleanly, which routinely causes power plant failures and extra pollution [2]. As mentioned, Cuba has offshore oil reserves, but they are hard to get to so production mainly happens onshore along the northern coast [6]. Cuba has four oil refineries owned by the state and in 2016 they distilled 134,200 bbl/day [6].

Coal

Cuba does not produce or import any coal for electricity generation.

Natural Gas

Cuba produces and uses natural gas for energy. In 2019, they produced and consumed 34 bcf of dry natural gas [6]. Cuba does not import or export any natural gas [6]. As mentioned earlier, Cuba has an estimated proven natural gas reserve of 2500 bcf [6].

Nuclear Energy

Cuba does not have any nuclear power plants or research facilities. In 1976, there were plans to build a nuclear power plant at Juragua on the southern coast, but the project was backed by the Soviet Union and was suspended in 1992 upon their collapse [9]. Investors have attempted to revive the project on more than one occasion but ultimately abandoned the plant again [9]. In 2016, Cuba and Russia signed a new agreement to cooperate on civil nuclear power, but it is unclear whether any further action has been taken to revitalize nuclear power generation in Cuba [9].

Renewable Energy Generation

Photovoltaics (PV)

The solar photovoltaic capacity in Cuba has been growing steadily and is expected to continue expanding. Cuba gets a large amount of solar irradiance with an average of 223.8 W/m^2, so it has a lot of solar potential [10].

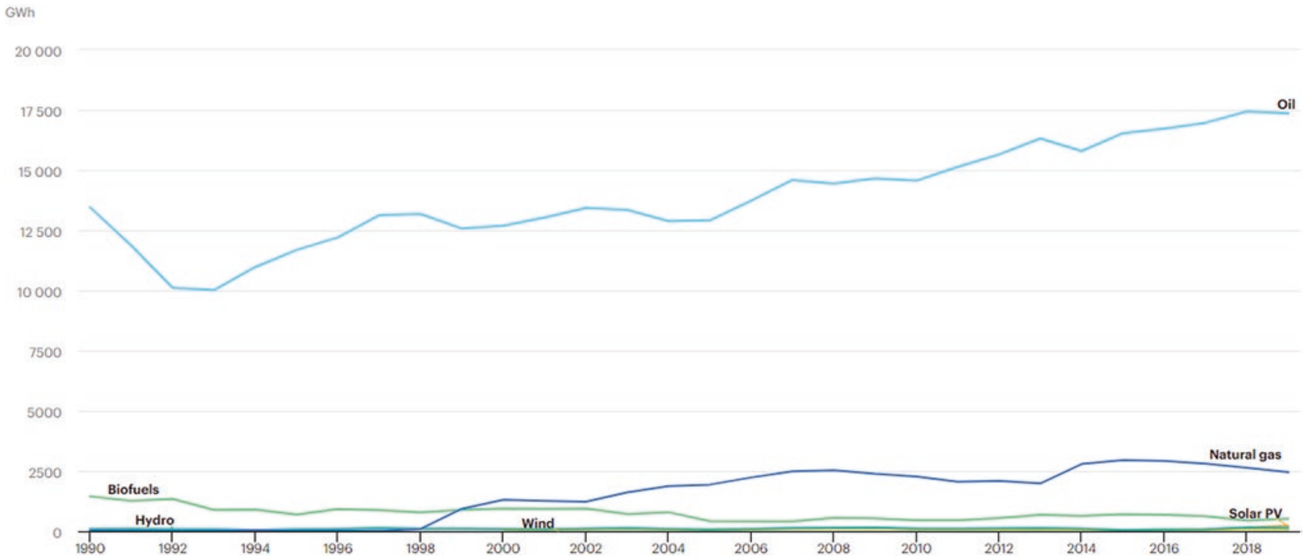

Fig. 2 Electricity generation by source in Cuba [8]

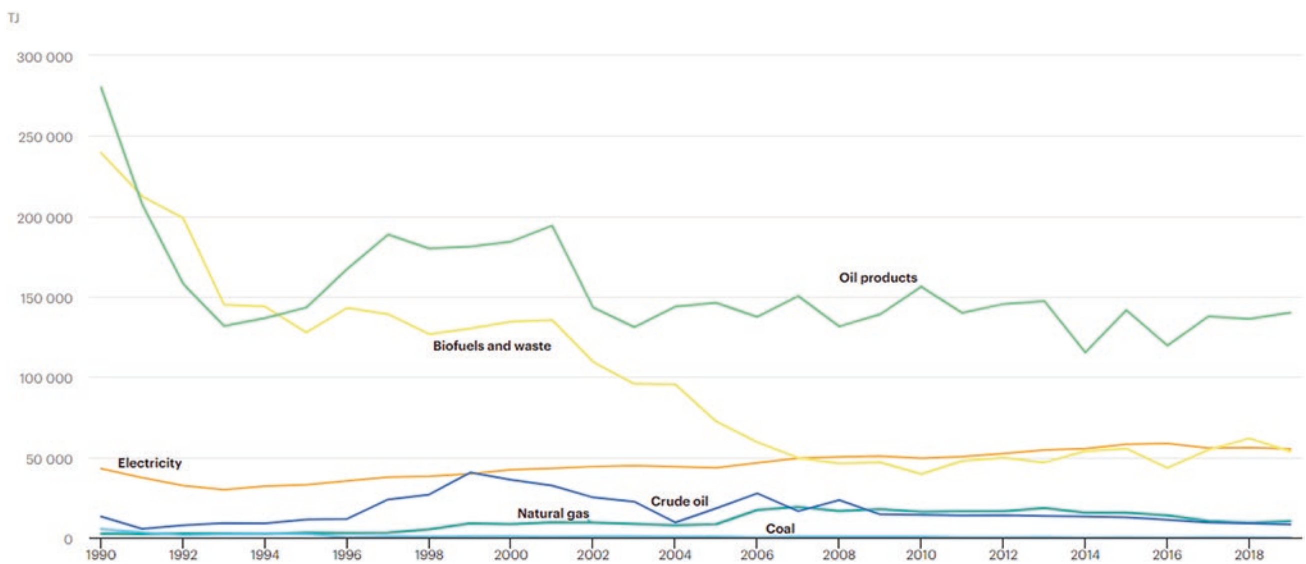

Fig. 3 Total final consumption of energy by source in Cuba [8] [8]

In 2009, they had a capacity of 1.8 MW installed [2]. The first government-funded solar farm began construction in 2013 in Cantarana and has a maximum capacity of 2.5 MW [2]. By 2016, the total installed solar PV capacity had grown to 37 MW and solar panels generated 39 GWh annually, which is 0.2% of the total energy consumption [11]. By 2017, they had 22 solar parks operating with 9476 solar panels and plans to have 12 more parks completed by the year end to increase the total solar capacity to 90 MW [11]. In the same year, the government began to implement plans to install solar on homes and rural schools, using more than 10,000 panels [11]. In 2019, a government investment program of 275 million pesos was granted for the construction of solar parks along with other renewable sources [11].

The government plans to have 191 solar parks in operation with a capacity of 700 MW and generate 1050 GWh annually by the year 2030, saving 240 million tons of oil [11]. In order to accomplish this large project, Cuba will need help from foreign investors and plans are already in place to build 17 solar parks with a capacity of 100 MW in Pinar del Rio, Mayabeque, Artemisa, and Matanzas [11]. All new solar parks must follow certain guidelines: They must be built on infertile land (so as not to take away precious fertile soil for farming), must be designed with consumer needs in mind, and must reduce losses by transmission and distribution; completed projects must improve and not destabilize electric grid; and they must be designed to withstand 150 km/h winds all while attaining international and Cuban standards [11]. All solar technologies in Cuba have an expected life cycle of 20–25 years.

Wind

Wind speeds in Cuba average 5.7 m/s at an altitude of 80 m [10]. The country has an estimated wind power potential of 2550 MW but plans to expand to only 633 MW by 2030 [2]. In 2019, there were plans to build 13 wind farms along the northern coast [2].

As of 2019, Cuba had only four experimentally constructed wind farms with a capacity of 11.2 MW and generating 21 GWh annually, with plans to add 13 more [2, 11, 12]. Large and modern equipment for the wind farms posed challenges and thus required experimental developments and the implementation of testing sites for the farms [13]. Two major wind farm projects are La Herradura 1 and La Herradura 2 encompassing a complex with a total of 54 turbines operating at 1.2 and 2.4 MW [13]. The La Herradura complex also contains a substation that is larger, more complex, and more modern compared to the national energy system [13]. Before any new wind farm project begins construction there is a testing phase during which scientists assess the wind resources in the area including speed and altitude in order to select the proper equipment [13]. Special consideration must be taken for the climate and strong winds during hurricane season [13].

Hydropower

Cuba has no major rivers or large inland bodies of water, so the use of large-scale hydropower is not prominent [14]. However, in the 1980s, a plan was developed to expand the national grid through the use of hydropower [15]. Most hydropower projects were in the form of power stations installed at the sites of existing irrigation dams [15]. Small hydropower plants allow for localized grids and have the potential to provide power to rural areas that the national grid does not reach [15].

It is estimated that Cuba has a hydroelectric capacity of 650 MW, but lots of waterways are in protected or naturally sensitive areas [2]. Therefore, the expansion goals are small, and there is no goal for an increase in hydropower capacity by the year 2030 [2].

As of 2017, they have 170 small-scale hydropower plants with plans to build 74 more [14]. The 170 hydropower plants have a capacity of 64 MW and can generate 100 GWh [14]. It is estimated that Cuba has a total small hydropower potential of 135 MW, and the installation of the 74 planned plants would add 56 MW to the current 64 MW capacity for a total of 120 MW [14]. Once those plants are built, they will have almost reached their total capacity from small hydropower plants [14]. The Cuban government has made a deal with the Kuwait Fund for Arab Economic Development for US$30 million to construct 34 of the new hydro projects as well as three substations that would connect hydropower to the national grid [14]. The first substation is expected to be completed by 2024 [14].

Ocean

In 2008, a workshop on clean ocean energy was held in Cuba to explore the generation of power from waves, tides, currents, temperature differentials, and offshore wind power [2, 16]. These sources of energy tend to be less variable than wind and solar, making them more reliable energy producers [16]. The waves off the coast of Cuba do not get very large compared to other parts of the world, but the tidal currents can be as fast as 5.18 km/h, and research was being done to harness the current energy [16]. Ocean Thermal Energy Conversion (OTEC) is a process that uses the temperature differences in the ocean to vaporize and condense a fluid, in turn driving a turbine [16]. OTEC provides further benefits in the form of harvesting seafood and seaweed, as well as yielding biodiesel and freshwater, and has the potential for applications in refrigeration and air-conditioning [16]. However, the workshop also explored the adverse environmental impacts of ocean energy including siltation, destruction of habitats, leaks of toxic materials, discharge of nutrient-rich water, and impacts of decommissioning the ocean facilities in the future [16]. In the end, it was determined that more research was needed on the implementation of each mentioned ocean technology as well as the long-term environmental impacts of such projects [2, 16].

In 2014, an article was published in Discover Magazine about energy-generating buoys in Cuba. The buoys described can average 20,000 kWh annually and would cost $30,000 each. However, no further information can be found on subsequent projects involving these buoys in Cuba, or any other ocean/wave energy capture systems, and as of 2016, no large-scale projects had been built or planned [2].

Geothermal

Cuba does not use geothermal energy, and there have not been any studies to determine the geothermal potential on the island.

Biomass

The government's energy revolution plan included a goal of building out biomass plants with a total capacity of 755 MW by 2030 [2]. The country produces a lot of sugar and rice, and the waste products from processing sugar and rice, namely bagasse and marabou, can be burned as biofuel.

At the end of June in 2020, the first biomass plant in Cuba synchronized its boilers as its final stage of construction and development [17]. The plant is located in Ciego de Avila next to the Ciro Redondo sugar mill and has a capacity of 60 MW [17]. Construction began in 2017 and after some minor delays was operational in January of 2020 with the installation of its first boiler [17]. Over the 72-h testing period of the first boiler, the plant generated 1550 MWh from 2120 tons of marabou [17]. The first boiler was subsequently synchronized to the grid in March 2020 with the second following soon after [17]. Upon completion and running at full capacity, the plant is expected to supply 122 tons of steam per hour and all necessary electricity (8 MW) to the sugar mill, while the rest of the power is returned through the grid to supply 50% of the provinces' power demand [17]. Between the months of June and November, the plant will consume marabou at 1200–1500 tons per day, and between December and May, the plant will consume 2100 tons of bagasse per day [17]. The plant is expected to reduce oil consumption by 100,000 barrels per year and reduce CO_2 emissions by 3000 tons per year [17].

Cuba has plans to build 18 more biomass plants next to various sugar mills by 2030. Two more of these plants, both with a 20-MW capacity, are currently under construction: One is in the Matanzas Province, and the other is in Villa Clara Province [17]. A third and 50-MW plant is scheduled to start construction this year (2020) in Artemisa Province [17].

Another type of biomass plant has been constructed in Cuba in 2019 [18]. The plant is located next to Enrique Troncoso mill and uses waste from a rice-processing plant to produce energy [18]. The energy generated by the plant is subsequently used for drying the rice, and another 2.4 MW of electricity is used to reduce the rice-processing plant's reliance on the national grid [18].

Biofuels

In the last few decades, Cuba has been against expanding their use of biofuels. Fidel Castro held an official stance that food crops should not be used to produce fuel while there are people starving [19]. In 2016, the country was producing the same amount of ethanol as they did in 1991, 1.81 thousand barrels per day [20]. When Castro died in late 2016, many saw an opportunity for the country to invest more in biofuels [19].

In 2017, an industrial-scale biodiesel plant began operation in the Granma Province [21]. The fuel is obtained from oil of the *Jatropha curcas* flowering plant, and the plant is expected to reduce the reliance on imported fuel by 26% [21].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

The Cuban electric grid is more than 40% of distributed generation; meaning that the power is generated near the point of consumption [2]. The goal of this setup is to increase the reliability of the electric grid and produce power close to the point of demand [2]. There are no reports of installed large energy storage systems in Cuba although there is potential for pumped hydro storage at the large number of small hydropower plants around the country. Additionally, compressed air and large-scale batteries and fuel cells would greatly add to the demand resiliency of the entire grid.

Cuba utilizes generators that burn oil for some of their energy production, but no large-scale batteries are used to store electricity. When the demand is high, the production often cannot keep up, resulting in rolling blackouts during the high-demand summer months [2]. If Cuba could utilize batteries combined with their distributed generation grid, it seems that these blackouts could be avoided by storing extra energy for use during demand peaks [2].

Country's Future Storage Direction

Due to the large solar potential, electrolysis of water is a promising source of hydrogen for Cuba [22]. Electrolysers connected to solar photovoltaics and wind turbines could be used to generate and store hydrogen for future use [22]. The electrolysers could be utilized only when the national grid is not relying on power from the PV or wind turbines to maximize the benefits of the renewable technologies [22].

Aside from the photovoltaic and wind turbine electrolysers described above, there is a bioelectrochemical system with potential. The large sugarcane industry in Cuba generates bagasse by-product that happens to be a substrate used for the growth of hydrogen-producing bacteria [23]. The bacteria and hydrogen can then be used in microbial electrolysis cells, up to 1 kWh, which is enough to power a single home [23]. This constitutes a bioelectrochemical system where microorganisms serve as the catalyst in the cell [23].

Cuba has many other options for hydrogen production including electrolysis of water and direct thermolysis [22].

In 2011, it was reported that Cuba's National Hydrogen Group was researching and testing hydrogen as a fuel source for vehicles [24]. With the recent increase in renewable developments in Cuba, it only makes sense to utilize a hydrogen network around the country. Whether this is in the form of the aforementioned hydro-vehicles, or simply the use of electrolysers and fuel cells alongside other renewable generation techniques as a way to store and redistribute energy, any use of hydrogen in such a manner would be beneficial [22].

Carbon Footprint

Most Recent Carbon Output

In 2018, Cuba emitted 25,000 kt of CO_2 [25].

Historical Trends of Carbon Footprint

Figure 4 shows the historical carbon emissions of Cuba in thousands of kt. They reached peak emissions in 1990, and then the values drastically reduce to political conflict in the country during the following years [25]. The more recent decrease is the result of the increased use of renewable energy.

Types and Main Sources of Pollutants

The main sources of pollution are industrial processes, vehicles, oil refineries, and cement and nickel plants (nickel is a naturally occurring resource in Cuba) [1, 25].

Air Quality

The air quality in Cuba is considered moderately unsafe according to guidelines set out by the World Health Organization due to their $PM_{2.5}$ concentration of 20 μg/m^3 being 15 μg/m^3 over the recommended maximum [25].

Energy Resiliency

Electrical Grid

Cuba's electrical grid spans the entire country, one of the most extensive grids among countries in the nearby region [11]. However, much of the grid is old and experiences transmission losses up to 17.6% [11]. In 1959, the generating capacity of Cuba's national grid was only 400 MW, and only 50% of homes had access to electricity [2]. By 1990, the capacity had grown to 4000 MW and reached 95% of households [2], and in 2014, they had over 6000 MW of installed capacity [2].

Cuba has experienced rolling blackouts for decades due to multiple reasons, namely the lack of fuel caused by geopolitical strife and failures among the grid such as transmission line breaks or power plant failures due to the burning of sulfur-rich oil [2].

The economic collapse in Cuba in the early 1990s caused long-lasting blackouts that were unpredictable, some lasting longer than 10 days [2]. Summer months continue to be a period of high demand during which blackouts may occur, and the government sometimes rations electricity [26].

Climate and Natural Disasters

Cuba is highly susceptible to adverse effects of climate change [2]. They have been experiencing increased dry periods and extreme weather events for many years already, and they will only continue to worsen [2]. Additionally, being an island nation, there are extreme changes to come in the form of rising sea levels. It is estimated by the International Panel on Climate Change that Cuba will lose over 3% of its land by 2050 due to sea level rise between 0.8 and 1.5 m in the next century [2].

Situated in the Caribbean Sea, Cuba is susceptible to hurricanes between June and November. The largest recent event was Hurricane Irma in September 2017; it was the strongest hurricane to hit Cuba in 80 years [27]. The storm caused lots of infrastructure and economic damage to the island with winds topping 160 miles per hour and huge ocean swells [28]. The floods lasted more than 3 days with many buildings and power lines destroyed causing more than $13 billion in damages [29]. The storm destroyed many crops and damaged sugar mills, which had lasting effects on the economy [29]. The Cuban government did not have the funds to help everyone at once and so had to prioritize where aid was sent first [28]. This caused some dissatisfaction with the government's response by locals, some of whom decided to move away from the coast when they learned materials to rebuild their homes would not be available for several months, while, at the same time, tourist locations were prioritized by government aid, resulting in some restaurants and hotels reopening within a matter of weeks [29].

In total, the flooding affected 158,554 dwellings, 980 health institutions, 2264 schools, 466 poultry farms, 95,000 hectares of cropland, 246,707 landlines, and 537 km of roads [30].

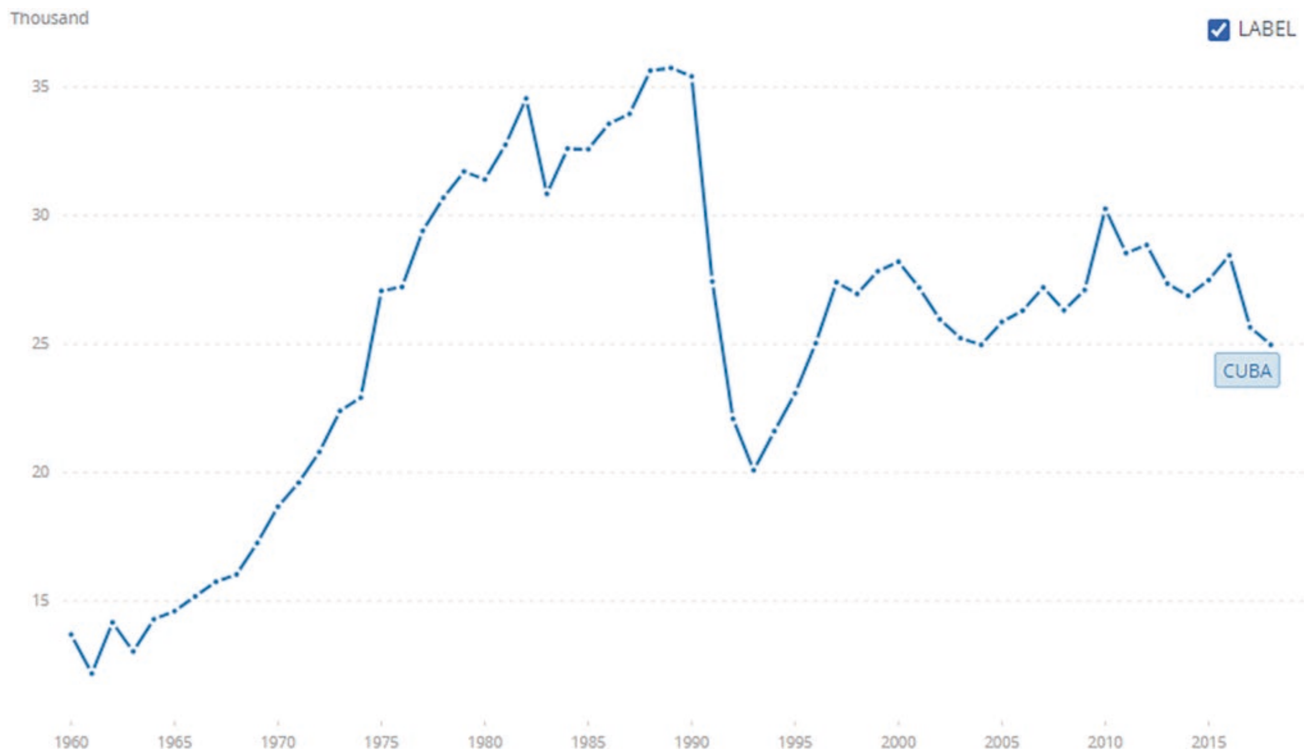

Fig. 4 Cuba's historical CO_2 emissions in kt [25]

After Hurricane Irma, many areas were left without power for several days. However, only weeks after the disastrous storm, the country's main electrical generator had been restored [31].

Due to the distributed generation network of the country, they have some resilience in the face of hurricanes and other natural disasters because each power production location services only a portion of the entire grid [2]. Therefore, they can be brought back online more quickly and do not cause far-reaching failures [2].

Grid Resiliency

Cuba does not have a large domestic fuel supply operation, although they have increased their capacity in recent decades due to geopolitical circumstances discussed in the next section [2]. As mentioned previously, the domestic oil in Cuba contains traces of sulfur that corrode equipment in power stations, leading to power plant failures and lasting blackouts [2].

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

Up until the early 1990s, Cuba relied on its relationship with the Union of Soviet Socialist Republics (USSR) for oil imports to support its growing demand and capacity for electricity produced by burning oil [2]. Upon the collapse of the Soviet Union, Cuba suffered greatly economically and had food, oil, and gas shortages that lasted several years [2]. In this period, they began expanding renewable sources, namely from solar photovoltaic and micro-hydro plants [2]. They also began exploring domestic oil and natural gas production in the hopes of supplying their own fuel [2].

In 2000, Cuba and Venezuela entered a barter agreement under which Venezuela would provide oil in exchange for professional medical services by Cuban citizens [2]. Cuba imported more than $14 billion worth of oil between 2003 and 2009 [2].

However, geopolitical strife in Venezuela caused supply issues, and their imports were diminishing in 2016 [2]. The Cuban government began to implement measures to reduce reliance on oil imports by decreasing fuel consumption through reduced bus services, reduced air-conditioning, reduced workdays and halving the allotted fuel amounts for government vehicles [2].

Relations with Global Community/Socioeconomic Influence

This part of the report talks about relations with the global community, specifically Paris Climate Accord, United Nations' standing and involvement, political conflicts, Iran/North Korea/China/Russia, Socialist v. Communist v. Democratic, etc., current renewable energy goals (2050), and education.

Cuba is committed to the climate goals of the Paris Agreement, and they were the 13th country to submit their nationally determined contribution in 2020. As mentioned earlier, they plan to prioritize energy and agriculture, forestry, and other land use sectors by generating 24% of electricity from renewables in 2030, increase efficiency, and increase forest cover among other actions [4].

Cuba is a member of the United Nations and supports their work. Member countries of the United Nations have voted for 29 consecutive years to demand the United States to end its trade embargo with Cuba [32]. The United States claims that the embargo is designed to promote democracy and respect for human rights, and so there is an impasse to this particular political decision [32].

Cuba and Iran both have a history of tension with the United States, so it is only natural that the two countries would be allied together [33]. Most recently, Cuba has outsourced the production of one of its COVID-19 vaccines to Iran [33].

Similarly, Cuba has maintained diplomatic relations with North Korea over their shared conflicts with the United States [34]. They have their own periods of tension but in 2016 agreed to a barter-based trade deal and continue to build their relationship [34].

Cuba has friendly relations with China, paying each other diplomatic visits and supporting one another's international affairs [35]. The two countries have trade agreements in digital television, agriculture, biological science, and technology and infrastructure, as well as culture, education, and health [35].

Cuba and Russia have discussed a strategic partnership, and Russia has mentioned deploying military troops to Cuba should the situation with Ukraine reach a point where Russia deems it necessary to have a military presence closer to the United States [36]. At the time of this writing (early 2022), Russia and Cuba are discussing a future of cooperation in international affairs [36].

Cuba is a single-party authoritarian regime that does not generally allow political opposition. This is the reason the United States has placed trade embargos on Cuba and claims to support the development of a democracy with an emphasis on human rights.

Education

Many rural schools are equipped with solar panels to power the local education system. Therefore, it is only natural that students learn about the solar panels on the roof of their school. Ciudad Libertad is a school that was a former army barracks but now holds classrooms for students from preschool through university [37]. One classroom is solely dedicated to renewable energy and environmental studies [37]. Students from all over Cuba travel here to learn in this classroom about energy conservation, recycling, and renewable energy [37]. Additional education is being provided to educators through a state-financed book so that education about renewable energy can be integrated into more school programs [37].

Summary

Current Energy Situation

Cuba produces a majority of its electricity from oil. Their electrical grid reaches the entire country and has a capacity of over 6000 MW. The breakdown of electricity generation in 2014 was as follows: 81% from oil, 14% from natural gas, 4% from biofuel, and 1% from other renewables [2]. Cuba uses renewables in the form of solar photovoltaics, wind energy, hydropower, and biomass. They do not use nuclear power, geothermal energy, or ocean energy although they have potential to take advantage of ocean energy and may have a future in nuclear power generation.

Future Energy Situation

Cuba has faced many challenges from political, to international relations, to natural disasters. As such, they have clear goals to reduce their reliance on fossil fuels (particularly foreign oil) and increase the share of renewables up to 24% of the generation mix by 2030. They seem to be well on their way to that goal, but they will continue to face hurricanes and political challenges that may prevent them from establishing a sufficiently resilient electrical grid.

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Haiti

Slobodan Petrovic and Tony Augustine

National Energy Introduction

As of July 1, 2021, the United Nations (UN) estimated that the population of Haiti was 11,541,685 and steadily rising at a rate of approximately 1.26% [1]. This puts the current population (on date of data retrieval) at 11,556,163 [1]. The country is 27,750 km^2, which gives a population density of around 419/km^2 [1, 2]. Over half of Haiti is mountainous regions, and the rest consists of valleys, plateaus, plains, and coastal areas [2]. It is a largely tropical country but does have semi-arid regions in the east where the mountains block the trade winds [2].

In 2019, 45.47% of the population of Haiti had access to electricity [3]. In rural areas, this number was reported by the World Bank in 2019 to be only 0.98% [4]. However, a different report from 2012 stated that 15% of rural areas have access to electricity, whereas the World Bank source stated that in 2012 only 3.92% had access to electricity [4, 5].

Energy Policies

In recent years, Haiti's government has been shifting its focus onto renewable energy alternatives and incentives. In 2017, the Haitian government put an exemption on import taxes for solar modules and inverters, though some customs fees are still in place [6]. The government had promised to install an additional 190 MW of solar generation capacity that would include 130 MW of photovoltaics (PV) and 60 MW of thermal power [5, 7].

In 2016, a decree of the Haitian government created the National Regulatory Authority of the Energy Sector (ANARSE) [8]. It was placed under the supervision of the Ministry of Public Works, Transport, and Communications (MTPTC). The ANARSE's mission is to encourage the growth of the energy sector by regulating the production, operation, transportation, distribution, and marketing activities of electricity within the nation's territory [8]. Their role is to make sure that laws and regulations that govern the electricity sector are upheld in an objective, a transparent, and a nondiscriminatory manner [8].

In 2019, the Haitian government worked with the World Bank to start the Off-Grid Electricity Fund (OGEF) [9]. The goal of the OGEF was to provide electricity to 200,000 households within 10 years. The fund works by investing debt and equity in companies that provide renewable off grid power access solutions to the people of Haiti (e.g., mini grids or pay-as-you-go solar products) [9]. The project is funded by the Clean Technology Fund and the Scaling up Renewable Energy Program (SREP) in low-income countries. As of 2021, it has invested in and provided grant money to different companies and projects [9, 10].

In 2020, the Haitian government made a plan to transition to 46% renewable energy generation by 2030 [11]. This would include at least 5.6% (20 MW) of bioenergy, 7.5% (30 MW) of solar, 9.4% (50 MW) of wind, and 24.5% (60 MW) of hydropower [11]. They also have an unconditional target of installing an additional 37.5 MW of hydropower by 2030 [11].

Domestic Resources

Haiti has many under-utilized domestic energy resources. They have no oil drills. Yet, it is predicted that they have oil reserves of around 142 million barrels and still a potential to produce 941 million barrels, which is yet to be discovered [12]. They also have about 4.5 Gm^3 (159 billion f^3) of natural gas underneath their feet and an estimated 33.98 Gm^3 (1.2 trillion f^3) that is still undiscovered [12]. While the possibility of natural gas exists, they have no natural gas power plants.

Furthermore, the country's solar potential is high with a practical average potential per day of approximately 4.68 kWh [13]. The wind potential is also strong, and the

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annual average wind speed was evaluated at an 80-m hub height and found to be 6 m/s [14]. Additionally, by fully utilizing small- and micro-scale hydropower, Haiti could generate an additional 896 GWh of electricity each year [14].

History of Energy

The island of Haiti was originally claimed by Spain, but the western third was later then ceded to France [15]. Before gaining independence in 1804, Haiti was the French colony known as Saint-Domingue [15]. The French enslaved African workers and used them to grow sugar. Doing so, Saint-Domingue became the wealthiest colony in the French empire. The slavery system in this colony was seen as one of the harshest in all of the Americas with a large amount of both violence and mortality [15]. Almost 800,000 Africans were imported to the colony to work in the plantations [15]. This is almost double the number of Africans brought to North America [15].

From 1791 through 1804, the enslaved people of Saint-Domingue and their allies fought a successful slave rebellion, and the country of Haiti was established [15]. The rebellion was not only between the enslaved population and Spain, but also between the slaves and the British, who fought to regain the control of the colony [15]. It was on January 1, 1804, that Jean-Jacques Dessalines, the new leader of the rebellion, announced the new nation of Haiti to the world, a world that was not fully prepared to accept its independence [15].

From here, Haiti was plagued by civil unrest, economic unknowns, and lack of skilled craftsmen, planners, and administrative members [16]. Much of the European powers and their Caribbean surrogates shunned Haiti, while slave-owners in the United States tried to ignore their existence and free states plotted trade routes [16]. Most importantly, Haiti's population did not have many of the basic necessities of life [16].

Eventually, after France recognized Haiti's independence in 1825 (in return for a large compensation fee), Haiti was also recognized by Britain in 1833 and then by the United States in 1862 [16].

In the 1980s, the United States attempted to get more military and commercial rights within Haiti. Following this, in 1905, they took control of Haiti's customs and gained a secure foothold in the financials and valuable concessions in the country [16]. Then, they occupied the country using US Marines from 1915 to 1934 and claimed that it was justified under the Monroe Doctrine [16]. Haiti and the United States signed a treaty that started out at 10 years, but was later extended, which established US financial and political domination [16]. In 1918, the elections were monitored by the Marines and the new constitution that was introduced allowed foreigners to buy and own land in Haiti [16]. The Marines were not withdrawn until 1934 and even after the United States kept direct fiscal control until 1941 and indirect control until 1947 [16]. The constitution of Haiti was amended in 1941 so that the future presidents would be elected by popular vote [16].

The United Nations' Stabilization Mission in Haiti (MINUSTAH) took authority over international intervention in June 2004 with a goal to stabilize political processes, to maintain security, and to monitor and to promote human rights [16]. MINUSTAH employees and personnel were volunteers from multiple countries around the world and Brazil-led military troops and police [16]. Various human rights organizations however have made claims that MINUSTAH, UN- and US-trained Haitian National Police force members have committed acts of brutality against political demonstrators and other citizens [16]. In December 2004, in Brazil hearings, the MINUSTAH commander testified that they had been strongly pressured by international communities to use violence [16].

Protests and riots occurred over the next few years for various political and resource scarcity reasons that led to the further decline in the Haitian economy. Following these, two major natural disasters struck Haiti in 2008; then again one hit in 2010, followed by another in 2012 [16]. The government reached a crisis point in late 2014 with a failure to organize parliamentary and local elections [16].

The last president, President Moïse, was sworn in February 2017 [16]. From the beginning, his administration was believed by many to be rampant with corruption [16]. Opposing forces believed that, according to the terms of the constitution, his term should have ended in February 2021. However, he, and most international organizations, held that he still had another year in office [16]. His opposition demanded his resignation, but Moïse refused and announced that he was intending to hold a referendum to allow for an amendment to the constitution [16]. This was postponed due to a state of emergency that he called after a spike in COVID-19 cases [16]. On July 5, 2021, Moïse named Ariel Henry the prime minister (making him the seventh person to hold this position since Moïse was sworn in) [16]. While opposing forces were questioning the legality of naming a prime minster without any legislative approval, on the morning of July 7, unidentified gunmen entered the presidential residence [16]. The gunmen assassinated Moïse and injured the first lady [16]. This has left a power vacuum at the highest level of the government in Haiti as Ariel Henry had not yet been sworn in as prime minister and René Sylvestre (president of the Court of Cassation) died of COVID-19 on June 23 [16]. Interim prime minister, Claude Joseph has announced he is in control and declared martial law, although the source of his authority remains unclear [16]. His assumption of presidential power relies on legislative consent, and the Haitian parliament was effectively dissolved in 2020 [16].

Breakdown of Energy Generation "Mix"

Energy Generation Mix

According to one source, Haiti generates, on average, 80% of its energy through the use of refined petroleum products that are imported [6]. Two other sources state that this number is higher, at 92–93% [11, 17]. The remaining energy is generated by hydropower plants and solar power within the country [17]. In total, there is 285 MW of installed generating capacity that turns into 1.092 TWh of power [17]. In 2020, the 7% of renewables generated in Haiti were comprised of 78 MW of hydropower and 3 MW of solar power [17]. It is worth noting that approximately 60% of the energy generated (by both renewable and nonrenewable sources) is lost due to transmission and distribution losses over a damaged grid [18]. This means that the country was left with approximately 0.44 TWh of electricity in 2020 after distribution.

It was reported by one source in 2018 that Haiti produced 40.4 TWh (3.47 Mtoe) of energy but had a total energy supply of 53.5 TWh (4.6 Mtoe) [19]. It is unclear where this additional energy came from. There is no information to be found about Haiti importing energy from only their neighboring country, the Dominican Republic, and it is unknown how else they could have obtained more energy that would have led to this discrepancy.

Energy Consumption Mix

In 2018, Haiti consumed 0.41 TWh of energy [19]. Excluding heating, cooling, and transportation fuels, 32% of energy consumption was residential, 25% due to commercial and public services, and 43% was industrial [17]. When taking heating, cooling, and transportation fuels into account, the residential consumption jumped to 70%, industrial dropped to 15%, and transportation consumed 13% of total energy available [17]. It is estimated that the peak demand for electricity in Haiti is 500 MW [17].

Fossil Fuels

Oil

As stated above, one source states that Haiti generates, on average, 80% of its energy through the use of refined petroleum products that are imported [6]. Two other sources state that this number is higher, at 92–93% [11, 17]. The country of Haiti does not produce or import any crude oil. Nor do they export any refined petroleum products, as there are no refineries located within its borders. However, they do consume large quantities of imported refined petroleum products. It is estimated that in 2015 they imported 20,030 bbl/day and that in 2016 they consumed 21,000 bbl/day [20]. Refined petroleum was the most imported product in 2019 with a total of US$286 million being spent on it [21]. In the same year, the petroleum imports mainly came from the United States ($282 million), El Salvador ($2.1 million), Jamaica ($703k), Mexico ($436k), and India ($214k) [21].

There are no oil drills in Haiti, although it is estimated that they have oil reserves of about 142 million barrels [12]. Furthermore, it is predicted that there is another 941 million barrels of crude oil yet to be discovered (some of this may be off the coastline) [12].

Coal

According to a 2018 report, on the low-end Haiti consumes 352,014 metric tons of coal annually and on the high-end 524,394 metric tons [22]. This coal is typically used in households for the purpose of cooking food, heating water, and other daily needs. In the 1980s and the 1990s, the USAID-financed Agroforestry Outreach Project tried to lessen the prevalence of deforestation in Haiti, which was done largely for the purpose of coal production.

This outreach project led to many Haitians starting their own woodlots. They grow native trees for the purpose of cutting them down 3–7 years later for use in making charcoal [22]. Since the woodlots were established, a decrease in soil degradation has been seen [22]. The vast majority of charcoal consumed in Haiti is produced within Haiti; however, it is possible a small amount is brought over from the Dominican Republic (about 216 metric tons) [22]. No source about official coal imports could be found.

Natural Gas

Haiti does not produce or consume any natural gas, so naturally it does not export or import it either. However, it is estimated that they have about 4.5 Gm^3 (159 billion f^3) of natural gas underneath their feet that is not being utilized [12]. It is predicted that there is also another 33.98 Gm^3 (1.2 trillion f^3) still undiscovered [12].

Nuclear Energy

The most recent numbers that could be found for Haiti's nuclear power output are from 2014 and range from 0% to 0.07% of the country's total energy output [23, 24]. The year with the highest nuclear power use was 1989, where it made up 2.19% of the country's total energy use [24]. However, if the second source is to be believed, implying that there is indeed a nuclear power source in Haiti, no information about it can be found.

It is worth noting that while it is possible that Haiti had some sort of nuclear plant before the earthquakes, it is unlikely their current grid would be able to handle such a facility. With a GDP less than US$50 billion, it is not believed that they would be able to purchase a nuclear reactor (as reactors are worth at least a few billion dollars) [25]. Furthermore, for technical reasons, their electrical grid would need to have a minimum of 10 GW to accommodate a large nuclear reactor [25]. As the current grid in Haiti is not of this scale and is subject to large losses in power due to the damaged state of the grid, nuclear may not be a feasible option at this time.

The most recent stances that the Haitian government has taken on nuclear energy have been positive ones. In 2007, they amended their relationship with the International Atomic Energy Agency (IAEA) by repaying US$330,000 in arrears [26]. They stated that they did so because they recognized the importance of the Agency's program work in the country and in development [26]. The year after this, in 2010, they reached out alongside 50 other developing countries to the IAEA and expressed their interest in establishing their first nuclear power plant [25].

Renewable Energy Generation

Photovoltaics (PV)

In 2020, it was reported that Haiti had only 3 MW worth of installed solar generation capacity [11]. It is unknown exactly what sources this 3 MW includes as no information can be found about how the data were collected. However, there are many companies who partnered with the Haitian government to create small-scale projects or microgrids over the years. It is possible that these could have been counted in the 3 MW total. One such company is called Earth Spark. They launched their first microgrid in 2014 with just 14 customers and expanded to 54 customers by the end of 2013, in the town of Les Anglais [27]. They then created a town-sized solar-powered smart grid that served 440 households (over 2000 people) in April 2015 [27]. This system is a hybrid generation system, with 93 kWp of PV capacity, 400 kWh of battery capacity, and a small diesel backup generator [27]. In 2019, they were able to create a second grid in Tiburon, Haiti [28].

Other companies have completed, or are in the process of completing, solar grids such as these. Another example is Sigora, which began connecting customers to electricity in 2015 and now operates two microgrids and one picogrid, with a third grid under construction [29]. Their microgrid in Môle-Saint-Nicolas has 200 kW of diesel and 200 kW of solar, and the one in Presqu'ile has 2.7 kW of solar and batteries [30]. They provide electricity to over 20,000 people and are under a 25-year power supplier contract with the governmental municipality [29].

Haiti has a large potential for even more solar projects to be put into place in the coming years. They have little monthly variation of photovoltaic power output over an entire year, meaning that the grid would be under less load stress than PV can cause in other locations [31]. Their theoretical average of global horizontal irradiance potential per day is approximately 5.54 kWh at an evaluated area of 27,048 km^2 [31]. The practical average potential per day of "level 1" land, meaning that it disregards any land use constraints and excludes land with identifiable obstacles to utility-scale PV plants, is approximately 4.68 kWh [31].

If the previously mentioned project for an additional 190 MW of capacity that would include 130 MW of photovoltaics (PV) and 60 MW of thermal power [32] is realized it would be comprised of a 55-MW (60 MW installed) fuel-flexible plant in Port-au-Prince, 20-MW arrays in Cap Haïtien and Gonaïves, 10-MW plants at Port-de-Paix and Jacmel, and a 5-MW facility in Jeremie [6, 32]. Furthermore, to provide balance to the generation capacity of the PV system, it would be fed by several smaller facilities at currently unspecified sites in the areas of Grand'Anse and Nippes [6].

Wind

As of 2014, there were no wind turbines installed in Haiti [33]. More recent information on this cannot be found, but it is strongly believed that if something had been installed it would have been quite newsworthy due to the emphasis the government is currently placing on diversifying the country's energy profile. It is reported that in the past there were plans for a substantial wind farm in Haiti, but it was cancelled because assurances could not be made that the government municipality would be able to accept the power on an as-generated basis [33].

According to the estimations by WorldWatch in 2014, there were many viable wind sites across Haiti that could produce energy at a cost of approximately US$0.11/kWh [33]. In 2010, the United States did a national assessment at an 80-m hub height, and it was found that the majority of the country has an annual average wind speed of 6 m/s [14]. The more populated areas of Port-au-Prince, Gonaïves, and Port-de-Paix have an annual average wind speed of 7–9 m/s [14]. This means that some of the areas with higher population density also have a greater wind speed, allowing for more power generation to balance a larger power draw. The Haitian government plans to install 50 MW of wind power by 2030 [11].

Hydro

As of 2021, one of Haiti's operating hydropower plants produces 54 MW [34]. This 54 MW is due to the rehabilitation work done on the Péligre Dam in 2016 [35]. The plant was originally constructed in 1956 and between 1969 and 1971 was upgraded with a powerhouse and three hydro-generating units [35]. From the time of installation in the 1970s up to the time of rehabilitation work, the dam underwent only basic maintenance and much of the mechanical equipment had reached the end of its life [35]. Average annual production had reduced to below 150 GWh of the original 320 GWh potential, due to equipment failures and reduced water volumes in the reservoir [35]. The work in 2016 rehabilitated one of the three hydro units, and plans were made to rehabilitate the, at the time, nonoperational second and third units [35].

No official report could be found about the rehabilitation of the second and third units. However, a news article stated on June 24, 2020, that the Haitian Minister of Public Works, Transport, and Communications (TPTC) had asked the foreign firm Alstom Comelex GE to redo the rehabilitation work on two of the three 18-MW turbines at the Péligre hydroelectric plant [36]. Based on this information, it can be assumed that, at some point, the other two turbines were indeed repaired. They are requesting the work be redone because it is reported that two turbines broke down a mere three months after more than a year of repair work [36].

The governmental municipality also reports that they have an additional five hydropower plants that produce a total of 4900 kW [37]. The five plants are named Saut-Mathurine Power Plant, Green Wave Hydro Power Plant, Drouet Hydro Power Plant, Caracol Hydro Central, and Hydro De Gaillard Power Plant [37].

As of 2014, hydropower was the country's cheapest electricity generation method at a rate of US$0.05/kWh [14]. By utilizing small- and micro-scale hydropower sites, Haiti could generate an additional 896 GWh of electricity each year [14]. Many of the small- and micro-scale sites that are the most promising are located near Port-au-Prince, a high-population city, allowing for full utilization of the energy [14]. The World Bank approved a project fund for Haiti September 21, 2020; its purpose is to scale up renewable energy investments in Haiti to allow them to expand and improve access to electricity for businesses, homes, and community services [38]. The spread of funding across the applicable energy sectors is as follows: 75% renewable energy hydro, 9% public administration of energy and extractives, 8% renewable energy solar, and 8% energy transmission and distribution [38]. The total project cost is US$6.90 million, and there is no information yet on how the funding has been used thus far [38]. This funding looks promising for the future hydropower development within Haiti.

Ocean

Haiti does not currently have any ocean energy in place, be it wave technology, offshore wind, or otherwise. No plans for future use of ocean energy could be found. No analysis of their wave potential or offshore wind potential appears to have ever been completed. However, they may have a great potential for it due to their long coastline.

When considering ocean energy for Haiti, there are a few key points of interest to keep in mind. Many coastal areas in Haiti rely on fishing for commercial and domestic use. Ocean technology's installation (mainly offshore wind) can impact the habitats and habits of fish and other ocean life, and this could in turn have an impact on fishing and the coastal economy [39]. This impact could be positive or negative [39]. It is likely that wave technology farms could generate a safe zone for fish to repopulate in, thus increasing their population and allowing for an increase in fishing [39]. There is a chance, however, that the installation of devices and the movements of turbines, anchor lines, and cables could change the local benthic ecosystem around the devices [38]. The benthic zone provides import nutrients for the organisms within the zone. The fish in turn feed on those organisms. A shift in it could lead to a shift in the local food web.

It is also important to keep in mind that Haiti is subject to not only torrential rains and flood conditions, but that these conditions are often caused by or paired with tropical storms, cyclones, landslides, earthquakes, and hurricanes. Since 2002, Haiti has been faced with a mixture of over 20 tropical storms, hurricanes, and earthquakes that claimed the lives of citizens and caused damages to infrastructure. Tropical storms, hurricanes, and cyclones start out at sea and move inland, meaning that ocean technology would be left in the path of severe weather conditions and would need to bear the brunt of the storms.

Geothermal

As it stands, there are currently no geothermal power plants in Haiti. No true assessment of the country's geothermal potential has been completed. Based on the regional assessments of the Caribbean area, it is likely that it is low [40]. They may not be able to utilize it for electricity production [40]. However, it might be fit for cooling systems in buildings [40]. This would be particularly efficient and effective in buildings that are operational for long hours, such as government offices and hotels [40].

Biomass

No plant that utilizes bioenergy is in operation at this time. However, there is one company that has plans in place to create one. The company creating the plant is named Bioenergy Haiti (BEH). The BEH was founded in 2012 and has been working on gradually creating a collection and technical landfill system that they could use for municipal and agricultural residual materials with the addition of energy recovery from biogas [41]. At this time, they appear to have established a steady collection and landfill system. They have plans to expand and state that a 1-MW biogas power plant will be functional by 2024, alongside a processing plant powered by 2 MW of solar panels [41].

This is the only company that could be found attempting to use bioenergy. The governing body of Haiti plans to have 20 MW of bioenergy in place by 2030 [11].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

Haiti does have some hydropower plants. Some of them may be capable of storing water for later energy generation. One such plant is the Péligre Dam. However, as stated above, it is unclear what the plants' current operating power is and how much water it can store for later energy generation use. Haiti also plans to add a large amount of hydro (at least 60 MW) to their energy profile by 2030, so this may greatly increase their energy storage [11].

Haiti also utilizes some battery storage for its solar-powered grids and facilities, as briefly discussed above. The batteries attached to grids seem to be used to maintain power levels at night and in emergent situations. There are some hospitals in the country that utilize solar energy and battery storage. The hospitals have recently replaced their lead–acid batteries with new Tesla wall units [42]. The wall units are expected to be more effective and have lower maintenance, as well as being more resistant to the Caribbean heat [42].

Country's Future Storage Direction

Haiti plans to increase their solar energy generation to 30 MW by 2030, so it stands to reason that their battery storage will also increase [11].

Carbon Footprint

Most Recent Carbon Output

In 2016, Haiti's contribution to global CO_2 emissions was only 0.01% at 3,086,897 tons [43]. This puts the country at 0.28 tons per capita [43].

Historical Trends of Carbon Footprint

Haiti's CO_2 emissions in tons increased 1.71% from the previous year [43]. This is approximately in line with their increase in population, which increased 1.35% that year, but typically increases at a rate of 1.26% annually [1, 43]. Since then, the country's emissions have continued to rise, and in 2018, they reached 0.33 tons of CO_2 per capita, which was a 1.77% raise from the previous year [44]. However, the following year, 2019, saw a decline down to 0.32 tons of CO_2 per capita, a −3.27% change [44].

The government of Haiti has signed the Paris Agreement. Their date of ratification is reported to have been July 31, 2017 [45]. The Paris Agreement aims to substantially decrease greenhouse gas emissions to limit global climate change [46]. This means that it would not be unexpected to continue to see Haiti's carbon emissions decrease in the future years, even as they continue to develop as a country. Haiti also signed the Kyoto Protocol on July 6, 2005 [44]. This protocol puts the United Nations Framework Convention on Climate Change into action by committing industrialized countries and economies to limiting and reducing greenhouse gas emissions following agreed individual targets [46].

Types and Main Sources of Pollutants

Over half of this is due to the transportation sector, 9.4% comes from buildings, 12.6% from the power industry, 8.2% from noncombustion sources, and 16.2% from other industrial combustion sources [43].

Air Quality

The air quality in Port-au-Prince Haiti appears to stay at a relatively healthy standard [47]. It ranges between approximately 20 and 40 US air quality index (AQI) and with $PM_{2.5}$ below 10.1 mg/m^3 over a 7-day period (when data were taken) [47]. However, there are some air quality concerns worth mentioning.

In 2015, it was reported that air pollution in Port-au-Prince and Cap-Haïtien could reach levels considered hazardous by the US Environmental Protection Agency [48]. This is mainly due to commercial and residential sources such as power generation, diesel generators, trash burning, use of charcoal and other biomass for cooking, and traffic congestion [48]. Road infrastructure in urban areas is extremely poor, and this both affects the safety of users and creates congestion and dust from passing vehicles [48]. Open trash burning is actively practiced in Haiti, and there does not seem to be any policy against it or limiting it [48]. The dominant fuels used for cooking and space heating, in the order of most to least used, are wood, charcoal, coal, kerosene, gas, and others [48]. It is reported that 9,461,611 people are affected by an illness related to household air pollution each year and 9593 deaths are reported to result from it per year [48]. Of those deaths, 1379 are reported to be children, with acute lower respiratory illness being the number one killer of children under the age of 5 in Haiti [48]. It was recommended in a study done by USAID in 2007 that the average life span of a Haitian is lessened by 6.6 years because of the impacts of indoor air pollutants created by burning biomass indoors [48]. In 2015, there was no National Air Quality Policy, and one can still not be tracked down [48].

Energy Resiliency

Electrical Grid

Electricité d'Haiti (EDH) is an autonomous state of body that has a monopoly on the distribution of electrical current on a national scale in Haiti [6]. The company was inaugurated on September 1971 and legally became a state body [6]. The EDH was created by the law of August 9, 1971, and is currently governed by a decree that was created on August 20, 1989 [37]. Their mission is to produce, transport, distribute, and sell energy throughout the entire territory of Haiti [37]. They report that they have approximately 2300 employees and 4 union groups that they officially recognize [6].

There is no national grid in Haiti. The largest electric grid is located in Port-au-Prince, and there are around eight smaller regional grids [6]. However, some towns that have EDH grids have been effectively abandoned by the company and must turn to privately owned resources for their energy needs [6]. Many of these users, and those families without an EDH grid available to them, rely on small diesel generators for their electricity [6].

In 2019, the energy sectors' regulatory body ANARSE began prequalification rounds for concessionaires to take over and expand electrical transmission, production, and distribution for a few of the country's regional grids [6]. This process was slowed by COVID-19, but they are expected to choose the concessionaires for the initial three grids in 2021 [6].

The grids in Haiti are often unstable, resulting in blackouts that can last days to weeks. According to a news article published August 12, 2020, some Haitian citizens have blackouts that have lasted as long as 33 days [49]. This is due to the unreliability of the electric utility companies, both private- and government-owned, who can decide when and how much power to output at will, to shortages of fuel, and the damaged state of the grid itself.

The shortages of electricity are often caused by a lack of the country's main energy resource, imported refined petroleum products. In 2019, Haiti received a large portion of its fuel from Venezuela. When Venezuela faced a governmental crisis, the effect in Haiti was profound. The acute fuel shortage faced throughout September 2019 sparked large-scale protests and riots that forced schools and shops to close and left hospitals barely functioning [50]. Haiti receives 20% of its operating budget from international funds, and when the president did not pass a 2019 budget, the government came to the point of owing US$130 million in arrears to the country's fuel suppliers [50].

The damage to the grid is because of a lack of consistent maintenance and the constant battering from natural disasters. This damage means that approximately 60% of the energy generated is lost during the transmission and distribution process [51]. Some of these losses may also be due to households that are connected illegally, as after the 2010 earthquake it was reported that half of the electricity consumers were connected illegally [52].

Climate and Natural Disasters

Historically Haiti has been hit with a number of natural disasters that compounded and led their economy to steadily decline. Haiti lies in a hurricane corridor and every rainy season is hit with small- to large-scale tropical storms that destroy crops and infrastructure alike [53]. Not only are they vulnerable to tropical storms and hurricanes, they are also vulnerable to landslides and cyclones and are often victims of widespread outbreaks of sickness and disease [13]. The outbreaks are in part due to damage that has occurred to the medical infrastructure and to a lack of early medical intervention policies. Conditions within the country deteriorate further each time another disaster strikes because the government has been largely unable to keep up with the speed of the destruction.

Climate change has a big impact on Haiti because it has led to increasing temperatures during the dry season, stronger tropical storms, and rainfall patterns that are unpredictable [54]. This has led to issues with a lengthened drought season, a decrease in rain in the dry season, food scarcity, flooding, and landslides [54]. Warmer sea surface temperatures could lead to more intense tropical storms, with higher wind speeds [55]. The National Oceanic and Atmospheric Administration has done modeling that suggests it will result in an increase in the number of category four and five hurricanes and an increase in wind speeds of up to 10% [55]. The warmer sea temperatures cause hurricanes to have 10–15% more precipitation [55].

Haiti has recently approved the National Risk and Disaster Management Plan 2019–2030 [56]. The plan calls for a resilient perspective while encouraging sustainable and inclusive development [56]. It was drawn up considering the multirisk and recurring nature of natural disasters in Haiti that have been aggravated by climate change and poverty [56]. They plan to implement it through a program that has strategies for both private and public sectors as well as a monitoring and evaluation system at different stages [56].

Furthermore, a Ministerial Committee was established and charged with the development of a National Risk Financing Strategy. The goal of the financing strategy is largely to help post-disaster public financing management within Haiti. This strategy will help to increase resilience and reduce the impact of disasters on citizens' well-being and to facilitate and speed up post-disaster recovery and reconstruction. No information can be found about when this strategy will be completed or who is on this committee.

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

As discussed above, Haiti relies largely on foreign-imported refined petroleum products. It is estimated that in 2015 they imported 20,030 bbl/day and that in 2016 they consumed 21,000 bbl/day [20]. Refined petroleum was the most imported product in 2019 with a total of US$286 million being spent on it [21]. In the same year, the petroleum imports came from the United States ($282 million), El Salvador ($2.1 million), Jamaica ($703k), Mexico ($436k), and India ($214k) [21].

Relations with Global Community/ Socioeconomic Influence

Haiti is a democratic country with the president chosen through popular vote since 1941 [16]. Haiti and the United Nations appear to have active relations, and Haiti signed the Paris Agreement in 2017 [45]. In 2016, the UN secretary-general apologized to Haiti for their part in the cholera outbreak and established a US$400 million trust fund to raise money to provide material assistance to those who had been affected [57]. As of October 2020, only $20.7 million had been pledged and the UN has been criticized for not allowing victims to participate in creating the assistance [57]. Although the original UN project MINUSTAH was discontinued in 2019, they still have an active presence in the country and state they are helping authorities that address immediate problems and structural instabilities [58].

The United States government and the Organization of American States (OAS) have both previously told Haiti to hold elections even though other advocates for democracy warned that current conditions would not be conducive to free and fair elections [57]. The United States also continued deportations to Haiti throughout the COVID-19 pandemic, and from March to October, 24 flights holding deportees arrived, including those who tested positive for COVID-19 [57]. The United States for many decades has had footholds and investments in the country of Haiti, and the relationship is made clearer in the History of Energy section of this analysis.

The World Bank is another long-time investor and aid coordinator for the country of Haiti. In 2020 alone, their commitments amounted to US$213 million [59].

Education

Of Haitians over the age of 15, a little less than half are illiterate [57]. Education quality is generally poor, and 85% of schools are private [57]. These schools charge fees that are often unattainable for low-income families [57]. The COVID-19 pandemic and civil unrest kept the majority of children (70%) from classes throughout the 2021 school year [57]. From September to November 2019, instability within the country kept an estimated amount of three million children from school, and then in March, the pandemic closed all school for 5 months [57]. Literacy rates are around 55% for both the sexes [60].

In Haiti, approximately 100% of people speak Haitian Creole, and more critically to note, about 90% of them speak only Haitian Creole [61]. Yet, classes above the first years of primary school are taught in French. Textbooks and tests are in French, although most teachers are not even fluent in the language [61]. In Haiti, those who speak only Creole are seen as second-class citizens, whereas bilingual (French and Creole) speakers are seen as first-class citizens [61]. This makes education even further out of reach for many citizens.

Primary school is taught in Creole, yet the test at the end of 5 years is in French, leading less than 2% of children to pass [60]. If a student decides to enroll at a secondary school, they often find that teachers are ill-prepared, materials are inadequate, and classrooms are in disrepair [60]. Many schools' fees are too expensive for the students to even consider enrollment. Once secondary education is completed, wealthy students can move on to a local university or one abroad while low-income students are often left unable to move upward [60]. Vocational school is an option for those who can get the funds together; however, travelling and residential expenses can be extremely high [60]. Although the Haitian constitution claims free education for all, the reality is that usually only the wealthy make it to tertiary or university level education [60]. To make matters worse, of those students who do make it, 85% choose to live abroad after completing their college education [60].

The World Bank states that they have improved the access to quality education by delivering learning materials to 50,400 students, 1800 teachers, and 203 public school directors [59]. They have also been given to 9700 students, 540 teachers, and 60 community public school directors [59]. They have provided training to directors and teachers on scripted reading and financial management [59]. Furthermore, they have provided grants to children in 57,600 public schools and 125 non-public schools and improved nutrition by providing school meals to 225 public schools and 60 community public schools [59].

Summary

Current Energy Situation

Haiti currently relies largely on foreign fuel sources for its energy needs. While it does utilize some renewable energy in the form of hydro and solar power, there are many critically underutilized resources available to them. Approximately 93% of their energy comes from the burning of refined petroleum products, and 7% comes from hydro and solar power [11, 17]. Because the grid is so damaged, over 60% of the generated energy is lost during transmission and distribution [18].

Future Energy Situation

The government has placed a large emphasis on diversifying their energy profile and has made plans for the country to run on 47% renewable energy by 2030 [11]. This would include at least 20 MW of bioenergy, 30 MW of solar, 50 MW of wind, and 60 MW of hydropower [11]. They also have an unconditional target of installing an additional 37.5 MW of hydropower by 2030 [11].

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Panama

Slobodan Petrovic and Samuel Gaumer

National Energy Introduction

Energy Policies

Panama is a Central American country with an ever-expanding electrical grid. The current installed capacity of around 3386 MW as of 2017 with the majority of this capacity coming from hydroelectric dams [1]. The current energy policies in place are working to help set a plan for long-term energy development and to reach these goals by 2050 [1]. In general, the plan is to continue to develop and create more generation sources for the electrical grid while also increasing the number of people connected to the grid. This is planned to be accomplished by running scenarios and seeing how the generation mix of the grid will be changing with these different changes. The hopeful end goal is that, by 2050, 70% of the energy demand will be able to be supplied by renewable energy sources [1]. In order to reach this goal, there is hope that the continual development and implementation of both solar and wind power across the country will be able to greatly increase the installed capacity [1]. Other changes are to continue the development of energy-efficient systems to slow the growth of demand to be at levels that are easier to provide using mainly renewable energy sources [1]. While hydroelectric energy is currently the most common generation type in the country, the forecasting predictions assume that future development of hydroelectric energy will mostly stagnate as other renewables see further development [1].

Trends in Generation Technologies

The general trend in energy generation is a major rise in hydroelectric and oil generation with minor though consistent increases in coal, wind, and solar power in the electrical grid [2]. Energy sources that are currently lacking in the electrical grid are seen in geothermal, bioenergy, and ocean energy. While all three sources have the potential to provide energy to the grid, currently little development is seen in these fields [2].

Domestic Resources

The domestic resources that Panama has available are mainly seen in the form of bioenergy production potential and the large quantity of hydroelectric potential [1]. Oil, coal, and natural gas are currently not being harvested from the country and are all required to be imported in for processing.

History of Energy

Panama's generation sources are mostly controlled by many private companies with the transmission lines being owned by the Panama themselves [1]. These companies are both domestic and international and have 100% ownership of their generation sources [1].

Breakdown of Energy Generation "Mix"

Panama's energy generation mix and consumption mix are shown in Figs. 1 and 2.

Fossil Fuels

Oil

The largest fossil fuel type consumed in Panama is oil with around 33,831.67 GWh (2909 ktoe) being consumed in 2018 [2]. This is mainly seen in the transportation sector with 18,735.93 GWh (1611 ktoe) going into that field alone in

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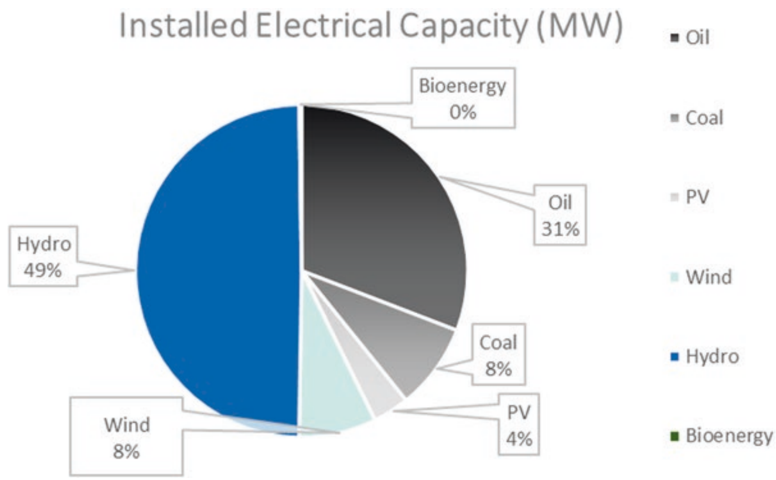

Fig. 1 Installed electrical capacity of Panama

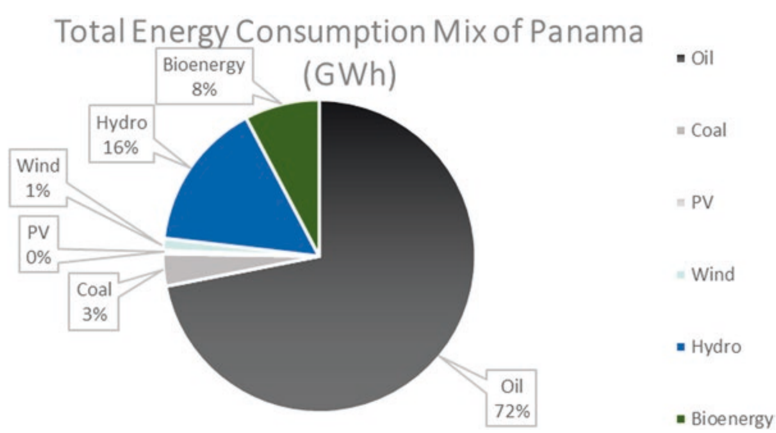

Fig. 2 Total energy consumption mix of Panama

2018 [2]. Oil is also used to generate electricity within Panama with two main oil types: bunker oil and diesel. For bunker oil, there are eight plants within the country all operated by different companies. AES owns and operates Estrella De Mar (72 MW), Pan-Am Generating has Panam (156 MW), Pedregal has Pacora (54 MW), ACP has Miraflores (174 MW), Valley Rise has El Giral (50.4 MW), Celsia has Cativá (87 MW), and Kanan has Santa Ines, Estrella Del Norte (93 MW), and Jinro has Jinro (57.8 MW) for a total of around 744.2 MW [1]. For diesel generators, there are three currently in operation: Celsia's Blm – CC (160 MW), Generadora del Atlántico's Gena – CC (157.75 MW), and Energyst's Cerro Azul (44.135 MW), leading to a total of around 361.89 MW of installed capacity [1]. This means that the total installed oil-based capacity is 1106.09 MW. With this large amount of installed capacity, oil is the second largest generating source in Panama generating 1409 GWh in 2018 [2], although it should be noted that this is a massive drop from 2949 GWh in 2017, showing that Panama might be transitioning away from oil-based electrical generation [2].

While there is a large generation sector of oil within the country, Panama does not harvest crude oil. Instead, they will either import refined petroleum or crude petroleum or refine it themselves [3]. There are a number of refineries within Panama that allow them to produce around 446 barrels of oil a day [4]. While this is nowhere near enough to offset the amount of oil they consume, it does help in providing work for the citizens as wells as offset some costs of purchasing only refined petroleum.

Coal

There is only one power plant in Panama that is powered by coal, and that is the PACO units 1 and 2. Each plant is designed to have a capacity of 150 MW for a total capacity of 300 MW [5]. Because Panama does not mine their own coal, the fuel source is imported from Colombia [3]. PACO was designed in order to provide power for the copper mine operated by Cobre and was constructed by Sargent & Lundy [5]. Apart from this plant, there are currently no coal plants used for electrical generation within the country and no public plans for future projects involving coal energy. Also given that currently there are no recorded coal reserves that could be mined even if Panama wanted to develop more coal-based energy within their grid, all of that coal would need to be imported in from other countries.

Natural Gas

Natural gas has only recently seen development with the first natural gas plant in 2018. AES Colón will be a power station powered by natural gas with an installed capacity of 381 MW and the ability to store 180,000 m^3 of liquid natural gas [6]. At the same time, there is development of a storage unit in order to help house all of this new LNG. This power plant is maintained by AES Panama, a company that operated many different power sources in Panama [6]. Before AES Colón, there has been no natural gas used for any form of electric generation within the country, and with a prediction that there is currently no reserves of natural gas within the country, all of this new fuel will need to be imported in from other countries in order to provide this electricity.

Nuclear Energy

Panama currently appears to have no intention of implementing nuclear energy into their power grid for the foreseeable future. With no current nuclear power plants, no steps being taken to develop the framework into a nuclear power program, and no research into uranium deposits within the country, if Panama were to try and implement a nuclear energy program, it would take a long time to get the framework in order to begin construction.

Renewable Energy Generation

Photovoltaics (PV)

The solar energy in Panama shows a lot of potential to be a good source of electricity in Panama, and even though there is a low current market, the future market is quickly growing. As of 2017, there is an installed capacity of around 127 MW, which is from around 13 different projects around the country [1]. In 2017, only 156 GWh was generated [2]. Looking at the 13 installations, currently, the largest farm is run by Llano Sanchez solar power, S.A., with the Don Felix, Milton, Sol Real, and Vista Alegre project that has a total capacity of 31.7 MW and was completed in 2017 [1]. The next largest is Solar Cocle venture that has an installed capacity of 27.5 MW; every other solar farm has an installed capacity less than 10 MW with some not even having 1 MW of installed capacity [1]. Solar is very new to Panama with the oldest farms being completed in 2013. While currently there is not a large amount of installed capacity in Panama, the future prospects of solar energy show a decent opportunity. On average, Panama's solar irradiance is 4.8 kWh/m^2/day, which is predominately in the middle of the country [1]. With the potential, there have also been a large number of projects that have received approval to begin development. In 2019, 14 solar licenses have been given out to different private companies to install 230 MW of solar energy across the country and another 11 provisional licenses amounting to an additional 261 MW [7]. With these new solar projects with different stages of development, there is going to be a much larger amount of solar energy introduced into the grid. One company that should be mentioned is Avanzalia Panama, which is working on a 150-MW solar farm in Panama and will become the largest solar farm in the country and is located in Penonomé [8].

Solar PV is not the only form of solar energy that is being developed in Panama; solar thermal is also seeing future prospects. One of Panama's energy goals that has been created is to have new buildings use 15% less energy than older buildings [9]. Currently, solar thermal energy is not used in Panama, and the applications that do appear are the focus around the idea of water heating instead of electrical generation. Between 2016 and 2019, a project was started to install 9000 m^2 of solar thermal systems in order to begin development of the solar thermal industry for the use of water heating to reduce electrical costs for many buildings with needs for hot water [9].

Wind

As of 2015, Panama has only one wind farm that is comprised of Penonomé I and II, resulting in a total of 270 MW of installed capacity generated from wind power [1]. This plant was developed by Union Eolica Panameña and connected to the electrical grid in that region [1]. With this installed capacity, Panama was able to generate around 588 GWh in 2018 [2]. While this is the largest wind farm in Central America, there is a large potential and plan for even more wind energy in the future. Looking at the average wind in different parts of the country at 200 m, the averages are around 5 m/s with a wind speed of 2 m/s and peak speed of 9 m/s [10]. These peak winds are seen on the western side of the country [10]. Along with this potential, there are future projects to make use of these winds; 662 MW of wind power has received approval for development in 2017, and as it continues to develop, more energy will be seen coming from wind power [1].

While currently not developed or planed, offshore wind energy could also have potential in Panama with the large ocean board on either side of the country. At 200 m up on both ocean sides, there are regions that get wind speeds up to 9 m/s and lows of 2.5 m/s [10]. If wind power continues to be developed within the country, then offshore wind could be another area to research.

Hydro

Hydroelectric power is currently the largest source of electricity in Panama with a total installed capacity of 1777 MW as of 2017 [1]. In 2017, alone 7254 GWh was generated by hydroelectric methods [2]. The large amount of generation comes from the 33 operating plants as of 2017 [1]. The most notable plant is that of Enel Fortuna that has been operating since 1984 and provides 300 MW of the installed capacity alone [1]. Although this plant has the highest installed capacity, it is an old plant and will likely have a lower efficiency now compared to when it was fist constructed. The next largest plant is Bayano from AES Panama; this plant is based around three dams and has an installed capacity of 260 MW [1]. Two of the dams were constructed in 1976, while the third dam was made in 2002 [1]. Continuing down the list, there is also Changuinola (222.5 MW), La Estrella–Los Valles-Esti (222 MW), Bajo De Mini (145 MW), Lorena (89.98 MW), El Alto (69.486), Gatun (60 MW), La Potra (57.9 MW), Monte Lirio (51.65 MW), and many more smaller plants that have an installed capacity less than 50 MW [1]. One of the largest details is the ages of many of these plants, in particular Gatun that began operation in 1912 and then again in 1934 after renovations [1]. A handful of dams on this list were built before or around 2000, so their efficiency over time will have expectedly decreased and could help explain why many new plants are also being developed in the country. Many of the smaller plants were constructed after 2010, showing a development of increased interest in hydroelectric energy in recent years [1]. Another detail that should be kept in mind is that except for some of the much larger plants most hydroelectric dams in the country are privately owned and operated and most plants have different private companies that manage them [1]. This open electrical market shows the opportunity for foreign investment that could help fuel the economy with many different energy generation sources, although one issue with this is that with almost every dam not operated by the same company, it means that how different plants operate, the quality of each individual plant, and the repair time in case and issue arises could vary widely.

Even with the currently large installed capacity within the country, there are forecasts claiming that there is still a large potential for future development. It is predicted that the potential of hydropower in Panama is around 11,879 GWh/year [1]. This means that there is quite a lot more energy potential that can be harnessed from hydroelectric power when it is already around 49% of the total installed capacity [1]. There are many sites that have been found around 95 different areas showing potential for hydroelectric energy [1], although most of these projects would be small scale with around half of them being under 1 MW potential [1]. The biggest issue is that it appears that no plants can be made to produce over 100 MW anymore due to all potential locations already being used [1]. One of the issues with hydroelectric energy in Panama is that they have droughts during their summer, December to April, which can go for long periods of time without rain [11]. This means that there is a decrease in water flow and in the amount of energy that is produced during those months from hydroelectric methods [11].

Ocean

Panama is a country with a lot of assumed ocean potential with large coastal areas that can utilize the tides and offshore wind potential that can also be set up [1]. On the Pacific Ocean side of the country, there have been recorded tide differences of over 5 m which could be utilized in developing a tidal energy system [1]. Even though the potential for a large ocean-powered system is theoretically in place, very little research has been done on making use of this great resource [1]. It is expected that in the future more tests will be conducted to see whether it is practical to develop an ocean industry, but until then, no power is created from ocean energy [1].

Geothermal

Currently, there are no geothermal plants in Panama, so the power generated by geothermal energy is 0 GWh [1]. The main reason for the nonexistence of geothermal plants yet is the high installation costs to create a geothermal plant and the lack of research about the potential for geothermal energy. The last evaluation of the geothermal potential in Panama occurred in the 1970s, so the data are out of date, and it is difficult to decide, given the lack of information [1]. Although currently there are plans to build a 5-MW geothermal plant in Chiriquí, which would start the geothermal industry in Panama [1], with a lack of research, it is difficult to decide the potential of geothermal energy; so more experiments would need to be conducted first before a plan for larger-scale project could be created. From a speculative point of view, there is a lot of potential for geothermal energy within the country because there are some known volcanoes in or near the country and it is near a fault line [11]. Both show the potential for a large amount of geothermal energy to be closer to the surface in Panama than in other countries and that it would be reasonable to investigate the geothermal landscape and how it has adapted.

Biomass

Bioenergy in the form of biomass and biofuel is a constant though small staple of energy in Panama with 3640.19 GWh (313 ktoe) of energy being produced by bioenergy sources in 2018 [2]. This has been around the expected yearly generation since 2000 where it dropped to 3198.25 GWh (275 ktoe) from 5198.61 GWh (447 ktoe) the previous year [2]. There has been a relatively consistent consumption of bioenergy over these past few years [2].

Looking at Panama's agricultural sector, two types of food produced could have by-products for bioenergy in Panama: rice and coffee [1], which both produce a husk that can be used as biomass when the respective food is dried. While there are other types of crops that could be grown for bioenergy, these two are already prominently grown and produce waste that can be used. Cane bagasse is another source of biomass that is predominately used in the sugar industry and has the potential to produce 28 GWh for the sugar-making process [1]. Another source of biomass is peat, which has recently been found in high abundance in parts of Panama. It is expected that the amount of peat available would be able to keep a 30-MW steam plant up and running for around 30 years [1].

Biofuels

Looking more on the biofuel side, bioethanol is produced as a waste product of the biomass and has been used in the gasoline in that area for a few years before taking a rest to build up more supplies. As other food industries arise in Panama, there is a chance for a large amount of biomass and biofuel to be produced [1].

In 2017, the first biogas plant began operation with an installed capacity of 8.1 MW [1]. This plant is operated by Interaseo Urbalia Panama and is powered by the biogas generated in the Cerro Patacon landfill [1]. This development shows a method of converting the large amount of waste that is produced that contains bioenergy into actual energy that can be supplied to Panama's electrical grid.

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

Currently, there is no recorded energy storage technologies in Panama although changes may be coming in the near future to help develop different types of energy storage within the country. The biggest factor is that AES Panama has been lobbying to get the rights to start developing battery storage technologies in Panama, so the changes in policy may lead to a new development in energy storage in the near future [12]. AES is the self-proclaimed "world leader in lithium-ion-based energy storage" and has been developing and implementing batteries into some of their projects for around 10 years [13]. This means that if approval is given to develop batteries for the electrical grid, the company that plans to begin the venture has a history with the technology.

Country's Future Storage Direction

While batteries are currently a hot form of energy storage, there are other type of energy storage that could be helpful for the country as they continue to develop their grid. One form that could be recommended would be pumped hydro storage as a large portion of Panama's electrical generation is from hydroelectric energy, so if there is ever excess energy, storing more water for the dams could be a viable option [1]. Another factor is the grid connections that Panama has with other countries. While not exactly energy storage, it would be possible to sell excess electricity to these other connected countries and purchase energy back when there is a need.

Carbon Footprint

Most Recent Carbon Output

In 2018, Panama had 9.3 Mt of CO_2 emissions, which would be around 0.03% of the global share [2, 14].

Historical Trends of Carbon Footprint

This has been a downward trend as of 2014 which saw an all-time peak for the country of 10.4 Mt of CO_2 emissions [2].

Types and Main Sources of Pollutants

While the industrial and electrical sectors decreased in emissions, the transportation industry has increased in emissions over time [2].

Air Quality

With this level of emissions, the air quality in Panama is still considered good with an air quality index (AQI) score of 25 with the main pollutant $PM_{2.5}$ having a concentration of around 6.1 μg/m^3 [15].

Energy Resiliency

Electrical Grid

Panama as a country has a population of around 4.177 million people, and of those 4.177 million, around 93.42% of the population has access to electricity [16]. As of 2008, the transmission network is made up of 2447 km of transmission lines with 2040 km being at 230 kV and 407 km being at 115 kV [17]. This grid is broken up into three main transmission lines aptly titled Transmission Lines I, II, and III [17]. Like most of Central and North America, Panama's grid operated at 60 Hz. Currently, there are plans to construct Transmission Line IV to help build resiliency into the grid and to better supply the country with power [18]. This line would add an additional 317 km to the existing electrical grid and help increase the theoretical maximum installed capacity by 1280 MW [18]. While this project could be helpful in increasing the resiliency of Panama's grid and has been proposed to be constructed by 2020, there have been many different delays as Indigenous communities claim that this project would interfere with their land rights [19].

The company that currently manages the electrical grid is Empresa de Transmisión Eléctrica S.A. (ETESA), a state-owned company that has been managing the grid since 1997 [18]. ETESA manages the high-voltage transmission lines as well as the interconnections to other countries [1].

As mentioned earlier, Panama is one of the countries that are a part of the Central American Electrical Interconnection System (SIEPAC) [1]. The SIEPAC is an electrical grid that has six Latin American countries connected to create one 1800-km-long electricity line consisting of 15 substations, 150 km of line, and two substations of which are in Panama itself [20]. These six countries are Panama, El Salvador, Costa Rica, Guatemala, Honduras, and Nicaragua [1]. This connection is on the western side of the country and is directly connected to Costa Rica [20]. With these interconnected electrical grids, it means that electricity can be easily bought and sold from country to country, which can both work as a means to increase the maximum installed capacity of a country and prevent waste from countries that overproduce energy.

Climate and Natural Disasters

Panama is a tropical country just north of the equator. In the lower regions of the country, the average temperature is expected to be between 21 and 32 °C [21]. The higher regions of the country are going to be colder with a temperature range of between 10 and 19 °C. Looking at the humidity, it is around 80% all over the year. Finally, the annual precipitation is around 1 m [21].

In terms of natural disaster potential, Panama has different types of disasters that can occur. Panama is very thin and in between the two oceans making it vulnerable to many types of natural disasters such as tsunami and hurricanes [11]. The Pedro Miguel Fault is also located very close to Panama, meaning that it is susceptible to earthquakes throughout the year [11]. During the summer as well, it becomes dry and hot, meaning that fires and droughts will also happen and damage the hydroelectric industry [11]. In summary, Panama is susceptible to earthquakes, tsunamis, floods, landslides, wildfires, different types of storms, and droughts. All of these make it apparent that a large amount of protection is needed year-round to ensure that the electrical grid is always functional given the increase in development in the country. One recent example of a natural disaster damaging the electrical grid in Panama and other Central American countries would be the damages caused by Hurricane Otto that occurred in 2016 and caused a large amount of damages to Panama, Costa Rica, and Nicaragua [22]. While the storm did not go through Panama itself, the amount of rain that was brought into the country because of Otto resulted in human casualties and damages to the agricultural market [22]. The rainstorms that occurred lead to landsides that caused most of the damages. In the end, eight people died in Panama because of Otto [22]. While this disaster was devastating, it appears to not have had a large effect on the Panama's electrical grid and it mainly affected the food industry.

A natural disaster affected the electrical grid of Panama in 2017. A heavy rain and lightning caused the malfunction of the electrical grid that led to a blackout [23]. This blackout did not just affect Panama though, all of Central America was affected by this one malfunction of the grid [23]. In total, this means that around 15 million people were left without power among these different countries because of one rainstorm in Panama [23]. This shows that there are many vulnerabilities to Panama's electrical grid; if not properly managed, it negatively affects not only Panama's grid but also the grids of every country that is attached to SIEPAC.

Grid Resiliency

While Panama does have their electrical grid connected to other countries and can import energy from those countries, it does not mean that their grid is immune to over demand. As time continues and more development occurs in the region, there is an ever-increasing amount of energy demand in the country that has led to many blackouts. In 2017, a blackout started in Panama, and it resulted in blackouts all throughout Central America, reaching as far as Southern Mexico [23]. This shows just how secure the grid must be because it is not just a grid for one country, but for many countries together. Another such incident happened in the beginning of 2019 when a blackout occurred in Panama for six hours just a few days before Pope Francis was to appear in the city [24]. While no cause for the blackout was given that goes to show how temperamental the grid is [24]. Part of this can be explained with the fact that the connections between the SIEPAC countries do not appear to have high-voltage DC (HVDC) or variable frequency drives (VFD) systems between the different countries. This makes it difficult to filter between countries' power, so if an issue arises in one grid, it can spread to the other grids without any form of filtration to lighten the damage. This can be resolved by developing HVDC substation or a VFD between the different countries to help better manage between outages.

While major blackouts do occur in that country and can lead to a cascading effect in the neighboring countries, what is more common in Panama is temporary decreases in available power consumption. According to people who have been living in Panama for some time though, even though there is wide access to electricity, minor blackouts or brownouts are also common in the region [25]. A brownout is a decrease in power in a region while not totally cutting power for that area [25]. This is a method to ensure that instead of a smaller area gets no access to electricity, a wider area receives less electricity in times on shortages [25]. The main issue with this type of power outage is that, while not for a long period of time, it occurs frequently enough that it could cause damage to appliances such as computers.

Another reason for vulnerabilities is the weather in Panama. Because it is close to the equator, near a fault line, and surrounded by oceans on both sides, Panama has many opportunities to face natural disasters throughout the year [11]. Some natural disasters affect the electrical grid in ways that are expected such as storms striking transformers or earthquakes damaging a line [11]. Others could have more severe ramifications for the electrical grid in indirect ways such as droughts, which have a terrible effect on countries that use a large amount of hydroelectric energy such as Panama [11]. For example, in 2013, a water shortage due to droughts forced Panama to more heavily regulate the energy consumption of their citizens as water was being taken away from hydroelectric dams, decreasing the amount of energy that can be generated greatly [26].

Regarding maintenance, it appears that many of these blackouts are solved relatively quickly, so it appears that groups are ensuring that the grid is taken care of. The main group in Panama looking after the grid is ETESA Panama, which is a state-owned company that manages the electrical district [1]. This means at least there is an organization in place to ensure all issues that arise in the grid are dealt with in a timely manner.

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

Panama, while not producing their own oil from mining, does not refine and export this refined oil to other countries. In 2019, they exported US$800 million, which was predominately exported to Ecuador with around 79% of all exported refined petroleum going to Ecuador [3]. Panama also imports both refined petroleum and crude petroleum. The value of refined petroleum Panama imported in 2019 was US$6.13 billion, 47.2% of it from the United States and 21.3% from China [3]. Panama imported crude petroleum worth US$4.24 from Colombia (45.4%) and Ecuador (35.1%) [3]. This means that for the case of Ecuador they most likely sell their crude petroleum to Panama and then purchase the refined petroleum back from them afterward. Panama also imported coal worth US$46.3 million, almost entirely from Colombia [3].

The final energy exchange that should be noted is the relationship Panama has with their grid-connected neighbors in SIEPAC. As stated earlier, the electrical grid in Panama is a part of the SIEPAC, which has the power grids of six Central American countries connected, so there is a share of power between them [1]. Through this grid connection, in 2019, Panama has exported electricity worth US$14.3 million, with 99% of the electricity to El Salvador and the remaining 1% to Guatemala [3]. In terms of imports, Panama imported around US$1.22 million of electricity in 2019, with 77.3% of the electricity coming from El Salvador and 22.7% of the electricity from Guatemala [3]. This shows that depending on supply and demand during the year Panama is more likely to export electricity to their neighbors, but for part of the year, energy must be imported in to handle the loads. Although it does affect the relationships between each of the participating countries again, they are all affected by issues that may only occur in one of the grids. Another circumstance about this interesting grid layout is the ownership of the grid. The grid is owned by a regional operations entity that is comprised of multiple different companies based both within and outside of the countries using the grid [1]. For Panama, the company that represents them is ETESA [1]. This means that because multiple groups have ownership of the grid, some of which do not actually use the grid, creating a common standard across the entire grid possess a difficult situation where all the companies would need to agree [1].

Relations with Global Community/ Socioeconomic Influence

Panama is currently a part of the Paris Agreement as of 2016 and has the goal to reduce their carbon footprint and work with "Collaborative Instruments for Ambitious Climate Action" to help them provide better tracking for their carbon emissions and carbon emissions of businesses within Panama [27]. These steps can help to create the framework to better price and manage the emissions of both Panama and other countries [27].

Education

When looking at both undergraduate and graduate programs available in Panama, there are only a few programs that appear to offer material that can be related to the electrical grid or renewable energy engineering. The most prominent program comes from Florida State University (FSU), which has an international campus located in Panama [28]. FSU offers an undergraduate program in electrical and computer engineering that among other things can help build an understanding of electrical system and can lead to improvements in the electrical grid [28]. This can also lead to the master's program offered there in electrical engineering that would again help refine the skills in electrical work and help prepare students for working on and with the grid [28].

Summary

Current Energy Situation

Panama has seen a very large increase in many of their generation sources with hydroelectric and oil energy seeing massive development in the recent years [1]. The solar, wind, and bioenergy industries are also developing and are all expected to have even more development in the future as Panama continues to prepare for 2050 and the energy demands then [1].

Future Energy Situation

The overall trend is to increase all forms of generation while putting changes in place to decrease consumption, although the future developments are expected to be covered mainly by wind and solar energy [1]. Another development is the current one and the issues arising with the fourth transmission line and how that will affect the electrical grid in the coming years [19]. As it continues to develop within the country, more energy may be available to export to their neighbors who are connected to SIEPAC. While there is still a large amount of energy generation that can be developed in the future years, there are still many fields that have not seen much development that could act as a deficiency to the grid's goal to increase diversity. The lack of geothermal and ocean energy within the grid could hinder the maximum capacity of the country, especially with the large amount of ocean access Panama has at their disposal. In any case as Panama continues to develop their grid, they will stand as an interesting example of how electrical grids can function by incorporating renewables.

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Puerto Rico

Slobodan Petrovic and Kyle Buchanan

National Energy Introduction

Energy Policies

Puerto Rico is a territory of the United States, which is not the member of the Paris Climate Agreement. As part of the Puerto Rico Energy Public Policy Act, the Puerto Rico Electric Power Authority (PREPA) must reach 40% consumable energy via renewable energy by 2025, and 100% by 2050 [1].

Trends in Generation Technologies

Around three quarters of Puerto Rico's energy consumption comes from petroleum-based products currently, although under the Puerto Rico Energy Public Policy Act that will continue to shift toward renewables [1].

Domestic Resources

Domestically, Puerto Rico has high sugar yields, which can be converted into biofuels, and high year-round solar irradiance [2].

History of Energy

Puerto Rico is a territory of the United States and as such has a history of relying on the United States for federal aid [2].

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Breakdown of Energy Generation "Mix"

Puerto Rico energy generation mix and energy consumption mix are shown in Figs. 1 and 2.

Fossil Fuels

Oil

Puerto Rico is using oil at a rate of 57,646 GWh/year [1].

The country imports 100% of oil and is using it for motor gasoline, distillate fuel, and liquefied refinery gases [1].

There is some evidence of undiscovered crude oil resources in a subsea formation off the coast of Puerto Rico; however, they the country has no capability to refine the crude oil [1].

Coal

Puerto Rico is using coal at a rate of 11,777 GWh/year [1].
All coal is imported, primarily from Colombia [1].

Natural Gas

Puerto Rico is using natural gas at a rate of 20,222 GWh/year [1].

The country does not produce any natural gas domestically. Nearly all natural gas is imported in the form of liquefied natural gas (LNG) through the Peñuelas terminal in Ponce [1].

Nuclear Energy

Puerto Rico currently has no active nuclear reactors, and there are no active plans to set up a nuclear power plant in the near future [1].

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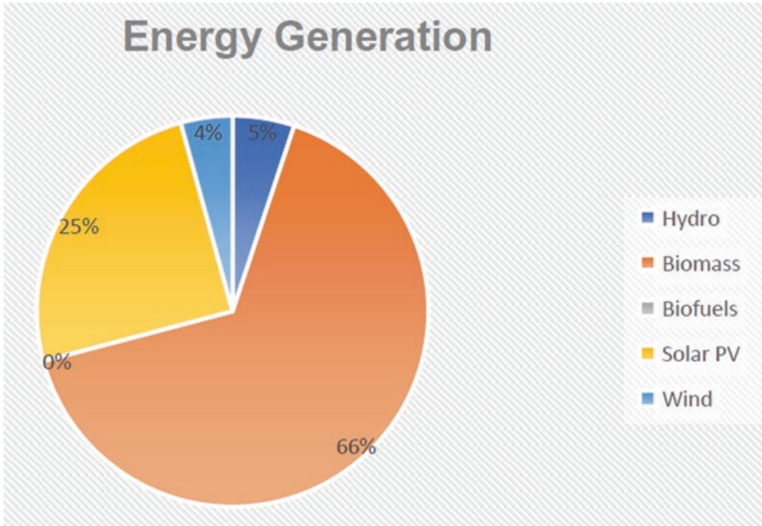

Fig. 1 Puerto Rico's energy generation

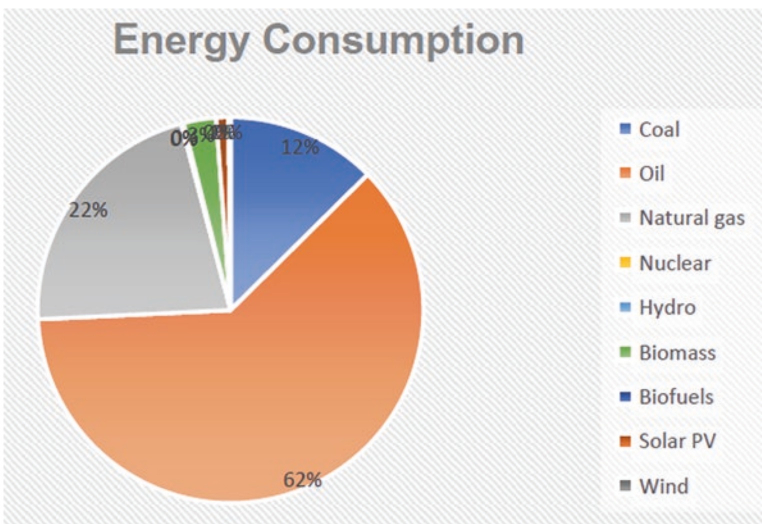

Fig. 2 Puerto Rico's energy consumption

Renewable Energy Generation

Photovoltaics (PV)

Utility- and small-scale PV have a total capacity of around 475 MW, generating roughly 959 GWh/year [1, 3]. The territory's largest solar farm, Oriana, started operating in 2016 and has a capacity of around 57 MW [1]. Puerto Rico has a split of utility- and small-scale residential PVs, although PREPA's utility development in recent years has outpaced the residential PV development [1, 3].

Puerto Rico has significant solar energy potential due to its high year-round solar exposure. Developers see this potential as well, leading to a large number of upcoming solar projects [1].

PREPA is planning to expand their solar capacity significantly over the next 5 years, adding 2740 MW of utility solar power [1].

Wind

Puerto Rico has only one operational utility-scale wind farm on the southern end of the island with a total capacity of 101 MW [1, 4]. While this farm has a significant capacity, it has faced many operating issues, making the actual yearly generation from wind power difficult to estimate [5].

Puerto Rico has limited onshore wind resources; however, offshore resources have some potential due to expansive coastal area.

There have been proposed onshore wind projects; however, none have been put into effect [1].

Hydro

Puerto Rico has 22.5 MW of hydropower capacity, generating roughly 197 GWh/year [6]. Many of these plants are quite old, which may lead them not reaching their full year-round capacity [1].

Puerto Rico has some untapped hydropower; however, the remaining untapped rivers are not large enough for new large-scale plants.

PREPA has been in discussion to revitalize some of the existing older plants to increase the power output and reliability [1].

Ocean

Puerto Rico has no substantial installed tidal power [7].

Puerto Rico is an island surrounded by ocean, so there is enormous potential to utilize ocean energy.

The Puerto Rico Ocean Technology Complex (PROTech) plans to build a 5- to 10-MW ocean thermal energy conversion (OTEC) facility in Yabucoa, Puerto Rico, which would then be the largest plant in the world [7].

Geothermal

Puerto Rico has no substantial installed geothermal power [8].

Puerto Rico has some geothermal energy potential [8].

There are no confirmed plans for setting up large-scale geothermal power.

Biomass

Puerto Rico has at least 290 MW of energy production, totaling around 2540 GWh of energy per year [8].

There is no biomass production capacity in Puerto Rico, although traditional agriculture nets at least 290 MW of energy [8].

There is a significant amount of biomass potential in Puerto Rico, totaling between 290 and 6800 MW [8].

Biofuels

Puerto Rico does not use any significant amount of biofuels [8].

There is no active biofuel production in Puerto Rico [8].

There is some biofuel production potential in Puerto Rico based on their biomass production, although no plans have been made to set up infrastructure to convert this biomass to biofuels [8].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

Puerto Rico utilizes some utility-scale energy storage, totaling approximately 6 GWh of capacity [8].

Country's Future Storage Direction

Relationship to new and increasing energy generation: Puerto Rico plans to add an additional 1440 MW of battery energy storage, primarily for the solar infrastructure, by 2025 [8]. Additional storage capabilities will be required for Puerto Rico to reach 100% renewable energy generation by 2050.

Carbon Footprint

Most Recent Carbon Output

Puerto Rico annually releases roughly 19.5 million metric tons of CO_2 emissions [9].

Historical Trends of Carbon Footprint

Puerto Rico has had a slow historical increase in greenhouse gas emissions [10].

Types and Main Sources of Pollutants

Fossil fuel usage in electricity and fuel production are the largest contributors to greenhouse gas emissions.

Air Quality

Puerto Rico has a good air quality being at or below the World Health Organization (WHO)s recommended exposure value [11].

Energy Resiliency

Electrical Grid

Puerto Rico has an aging grid that underwent substantial damage in 2017 from Category 5 Hurricanes Maria and Irma that struck in quick succession [12]. These hurricanes left almost 100% of the population in the island without power [12]. There has been some rebuilding of the grid, although it is still considered unstable and needs substantial revitalization [13].

In 2020, the Puerto Rican government signed a contract with LUNA Energy Consortium for $12 billion to renovate and operate Puerto Rico's energy grid [14]. This contract signs over the responsibility of revitalizing Puerto Rico's energy grid to private entities, who are guaranteed hundreds of millions of dollars over the course of the next 15 years [14]. There has been a concern over the capabilities of the consortium to properly fix Puerto Rico's lacking infrastructure, partially due to the contract not meeting the expected $20 billion cost that it would take to fix the grid issues [14].

Puerto Rico's energy grid is considered unstable due to semi-frequent blackouts and exposure to extreme natural events, such as hurricanes [13].

Puerto Rico's grid is much less reliable than their counterpart, the United States [14].

Located on an island, Puerto Rico makes transporting grid components from the mainland United States or other countries a bit more costly. This poses a cost barrier to the grid revitalization effort.

Climate and Natural Disasters

Puerto Rico subjects to a range of natural disasters including earthquakes, tsunamis, landslides, and possibly most of all hurricanes.

Puerto Rico has some natural resources; however, they heavily rely on imports for goods and energy [1, 2].

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

Puerto Rico has a heavy reliance on imported fossil fuels, with no fossil fuel generation domestically [1].

Relations with Global Community/Socioeconomic Influence

Puerto Rico is a territory of the United States, which is not a current member of the Paris Climate Agreement.

Being a territory of the United States, Puerto Rico has strong standing with the United Nations and many political allies.

Current Renewable Energy Goals

As part of the Puerto Rico Energy Public Policy Act, the Puerto Rico Electric Power Authority (PREPA) must reach 40% consumable energy via renewable energy by 2025, and 100% by 2050 [1]. Puerto Rico is transitioning to a more privatized ownership of their energy grid. This means until 2035 they will rely on the effort and results of the LUNA Energy Consortium in order to revitalize the energy grid [14].

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Uruguay

Slobodan Petrovic and Andrew Reed

National Energy Introduction

Uruguay is a small country in Latin America with a population of 3,461,734 (2019) and a GDP of US$59.6 Billion (2018). The country has 176,220 km^2 of land with rolling plains and hills, including a forest area of 19,890 km^2 [1]. The land and climate are suitable for good agriculture and livestock, while Uruguay also has 410 miles of coastline with beaches. The climate is a temperate grassland, and the forest percentage is not seeing the same drop seen in other Latin American countries.

In Uruguay, 100% of the population has access to electricity, with an estimated total installed capacity of 4.808 GW in 2016 [2]. In 2019, Uruguay's total installed capacity was up to 4.920 GW, according to Uruguay's National Energy Balance Report [3]. According to the US Energy Information Administration, Uruguay exported 1000 GWh in 2018 [4]. This is a substantial surplus of electricity.

Over the last decade, Uruguay has shifted toward renewables with a great speed and remarkable execution. Renewable energy policy is a driving factor for the shift in energy system design for the country. By 2013, renewable energy including hydropower accounted for 83% of electricity generated in Uruguay [5]. The main sources of this renewable energy generation are hydropower and wind, with the former accounting for 60% of the total renewable energy generation [6].

Fossil fuels capacity in Uruguay stood at 1.2 GW as recently as 2018, with 300 GWh generated per year since 2018 [4]. Of the total electricity produced in Uruguay in 2016, an estimated 29% came from fossil fuels [2]. Renewable capacity was 3.8 GW in 2019, up from 3.3 GW in 2016, 2.9 GW in 2015, 2.4 GW in 2014, 1.8 GW in 2011, and 0.9 GW in 2009. Renewable energy generation was 16,000 GWh in 2019 [4]. In 2017, 42% of the total installed generation in Uruguay was nonhydroelectric renewable sources [2].

The government-owned electricity company is called UTE. Grid electricity is owned and operated by UTE, providing 100% access to electricity across Uruguay. UTE is also the issuer of PPAs in auctions to bidding developers. The electricity is regulated by an agency called URSEA [5] (Fig. 1).

Energy Policies

Uruguay has a long-term policy for energy called the National Energy Policy 2005–2030. This was discussed in 2005, put into Energy Guidelines in 2006, and the policy was approved officially in 2008, which covers the gamut of energy objectives for the country. This energy policy aims to tackle key issues that affect the country's energy infrastructure, imports and exports, resource allocation, and environmental concerns. The policy includes sections on energy efficiency improvements, huge growth in renewable energy share of the energy portfolio, and reducing fossil fuel dependence. Environmental concerns are also considered in policy. For example, all power plants with a capacity >10 MW require an environmental authorization and permit, as outlined in Decree 349/005 [7].

The year 2010 saw the approval of a decree to promote an even greater increase in renewable energy share of electricity in Uruguay. The government committed to increasing renewable share of electricity from 6% to 15% by 2015. Decree 354 on the Promotion of Renewable Energy was approved by the Ministry of Energy, Mining, and Industry in 2010. The main idea of this decree is a substantial increase in renewable energy contribution to electricity generation in the country. This locked into place a system in which UTE has 20-year PPAs with renewable electricity generators, buying their excess electricity at fixed rates [7].

The biggest tool for Uruguay's deployment of renewable energy growth was in the form of auctions. UTE, the

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Fig. 1 Map of Uruguay. (Source: The World Factbook [2])

government-owned electricity company, gives Power Purchase Agreements to bidders. These auction bids are released as decrees that offer a capacity for certain types of power generation such as wind or biomass. This allows Uruguay to carefully develop power in a way that can benefit the country as a whole and the local region. An example is Decree 403/009, which puts up 150-MW wind power as an auctioned PPA with the agreement that wind farms in the 30–50 MW range could bid as long as they were providing at least 20% power locally.

Renewable energy growth outlined in the National Energy Policy also allows for UTE to do its own auctioning and leasing for wind and solar power projects. An example of a large agreement is a 2012 bilateral agreement for wind development with the Brazilian company, Eletrobras, the largest electric company in Latin America [5]. The year 2012 saw further decrees regulating smaller wind farms in the 150 kW–60 MW range consuming at least 50% of their generated power and connected to medium- or high-voltage grids. The government would agree to 20-year PPAs for buying excess electricity [5]. One of the targets of the National Energy Policy from 2008 was a 15% share of electricity generated from renewable energies such as wind power and biomass.

Other policies for renewable energy growth include the following:

- Energy Efficiency Obligation: Uruguay enacted policy to create 437 GWh of savings per year from energy efficiency improvements in the natural gas, electricity, and fuels sectors. Utility companies were required to give 0.13% of their sales to energy efficiency improvements. This policy has been in force since 2016, according to International Energy Agency (IEA) [7].
- Solar *photovoltaic* (PV) electricity available for dispatch, according to 2013 policy.
- Tax exemptions for clean energy companies, in force since 2012.
- PV: Decree stipulating PPAs between UTE and PV electricity producers. Three different categories: 0.5–1 MW with a maximum total of 1 MW, 1–5 MW with a maximum total of 5 MW, and 5–50 MW with a maximum total of 200 MW. As of 2014, there was a total of 194 MW in the signed PPAs with UTE [7].
- Solar Thermal Energy Plan in 2012: Bringing solar thermal to Uruguayan residencies to heat water. Incentives include financing by the Public Mortgage Bank, 5-year warranties through public insurance bank Bombay Stock Exchange (BSE), and installation by accredited companies, supervision of equipment by Regulator of Water and Energy (URSEA), and offer of electric bill discount of 700 UYU/mo (US$30/mo) for 2 years for the first 2000 users of the new solar thermal energy systems.
- Decree on net-metering for renewable generation with 6 kW or less capacity. This has been in force since 2010. UTE buys the excess energy produced at a retail price of the energy. Higher capacity is allowed as well with some authorization [7].

Breakdown of Energy Generation "Mix"

Energy Generation Mix (Fig. 2)

Energy Consumption Mix (Fig. 3)

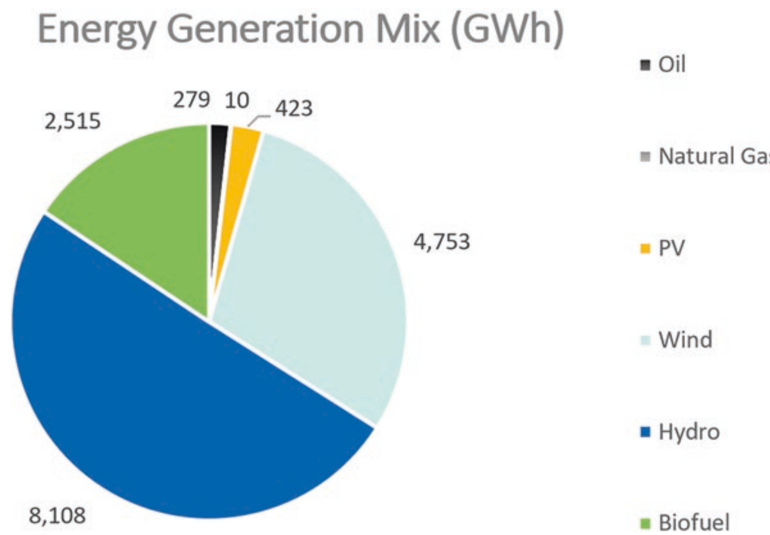

Fig. 2 Energy generation mix in Uruguay 2019. (Source: IEA Data [7])

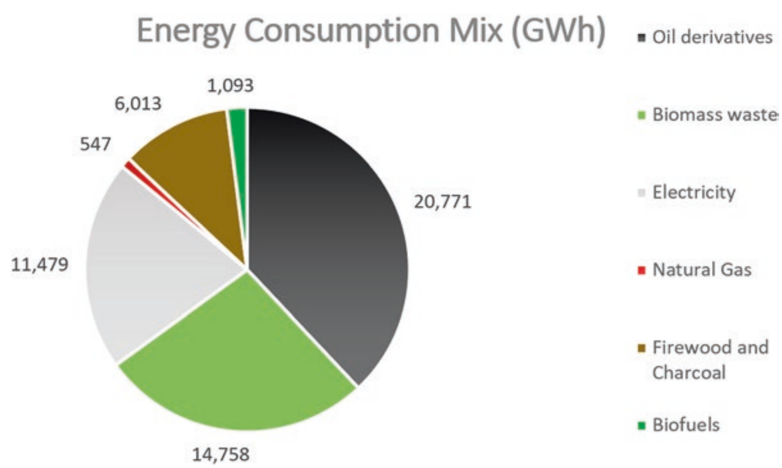

Fig. 3 Energy consumption mix in Uruguay 2019. (Source: National Energy Balance 2019 [3])

Fossil Fuels

Oil

Uruguay produces no crude oil. Uruguay imported 2187 and 2087 kilotons of oil in 2018 and 2019, respectively [7]. Import partners include the United States, Angola, Nigeria, and Columbia for oil imports [8]. No producible offshore oil has been drilled yet in Uruguay after decades of search. Uruguay's national oil company Administración Nacional de Combustibles Alcohol y Pórtland (ANCAP) has offered offshore bidding rounds, with the first round being in 2009. This saw contracts awarded to a consortium of Petrobras, YPF and GLP for exploration and production. Another bidding round took place in 2012 with blocks awarded to BP, BG, Total, and Tullow Oil [9]. A third bidding round took place in 2016. Australian company Petrel Energy tested sand from onshore testing area at the Cerro Padilla-1 well and did not consider the results a success [10]. The final energy consumption of oil equals the supply in Uruguay. Oil products come from the only oil refinery of Uruguay, the Eduardo Acevedo Vázquez refining complex at La Teja in Montevideo, which can produce 50,0000 barrels a day. The refinery produced 41,000 barrels a day in 2019. ANCAP plans to upgrade the refining complex over the next few years, with a planned shutdown in 2023 for maintenance. KBR Inc. was brought in for upgrading equipment and engineering services in 2020. The 2023 maintenance will also include a project for coprocessing of renewable feedstocks into fuel [11].

Coal

Uruguay has no coal production within its borders. There is also little coal consumption in Uruguay, with the only coal consumption being metallurgical coke at 0.1 million short tons (Mst) per year, which has been steady since 2017 [4]. IEA data show that coal imports into Uruguay are 3 kilotons of oil equivalent (ktoe) per year since 2016 [7]. The lack of coal is a leading factor for Uruguay's transition to a renewable energy system. Having no coal in the picture allows for the energy system to be more open to energy transition to alternative sources. Countries with coal reserves have more complications with energy transition from coal-powered electricity generation.

Natural Gas

Natural gas is a major component of Uruguay's realization of a renewable energy infrastructure as part of its National Energy Policy, helping to complement the variability of the renewable sources. Uruguay produces zero natural gas within its borders [4]. In total, 70.79 million m^3 is consumed each year, all of it imported into Uruguay [2]. Uruguay imported 3382 TJ gross natural gas (939.5 GWh) in 2019 [7]. Uruguay reports around 81 ktoe of natural gas supply in 2019 versus around 50 ktoe consumed.

The Cruz del Sur Gas, completed in 2002, is an underground gas connection that runs 125 miles between Buenos Aires in Argentina and Montevideo in Uruguay. There are two pipelines with a capacity of 6 million m^3 of natural gas per day. Uruguay signed an agreement with Argentina in 2007 for the construction of a regasification plant in Uruguay called GNL del Plata. GNL del Plata was to be a floating liquefied natural gas (LNG) regasification and storage plant located off the shore of Montevideo. ANCAP and UTE's joint venture Gas Sayago gave a contract to Foster Wheeler from the United States to design and build the project. GDF-Suez from France was awarded a 15-year Build, Own Operate, and Transfer (BOOT) contract in 2013. The development will be a first stage of 10 million m^3/day capacity and a second-stage expansion to 15 million m^3/day. However, Argentina's priorities shifted and eventually the country pulled out of the deal in 2012, as Argentina discovered its own domestic shale oil potential. After the deal was cancelled in 2015, Gas Sayago has dealt with debt issues, with the closing and liquidation of Gas Sayago in 2019. Thus, the project has not materialized [12–16].

A major project for Uruguay's plans is the US$500 million Punta del Tigre B Combined Cycle project, which includes two gas turbines, two recovery boilers, and a steam turbine. This plant captures steam from the two gas turbines to raise capacity from 350 to 532 MW. The project is run by UTE with the objective of satisfying electrical demand for renewable energy. The system is capable of recovering natural gas, and diesel can be used as an alternative fuel [16]. Situated next to this new project is Punta del Tigre A, a thermal generation plant with a capacity of 320 MW. The two plants provide the primary thermal backup to Uruguay's renewable generation on the grid [16–18].

Nuclear Energy

Uruguay has no nuclear power generation within its borders. There are no nuclear installations, nuclear fuel storage facilities, or nuclear research laboratories. Uruguay itself has a strong regulation system for emergencies preparedness with nuclear power, with Ministry of Industry, Energy, and Mining (MIEM)'s National Regulatory Authority in Radiation Safety (NRAR) being in charge of monitoring and regulating all aspects of radiative supplies and sources for the country [19]. A team of nuclear experts from the International Atomic Energy Agency (IAEA) completed a 2-week nuclear security advisory mission in November 2019, at Uruguay's request [20]. The advisory meeting did not involve seeking nuclear energy as an option for the country, which is not unexpected given the amount of exported electricity from the country already.

Renewable Energy Generation

Photovoltaics (PV)

Solar capacity stands at 0.3 GW, with 400 GWh generated in 2019 [4]. Total photovoltaic capacity in Uruguay was at 254 MW in 2019. This is a huge success considering the capacity was only 4 MW before 5 years [3]. Uruguay has strong solar potential, averaging 1700 kW/m^2 for a year of sunlight [6]. Solar energy irradiation is the highest during November through February and the lowest during May through August [21]. The annual average global horizontal irradiation is 4.4 kW/m^2 [22]. Thus far, only 1% of total energy production comes from solar. Despite having an electricity surplus already, Uruguay has been focusing on growing solar capacity locally for key areas like off-grid schools, hospitals, and new buildings. Uruguay has had legislation supporting solar only since 2013 [6]. The Investment Promotion Law in Uruguay incentivizes solar energy in many capacities—manufacturing locally, using solar generation, and installing solar generation [6]. Much of the installation is the result of incentives put in place in July 2010 with Decree 173/010 for microgeneration. The decree also includes incentives for microgeneration with biomass, wind, and even small hydroelectric plants. Over 125 photovoltaic generators are contributing to Uruguay's electrical grid [3]. Microgenerators for photovoltaics contributed 2.1 GWh to the grid in 2014, but this share rose to 29.9 GWh in 2019 [3].

There have been many recent medium-scale photovoltaic plants developed in the favorable regulatory environment. With a maximum size set at 200 MW, UTE began signing 10-year contracts for sale and purchase of energy to the grid with PPAs. The first pilot project was a 480-kV plant installed in 2013 called ASASHI, with the objective of developing training and technical evaluation for similar projects moving forward [23]. A large-scale example is the first PPA signed with UTE for a plant located in Salto. Developed by Fotowatio Renewable Ventures (FRV), the 64-MW La Jacinta solar plant began supplying electricity to UTE's grid in 2015. The plant cost was US$95 million and is expected to reduce CO_2 emission by 74 kilotons per year [24].

Wind

Wind is a major part of Uruguay's successful transition away from reliance on imported energy, variable hydropower, and fossil fuel emissions. The average wind speed is 6–9 m/s at 90 m up in Uruguay [25]. Uruguay went from no wind power generation in 2007 to being a world leader in 2013. This was driven by a strong desire to have more secure energy profile in the country. In total, 4752 GWh was generated from wind in 2019 [4]. Uruguay now has 1525 MW of installed wind capacity [26].

In 2007, with a US$1 million loan from the United Nations Development Program and US$6 million from the national budget, Uruguay developed its Wind Energy Program. Included in the program was the creation of competitive bidding for wind park development, feed-in tariffs for smaller wind generators, and training for UTE staff [27]. The national plan involved UTE having to buy all the energy created as standardized prices. Large wind energy became a big piece of Uruguay's infrastructure in 2008 when the first wind farms began. The rise of wind really began as wind capacity jumped from 59 MW in 2013 to an increase of over 300 MW every year between 2014 and 2017. In total, 43 large-scale wind farms were contributing to the energy grid by the end of 2017. The electricity generated from wind rose from 144 GWh in 2013 to 4752 GWh in 2019. Although only 2.2 MW was installed in 2019, and none in 2018, wind had achieved a 31% share of the Uruguay's installed capacity [3]. The 43 wind generators have an average size of 34.25 MW. The list has a total of 1507 MW of capacity connected to the UTE grid itself. The majority of these wind farms were created between 2014 and 2017 [28].

The largest of these wind farms is the Pampa wind farm with a capacity of 141.6 MW. Located in Tacuarembó, the Pampa wind farm was the 13th commissioned wind farm in Uruguay. The Nordex Group, a wind turbine manufacturer, completed the farm in 2016. The wind park consists of 82 wind turbines and will supply energy to UTE in a 20-year PPA. The US$275 million investment was financed by international banks (70%) and Uruguay national banks (30%) [29, 30].

Hydro

Uruguay historically has relied heavily on hydroelectric generation. The geography of Uruguay includes four major river basins with tributaries and powerful rivers. This renewable source is variable depending on the hydrology conditions of the year. Annual rainfall varies between 39 and 59 inches (100–150 cm) per year. In total, 7839 GWh of hydroelectric energy was consumed in Uruguay in 2019 compared with 6139 GWh in 2018, with the difference attributed to 23% above average rainfall [3]. The total capacity stands at 1538 MW of hydropower [3]. This hydropower accounted for 31% of total installed capacity in Uruguay in 2019, down from 76% in 1990 [3]. All other renewables make up 2.2 GW of capacity [4]. Uruguay has four hydroelectric plants. The Baygorria Dam (108 MW), Rincon del Bonete (152 MW), and the Constitución (333 MW) lie on the Rio Negro cutting through the middle of Uruguay, while the Salto Grande Dam is on the Uruguay River on the border between Uruguay and Argentina.

Salto Grande Dam, constructed 40 years ago, is an 1890-MW power plant owned and operated by the Salto Grande Mixed Technical Commission (CTM), a binational organization. The generated power is shared via an interconnection ring with 500-kV lines and four substations [31]. Of the 7839 GWh produced in Uruguay in 2019, 4510 GWh was produced by the Salto Grande Dam. Salto Grande Dam is currently being renovated in three stages over 30 years, starting in 2019. Emerson, a global technology and engineering company, was awarded a contract in 2020 for modernization of 14 hydroelectric turbines with its proprietary automation technology [32]. The initial stage is expected to cost US$80 million. Baygorria is also being renovated starting in 2019, with a cost of US$50 million [6]. UTE released a call for offers in late 2020 for this refurbishment [33].

Ocean

There is no current wave energy generated in Uruguay. A detailed analysis into the ocean wave potential of Uruguay was released in 2015 showing a good opportunity that exists for using wave energy in the energy generation mix. The study found that wave energy converters used in the Rio de La Plata zone of the Atlantic Coast off Uruguay can be used due to relatively benign waves and steady waves. The mean average of 30 kW/m of wave power was found in deep waters, with 7 kW/m in Rio de la Plata outer zone and 1 kW/m in the intermediate zone. The study found that the La Paloma-Chut Uruguayan coast is the best bet for wave energy potential developers [34].

Geothermal

There is no geothermal production of electricity in Uruguay. Studies have looked into the geothermal gradient and terrestrial heat flows in the Norte Basin as part of the Guarani Aquifer System. There is no specific potential outlined for the usability of this thermal wells as of 2021 [35].

Biomass

Although the large hydrogeneration and growth of wind contribute greatly to Uruguay's renewable energy profile, biomass has grown significantly in scale and in share of energy. This includes biomass waste, firewood, and charcoal imports. The cellulose pulp industry is the significant driver of biomass contribution to electrical generation in Uruguay [3]. Solid biomass grew from 13.9% of the national total primary energy supply in 2000 to 29.5% in 2012 [5]. Biomass now makes up 40% of energy supply in Uruguay, in large part due to the growth of the cellulose industry's contributions to electricity generation. In Uruguay, 15% of the electricity generated is from biomass, mainly from forestry and some waste from the beef industry and oils. Biomass electrical capacity reached 400 MW in 2013 and has remained steady around this mark [6]. Generation from biomass and waste has been steady around 2500 GWh annually since 2015 [4].

Decree 367/010 in 2010 brought biomass into the renewable energy picture for Uruguay. Feed-in tariffs were offered for paying potential biomass generators for capacity and electricity generated, so long as they had a local content percentage of 30%. This decree only yielded around 600 kW of capacity built in the country for biomass. In 2015, new legislative efforts and consultations were being undertaken to develop biomass [5]. The hope was that biomass will be available for dispatch, given the variability associated with the other potential renewable energies, and there will be the seasonal variability of available hydropower in Uruguay [5]. Uruguay's National Energy Policy set a target in 2015 for 30% of urban and agricultural waste to be processed into usable energy. This target accounts for biomass generation and processing waste from the urban capital of Montevideo. The plant for this processing was not officially commissioned to be built as of 2015 [5].

Uruguay's first pulp mill is also its largest, located in the city of Fray Bentos. This mill, with approximately 130 MW capacity, is run by UPM, a global forestry industry company. Constructed in 2007, this pulp mill served as a valuable backup for the drought situation in Uruguay in 2008 and 2009 [36].

Biofuels

The production of biofuels in Uruguay has been steady around 0.9–1 Mb/d since 2013. Fuel ethanol production and biomass-based diesel production are around 0.5 Mb/d, with data from EIA confirmed as recently as 2018 [4]. There are two bioethanol plants in northern Uruguay from Alcohols of Uruguay (ALUR), which also runs two biodiesel complexes located in Montevideo. These plants generate a combined 80,000 m^3 per year of biofuel and glycerin from used oils like frying oil, vegetable oil, and beef fat [3]. The Biofuels Law was enacted in Uruguay in 2007, which included financial incentives, like exemption from taxes for 10 years, and mandates for the blending of bioethanol, and biodiesel blends using local biofuels when possible. This law allowed biofuel producers an exemption from Uruguay's state monopoly limitations. Producers may have a choice for exporting or offering to ANCAP, Uruguay's national fuel organization [5].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

Currently, there is a lack of energy storage integration into Uruguay's electrical grid. The Uruguay currently has no hydroelectric pumped storage capacity, according to EIA [4]. The increasing renewable energy profile of Uruguay has also increased the usefulness of energy storage techniques for solar and wind integration. UTE has considered energy storage facilities as a key component of its smart grid plan for storing surplus energy created by the energy providers who take advantage of Uruguay's friendly energy-purchasing regulations [37]. The increasing microgenerators within Uruguay also open the energy storage market for the country. Demand management regulations by UTE and new low-voltage contracts offered to consumers create an opportunity for energy storage installation to bring in additional money for the consumers.

Country's Future Storage Direction

A recent study shows Uruguay's low-voltage consumers can benefit from energy storage for arbitrage and for reactive power compensation [38]. Uruguay saw one of the first battery storage systems integrated into the grid in 2021 on a dairy farm in an area 62 miles west of Montevideo. The system will include PV panels and will power five public buildings and two farms. This will reduce annual electricity consumption at the dairy farm by 90% [39].

Carbon Footprint

Most Recent Carbon Output

CO_2 emissions were at 7.3 million tones CO_2 in 2018.

Historical Trends of Carbon Footprint

According to the data from the International Energy Agency, CO_2 emissions history is as follows (Fig. 4):

Historically, the variability of rainfall had played a consistent role in the contributions of fossil fuels to the Uruguay's electricity generation. Thus, years with less rainfall have seen greater CO_2 emissions [3]. Total CO_2 emissions from the energy sector are from transportation primarily, followed by much smaller contributions of industrial, agricultural, mining, and public services [3]. Along with the previously mentioned increase in vehicle electrification, a pilot project is underway for the production of green hydrogen through hydrogen electrolysis, with the aim of decarbonizing the transportation system in Uruguay. This is being undertaken by the state oil and gas company (ANCAP), UTE, and the Ministry of Industry, Energy, and Mining (MIEM). They are focusing on adding long-distance hydrogen busses and trucks. There are also private investments in hydrogen trucks for the logging industry [6].

Types and Main Sources of Pollutants

This was almost entirely from petroleum, with 0.1 million CO_2 produced from natural gas consumption [4]. CO_2 emissions were 1% lower in 2019, according to Uruguay's National Energy Balance 2019 [3]. When considering the offset of plants used for biomass, this number is lower.

Air Quality

According to the World Health Organization, Uruguay's air quality is considered to be safe at 9 μg/m^3 for annual mean concentration of pollutants in the air [40].

Energy Resiliency

Electrical Grid

Uruguay's transmission system has 61 km of 60 kV lines/cables, 4575 km of 150 kV lines/cables, 11 km of 230 kV lines/cables, and 1143 km of 500 kV lines/cables. The distribution system consists of 5058 km of 30 kV and 60 kV lines/cables, 53,688 km of 6 kV, 15 kV, and 22 kV lines/cables, and 28,466 km of 230 V and 400 V lines/cables. There are 92 transmission system substations and two 50/60 Hz power frequency converter substations at the interconnections with Brazil [26]. Uruguay has major interconnections with Argentina at 2000 MW and with Brazil at 570 MW [3]. Uruguay exported 3010 GWh in 2019, more than twice the exports in 2018. In total, 80% of the exported energy was to Argentina, while the remaining 20% was to Brazil [3]. The exported energy is greater with the high amount of generation in Uruguay at night from the wind farms [41].

The variable power from wind often leads to a surplus of electricity generation in Uruguay over its demand. This surplus is exported to neighboring countries Brazil and Argentina. In 2019, Uruguay exported 2.9 MW of excess

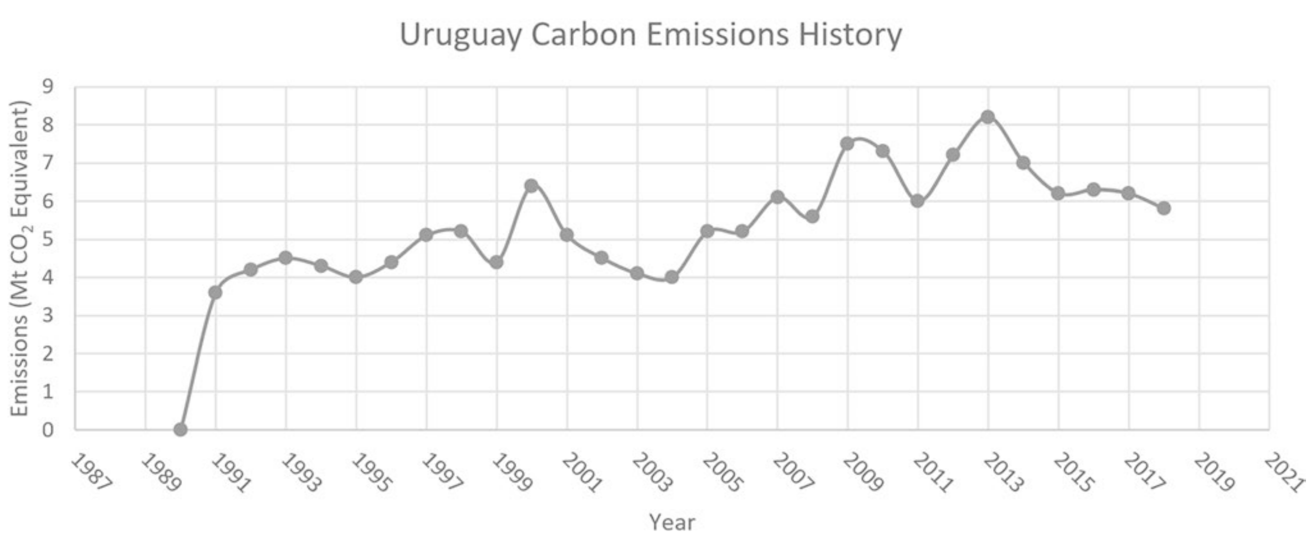

Fig. 4 CO_2 emissions history of Uruguay. Data from IEA [7]

electricity, amounting to over one quarter of Uruguay's electricity demand for the year [6]. With the electricity infrastructure already built in Uruguay, there is little need for investment in the creation of new renewable sources. Uruguay will be more focused on upgrading existing infrastructure in the coming years. Uruguay's government still expects a growth of 2% per year in electricity demand [6]. One continued issue for the pricing structure is the high residential electricity tariff compared with the corporate price. The privatization of the electricity sector has been the subject of criticism within Uruguay [42].

Climate and Natural Disasters

Uruguay is a land at risk for the effects of climate change due to its low land level toward the ocean, reliance on hydro sources for power and agriculture, and particular vulnerability to droughts. The country suffered floods in 2019 that displaced over 17,600 people [43]. Approximately 70% of the population lives by the coast [44]. There are flood risks during La Niña phases and drought risks during El Niño. Uruguay could see a temperature increase of 2–3 °C by 2100, and rainfall is expected to increase. Uruguay is also vulnerable to hailstorms, tornadoes, and heat waves. The country itself does not contribute much to the global greenhouse gas (GHG) emissions due to its small size and renewable profile.

Grid Resiliency

Grid resiliency in Uruguay is dependent on continued regulations from UTE for the interconnections of the variable renewable sources and the current funding going into infrastructure improvements. Uruguay's grid outlook is still challenged by a high reliance on variable hydropower and no active cross-border market with neighboring countries, according to the International Renewable Energy Agency (IRENA). Uruguay can improve its grid resiliency by taking advantage of its high interconnection capacity with Argentina and Brazil [41]. The lack of energy storage is also leading to a greater risk factor for the country. Uruguay is on track for creating new smart grid integration and having intelligent networks for the generation. Blackouts are of concern in Uruguay as well, with the extreme example being the massive blackout that originated in Argentina in June 2019. The blackout itself was caused by a transmission fault in the interconnection of Argentina with Paraguay and Uruguay. A fault occurred in a 500-kV line near Buenos Aires that caused a cascading failure through the interconnection [45]. An estimated 48 million people were without power for a 24-hour period, including all of Uruguay. Uruguay's grid resiliency will be improved by the addition of electric vehicle charging stations. Uruguay's Ministry of Industry believes that the excess electricity can be used within its borders for electric transportation. In total, 60 charging stations called SAVE have been placed at stations all over the country by UTE. Electric vehicles can be imported without duty charges [6].

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

Uruguay enjoys healthy relationships with the international community in terms of trade, human rights agreements, and climate change pacts. Uruguay has agricultural exports and considerable number of partnerships and initiatives. Uruguay was a founding member of the United Nations (UN), signed the Kyoto Protocol and Paris Agreements, and has impressed the international community with a strong democratic system of government. Uruguay often acts as a peacekeeper in international mediations. The United States and Uruguay have maintained strong ties for trade and cooperation on human rights issues. As a founding member of Mercosur, a regional economic partnership with neighboring countries including Argentina, Paraguay, and Brazil, Uruguay has shown a commitment to cooperation in Latin America. Uruguay has also shown itself to be a reliable partner in trade. In 2020, Luis Lacalle Pou became the president of Uruguay, shifting power to the National Party. President Pou has had favorable meetings with local neighboring presidents [46–48].

Relations with Global Community/ Socioeconomic Influence

Uruguay submitted its first Nationally Determined Contribution (NDC) to the Paris Agreement in 2017. The NDC includes objectives for climate change mitigation and measures of adaptation to changes. Included in the NDC is a goal for 24% reduction of 1990 CO_2 emissions by 2025 [39]. Uruguay has worked with the UN submitting national communications to the Convention United Nations Framework on Climate Change. The Uruguayan government also has a project funded by the Green Climate Fund (GCF) for advancing its National Adaptation Planning. The plan will be implemented by Uruguay's Ministry of Housing, Territorial Planning, and Environment (MVOTMA) to advance objectives of reducing vulnerability to climate change and facilitating adaptation [39]. Uruguay continues to work with the UN on the Sustainable Development Goals (SDGs), even with a new administration raking over the country's leadership in 2020. Uruguay submitted a Voluntary National Review in 2021 describing its work toward all SDG priorities [42]. Uruguay's SDG partnerships and commitments include the Climate and Clean Air Coalition, the UN's Green Economy, and the Ocean Conference [43].

Education

ETRELA is a program for improving education and training for renewable energy in Latin American countries. Uruguay is a part of this program, run by the Latin American Energy Organization (OLADE), which includes face-to-face training and online courses for photovoltaic, wind, and solar thermal [49]. MIEM offers training and educational materials for photovoltaic and solar thermal, designed for nonprofessional technicians in these areas [50]. Solar Energy Laboratory (LES), part of Uruguay's free public Universidad de la Répública, offers courses for engineering students such as Solar Resource Fundamentals, Solar Thermal Energy, and Solar Energy Conversion [51]. Uruguay's Technological University (UTEC) offers a Renewable Energy Engineering Program that saw its first five graduates in 2021. The degree program has specializations in solar and wind energy and also offers a path to technologist position after six semesters [52].

Summary

Current Energy Situation

Uruguay has gone through an incredible shift in energy generation sources in the last 20 years. The design of a renewable energy system for a country is being exemplified by the results of Uruguay's transformation over the last few decades. While the bulk of energy in the country is used to be supplied by oil and electrical imports, Uruguay now is a net exporter of electricity, thanks to the introduction of large-scale wind farms, biomass generation from pulp mills, and photovoltaic generation.

Future Energy Situation

The expansive national reforms for energy have created an attractive renewable energy investment market that quickly became a world-class example of how to use regulations and financial schemes to do so. Auctions and net metering have allowed bidders to be incentivized to produce as much energy as possible for UTE to purchase. The interconnections with neighboring Argentina and Brazil will continue to provide outlets for exporting excess energy generation for Uruguay. The addition of natural gas will provide a balance for the variability of the hydroelectric and wind generation along with the thermal generation in Uruguay. To improve grid resiliency, Uruguay must continue to improve the design on the overall energy system to provide a series of protections against climate change effects, like low rainfall slowing the hydropower generation, and grid blackouts, like the one seen in mid-2019. The future of energy in Uruguay will rely on the continued improvement of smart grid technology and intelligent market schemes from MIEM and UTE, as well as the continued friendly relations with bordering countries keen to purchase Uruguay's excess renewable energy output.

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Venezuela

Slobodan Petrovic and Morgan Lanen

National Energy Introduction

Energy Policies

Venezuela has long been a giant in the oil industry. In 1998, the country cut off the open oil sector to foreign countries, resulting in the country taking on a more prominent role in oil production [1]. By 1999, the Ente Nacional del Gas (ENAGAS) had been created to regulate transmission and distribution of gas in light of all levels of the gas sector having been opened to the private sector [1]. In the electricity market, in 2007, Venezuela nationalized private operators and gave the Corporacion Electrica Nacional (CORPOELEC) the charge of all generation, transmission, and distribution of electric power [1]. In 2007, Gazette 38,683 (a resolution) defined “renewables” as solar, wind, hydropower, biomass, geothermal, ocean, and hydrogen technologies [2]. In 2011, an energy efficiency bill was passed establishing incentives and penalties for power and water consumption [1]. In the same year, Venezuela set a capacity goal of 613 MW for additional renewables, 500 MW of which was to come from wind turbines, by 2019 [2]. This country-wide goal resulted in the 2013–2019 Homeland Programme that established more goals for diversifying Venezuela’s energy mix and further developing renewable energy generation [2]. In 2015, Venezuela dedicated itself to the 2030 goal to reduce greenhouse gas emissions by 20% [1].

Domestic Resources

Located on the east coast of South America, Venezuela has great energy potential. As will be observed in the sections that follow, the country has immense oil reserves and potential and has used that to propel the people to the modern era. The coast provides opportunities for oceanic hydropower and offshore wind energy generation. The country embraced onshore hydropower generation in many rivers that originate in the jungles.

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History of Energy

Venezuela began its long history in the world’s energy sector with the installation of its first oil well, Zumaque, in 1914 [3]. In 1928, Venezuela became one of the world’s largest oil producers under General Gomez’s rule [3]. By the early 1930s, the country was supplying almost half of the US crude oil imports using 55% of Venezuelan production [4]. When the United States placed a tariff on foreign oil within the decade, the financial strain on Venezuela prompted it to quickly turn to the European market [4]. In 1935, when General Gomez passed away, Venezuela was left in poverty due to the dependency on oil contracts fashioned by Gomez himself [4]. The government entities that took over in 1935 reformed the oil industry and its standards on the wholesale market with the production companies working in the country [4]. By 1943, an agreement was attained where there was a near 50/50 split, one of the first 50/50 splits between the country and oil producers [4]. This initial agreement did not set well with the Venezuelan government and shortly after 1943, a truer 50/50 split contract was signed [4]. In the late 1940s, the Minister of Development, Juan Pablo Perez Alfonzo, took a bold move to take the Venezuelan royalty oil (oil reserved for Venezuelan use) and sell it directly on the world market [4]. Alfonzo’s actions broke the near monopoly that the Anglo-Saxon producers had [4]. The late 1970s saw the first appearance of alternative energy forms with a focus on hydropower [5]. In 1983, Venezuela signed in its first National Energy Plan [5].

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Breakdown of the Energy Generation "Mix"

Energy Generation Mix

Figure 1 shows the energy generation mix of the Venezuelan energy profile.

Energy Consumption Mix

Figure 2 shows the fuel consumption mix of the Venezuelan energy profile.

Fossil Fuels

Venezuela's energy sector consists of 51% fossil fuels mainly consisting of oil and natural gas production (Table 1).

Oil

As of 2016, Enerdata's Country Energy Report on Venezuela reported that the country used 51% of 54.6 million tons of oil equivalent (Mtoe) of the total energy the country produces [1]. In terms of crude oil, 1.484 million barrels per day were produced as of 2018 [6]. Approximately 1.656 million barrels per day were exported to foreign countries. However, it did not import crude oil according to a 2015 report [6]. As of 2015, refined oil was produced at 926,300 barrels per day with 325,800 barrels exported a day and 20,640 barrels imported in a day [6].

Coal

Venezuela currently has no significant coal production, and no plans for such facilities have been found.

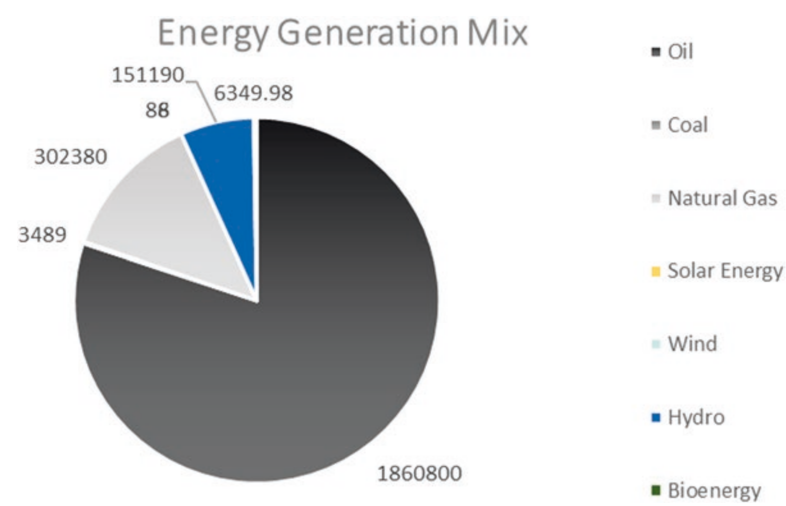

Fig. 1 Energy generation in Venezuela

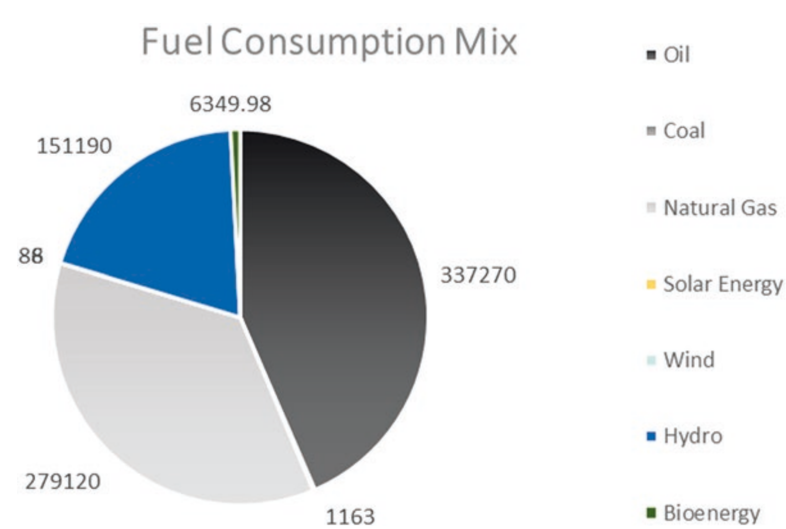

Fig. 2 Fuel consumption mix in Venezuela

Table 1 Fuel summary of Venezuela

Fuel	Quantity	Installed capacity (MW)	Energy production (GWh)	Energy consumption (GWh)	Imports (GWh)	Exports (GWh)
Oil	2	NA	1,860,800	337,270	35.06736	3367.0782
Coal	2	NA	3489	1163	0	4879.4724
Natural gas	7	2613	302,380	279,120	0	0
Nuclear	0	0	0	0	NA	NA
Solar energy	NA	5	6	6	NA	NA
Wind	3	71	88	88	NA	NA
Hydropower	4	16,521	151,190	151,190	NA	NA
Ocean	0	0	0	0	NA	NA
Geothermal	0	0	0	0	NA	NA
Bioenergy	NA	NA	6349.98	6349.98	NA	NA

Natural Gas

The Enerdata country report recorded that of Venezuela's 54.6 Mtoe of energy used, natural gas contributed to 38% [1]. The Central Intelligence Agency (CIA) World Factbook reported that Venezuela produced 27.07 billion cubic meters of natural gas as of 2017 and estimated that the country has neither exported nor imported natural gas [6]. As of 2018, there were 5.739 trillion cubic meters of proven reserves of native natural gas [6]. The native natural gas production typically coincides with their oil production near the coast of Venezuela.

Nuclear Energy

Currently, Venezuela has no nuclear facilities, but it is a member of the International Atomic Energy Agency (IAEA).

Renewable Energy Generation

On September 18, 2013, Venezuela committed to developing its national electric grid by forming the Electric Mission Venezuela (Misión Eléctrica Venezuela) [7]. The objective of the Electric Mission Venezuela was to strengthen the energy sector and encourage energy diversification into renewables by implementing action plans to meet the demand and efficient use of electricity [7].

Photovoltaics (PV)

Venezuela currently does not have any notable solar energy plants, and no plans for setting up one have been found. However, solar thermal technology is not unheard of in Venezuela. While there are no reported energy generation units fueled by solar thermal technology, many residential facilities use solar thermal as a means for water-heating and small energy generation. This is mostly due to Venezuela's blackout history. One of the first reported solar thermal installations was for the Maternity Hospital Concepcion Palacios in Caracas in 1982 [5]; 75,000 liters of hot water flows daily into the hospital at 50 °C from only 200 m^2 of solar collectors [5].

Wind

Venezuela currently does not have any notable wind energy fields, and no plans for setting up one have been found.

Hydropower

The CIA reported that hydroelectric energy generation was approximately 49% of the total installed capacity in 2017 [6]. The Guri Dam located near Orinoco is responsible for 10,200 MW of the country's electricity production from a 36 trillion gallon maximum capacity in the lake supplying the potential energy [8, 9]. As of 2015, the Guri Dam was the fourth largest dam in the world, originally contracted in 1986 by HPC Venezuela C.A., Alstom Hydro, ABB, Andritz Hydro, and Voith Hydro and currently operated by CVG Electrificacion del Caroni C.A. [8, 9].

Venezuela has realized its great potential for hydropower. The four major hydroelectric dams (Caruachi, Guri, Macagua, and Tocoma) cover the Coroni and Orinoco rivers. Therefore, the four dams only cover two of the ten potential sources of hydroelectric power. Table 2 shows the major rivers in Venezuela and their specifications such as drainage area and outflow [10].

From Table 2, it is clear that large rivers in Venezuela already supply or have potential for hydroelectric dams.

Table 2 Index of Venezuelan rivers for hydroelectricity

Name of the river	Length (km)	Length (miles)	Drainage area (km^2)	Outflow	Countries in the drainage basin	Venezuelan states in the drainage basin
Orinoco	2140	1330	880,000	Atlantic Ocean	Venezuela, Colombia	Amazonas
Caroni	952	592	95,000	Orinoco River	Venezuela	Bolivar
Rio Negro	2230	1386	691,000	Amazon River	Venezuela, Colombia, Brazil	Amazonas
Apure	1038	645	167,000	Orinoco River	Venezuela, Colombia	Táchira
Caura	723	449	28,163	Orinoco River	Venezuela	Bolivar
Meta	804	500	93,800	Orinoco River	Venezuela, Colombia	Apure
Catatumbo	500	311	22,317	Maracaibo Basin	Venezuela, Colombia	Zulia
Guárico	525	326	NA	Apure River	Venezuela	Guárico
Casiquiare	326	203	42,300	Rio Negro	Venezuela	Amazonas
Ventuari	520	323	NA	Manapiare River	Venezuela	Amazonas

Ocean

There are no reported units of oceanic hydroelectric power at the time of writing. However, since the country is on the east coast of South America, it has the potential to tap into the power of the Atlantic Ocean.

Geothermal

Venezuela currently does not have any notable geothermal energy plants, and no plans for setting up one have been found.

Biofuels

While biofuels are not the main source of energy in Venezuela, they contribute 1% of the 54.6 Mtoe of energy the country consumes [1].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

Because hydropower is driven by the potential energy of water, the storage capacity of each dam is subject to the space allotted for water collection in the reservoir behind the dam. The overall storage capacity of the hydropower sector is well over 35,500 MW [11]. An inspection of the solar energy businesses in Venezuela and the storage technologies they use reveals that the country has deep cycle batteries and solar water-pumping systems [12]. As for the storage of fossil fuels, the extra supply is left in its natural habitat and does not require extra storage measures except for transportation.

Carbon Footprint

Most Recent Carbon Output

As of 2017, the CIA approximated 129.9 million metric tons (Mt) of carbon dioxide emissions from energy consumption alone [6].

Historical Trends of Carbon Footprint

However, since the use of renewables and implementing conservation measures on electricity usage, Venezuela has seen a 24% reduction in carbon dioxide emissions from 2010 to 2016 with a continuous downward trend predicted from further estimates [1] (Fig. 3).

Types and Main Sources of Pollutants

Crude oil production contributes to much of the pollution within Venezuela. However, there are other factors that contribute to the pollution [13]. They include steel and aluminum production, fertilizers, and waste burning [13].

Air Quality

According to the World Health Organization's air quality guidelines, Venezuela's air quality is moderately unsafe with $PM_{2.5}$ concentrations at approximately 17 μg/m^3 [13]. This exceeds the standard maximum of 10 μg/m^3 for air

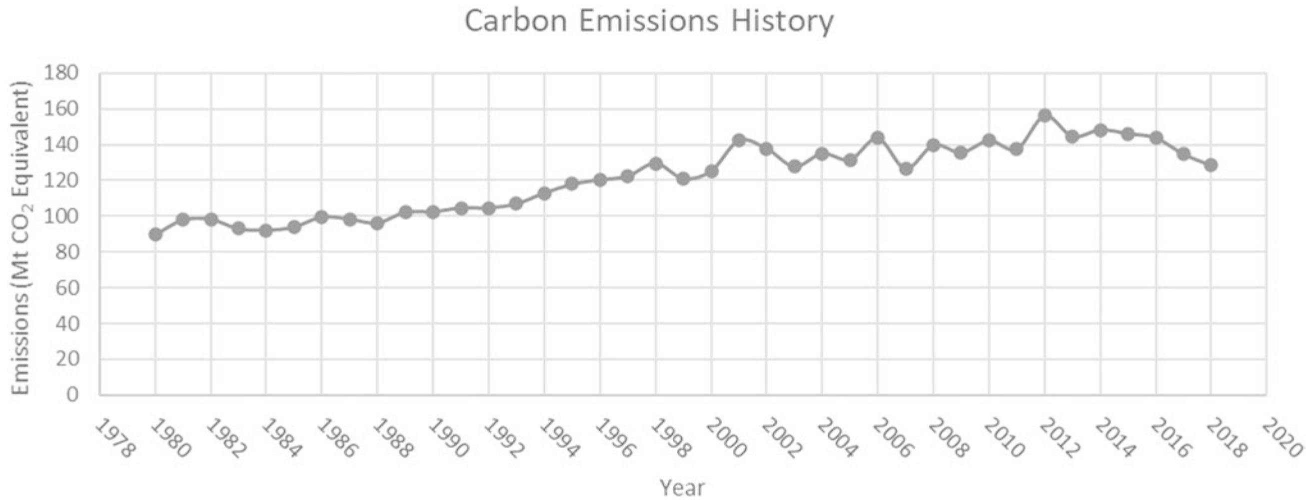

Fig. 3 Venezuela's carbon emissions trends

quality [13]. For perspective, $PM_{2.5}$ are inhalable pollutants of approximately 2.5 μm or smaller [13].

Energy Resiliency

Electrical Grid

Venezuela experienced a surge of electrical development in the early twentieth century when its oil fields were being founded [14]. Many of the country's generation facilities, both fossil and renewable energy, have been in operation since the late 1950s making them over 50 years old [14]. The Venezuelan electric grid has two verified interconnects: one with the Colombian grid and the other with the Brazilian grid [14].

Venezuelan officials reported to the US Government Accountability Office that most of the electricity produced in Venezuela comes from a poorly maintained hydroelectric grid [15]. "Prolonged drought, mismanagement, and lack of maintenance of oil refineries, among other problems, are primary factors causing electricity and gasoline shortages" for Venezuela [15]. On August 29, 2019, plans were started aimed at restoring the electric grid in several states [16]. After initially supporting the restoration and saying the Corporacion Andina de Fomento (CAF) would provide $400 million, Juan Guaido, a Venezuelan politician, later rejected the plan stating that there were better and cheaper alternatives [16].

Climate and Natural Disasters

Venezuela is geographically located on the east coast of South America with extensive access to the Atlantic Ocean and lush rain forests in the interior. The natural environment of the country explains its highly developed hydroelectric generation system and warrants further development. However, the tropical and rain forest landscape has often led to major landslides and floods that wreak havoc on local communities [17]. While it seems this would still benefit Venezuela's hydroelectricity network, the country also experiences severe drought, as was observed previously [15]. For example, by the end of 2015 to the beginning of 2016, a drought caused by the El Nino (a climate cycle caused by the Pacific Ocean that has widespread effects on global climate) created major disruptions in hydroelectricity generation [7].

Grid Resiliency

Venezuela has had a long history of electrical blackouts. Many of the country's states rely on hydroelectricity. However, drought leads to an inadequate supply of electricity that in turn leads to outages and the use of emergency and energy conservation measures [7]. In 2009, during a severe drought, the country was force into emergency conditions as state-wide blackouts occurred [7]. The Venezuelan government ordered rolling shutdowns in the hope of reducing the strain on the dams [7]. These events occurred again during the 2013 drought [7]. In 2019, another severe drought hit and the country yet again fell into emergency conditions, and it continues to be a problem that has caused further damage to the electric grid [7, 15].

Geopolitical Conditions

Reliance on Foreign Fossil Fuels

Venezuela's geopolitical conditions are extraordinarily tied to the history and development of the country's energy sector [4].

As of December 31, 2016, over six million subscribers are being served by a single state-owned corporation called Corporación Eléctrica Nacional (CORPOELEC) [7]. The CORPOELEC is charged with the generation, transmission, distribution, and commercialization of electric power [7]. A single governmental organization in control of all factors related to the electricity sector constitutes a natural monopoly and has unlimited entry into generation and services for their subscribers.

Venezuela's history shows how previous governmental entities have played a role in developing the country's oil industry [4]. They are responsible for its oil exports around the world [4].

Relations with Global Community/ Socioeconomic Influence

In a report to the United Nations' Sustainability Development Goals knowledge platform, Venezuela has stated its desire to relieve the stress on its hydroelectric dams by installing "thermoelectric" plants [18]. This should in turn help the energy crisis discussed earlier and build greater energy resiliency [18].

Due to economic hardship in Venezuela, there has been political strain in relationships with neighboring countries due to 4.5 million refugees fleeing Venezuela since 2014 [19]. The Venezuelan government has been unstable when observed over the last 100 years [4]. At the time of writing, the UN Human Rights Council is working on the first International Investigative Mechanism for the "atrocities" in Venezuela regarding the treatment of Venezuelans [19].

Education

Venezuela has many universities, both private and public. Many of the universities teach electrical engineering and science courses with some offering environmental studies. There is not much record on energy or environmental studies at the primary education level. Due to the country's increased reliance on hydropower, the universities do teach Venezuelans about such renewable energy and are not against the expansion of renewable energy education. While energy is at the forefront of the Venezuelan government's thinking, only just over half the population reaches secondary (high) school and less than that attend colleges [20].

Summary

Current Energy Situation

Venezuela has been a large producer in fossil fuels for many decades. By supplying a large amount of electricity using hydroelectric dams, the country has been able to make its revenue from crude oils.

Future Energy Situation

The current energy crisis leaves the Venezuelan government in search of measures for energy diversification, and in light of global sustainability goals, it has ventured into the idea of geothermal, solar, and wind energy production. The country plans to stabilize its electrical grid and move forward into sustainable energy development.

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Part V

Europe

European Union

Slobodan Petrovic and Nathan Margoshes

National Energy Introduction

The European Union (EU) is a union of 27 countries mostly located in Europe [1]. The members of the EU are the following: Austria, Belgium, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden [1].

Energy Policies

While energy policy is largely left to the member states, the EU had a few notable overarching energy policies. The 2015 Energy Union states the main goals of the EU's energy policy are the following: to diversify Europe's sources of energy, to ensure the functioning of a fully integrated internal energy market, to improve energy efficiency and reduce dependence on energy imports, to decarbonize the economy, and to promote research in low-carbon and clean energy solutions [2]. The other is the European Green Deal that provides an action plan to boost efficiency and increase biodiversity. This plan focuses on investments needed and financing tools that are available [3].

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Trends in Generation Technologies

Breakdown of Energy Generation "Mix"

Energy Generation Mix

Historical trends for the electricity generation are shown in Fig. 1. The European Union's energy generation mix is very nuclear and renewables heavy. As of 2019, nuclear accounted for 34% of the electricity generated, bioenergy 22%, coal 17%, natural gas 9.1%, wind 5.5%, hydro 4.8%, oil 3.9%, and solar 1.8% [4] (Fig. 2).

Energy Consumption Mix

The European Union's energy consumption mix is largely dominated by petroleum products that account for 35.9% of the energy consumed, followed by natural gas at 21.3%, coal at 15.2%, renewables at 14.6%, and nuclear at 12.9% [5] (Fig. 3).

Fossil Fuels

Oil

It is estimated that the European Union consumes an estimated 12.89 million bbl/day of refined petroleum products [6]. The majority of this is used for transportation, with road transit itself accounting for 47.5% of the oil consumption [7]. However, 262,967 GWh of electricity was generated from oil in 2019 [4]. The European Union produces an estimated 1.488 million bbl/day of crude oil and 11.66 million bbl/day of refined petroleum products; 8.613 million bbl/day of refined petroleum is imported, and 2.196 million bbl/day is exported [6]. The majority of the oil the European Union

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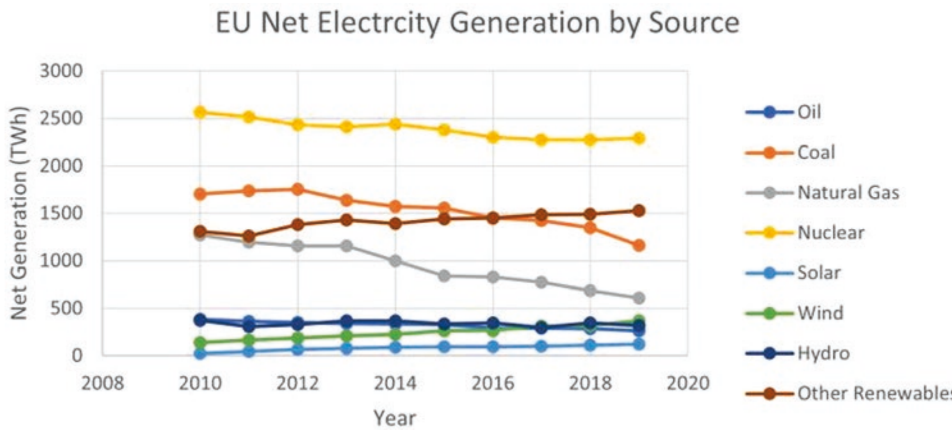

Fig. 1 Historical trends of electricity generation by source for the European Union [4]

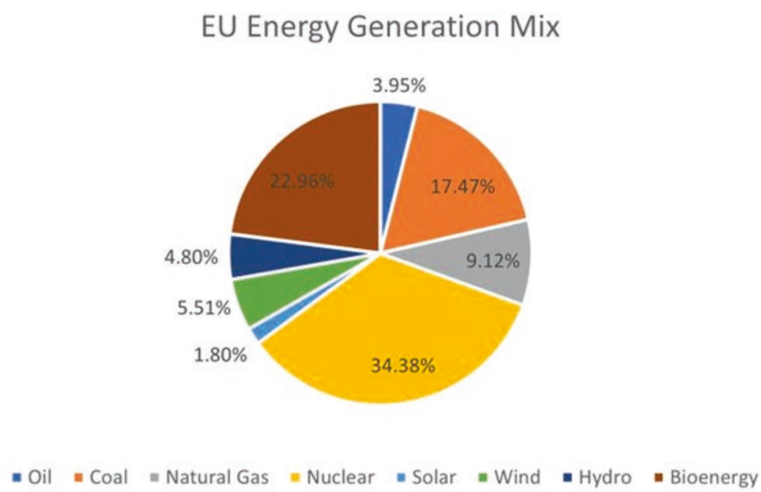

Fig. 2 A breakdown of the European Union's energy generation mix [4]

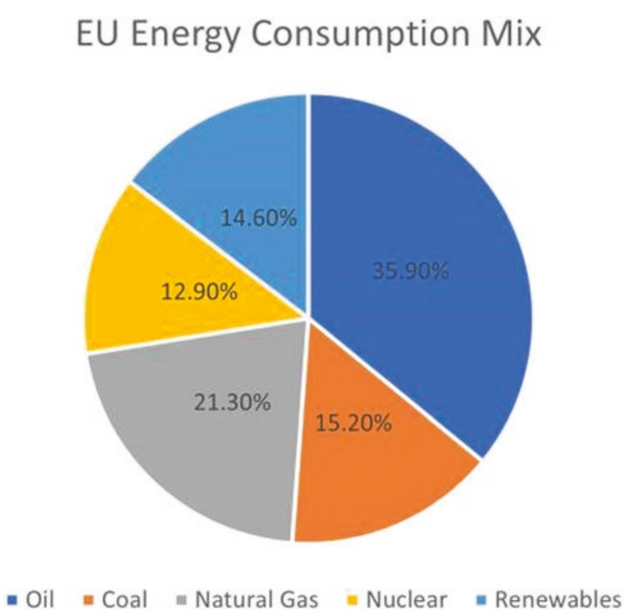

Fig. 3 A breakdown of the European Union's energy consumption mix [5]

imports is from Russia, accounting for 29.8% of imports. The rest of the oil comes from a variety of sources: 8.7% from Iraq, 7.4% Saudi Arabia, 7.2% Norway, 7.2% Kazakhstan, 7.1% Nigeria, 6.1% Libya, 4.6% Azerbaijan, 3.9% Iran, 3.9% the United Kingdom, 2.4% the United States, and 11.6% others [8]. It is estimated that across the European Union there are 5.1 billion barrels of crude oil reserves [6].

Coal

In 2019, it is estimated that the European Union consumed 176 million tonnes of hard coal [9]. From this, 1,163,764 GWh of electricity was generated in 2019 [4]. In 2019, there were only two coal-producing countries left in the European Union, namely, Poland and the Czech Republic. Poland produced an estimated 61.6 million tonnes, while the Czech Republic produced an estimated 3.4 million tonnes [9]. The European Union imported an estimated 130.9 million tonnes of coal in 2019 and exported an estimated 2.3 million tonnes

[10]. The European Union receives 42.3% of their imported coal from Russia, 18.3% from the United States, 13.4% from Colombia, 11.6% from Australia, 4.0% from Indonesia, and 10.5% from others [8].

Natural Gas

The European Union consumes an estimated 428.8 billion cubic meters of natural gas annually [6]. From this, 607,785 GWh of electricity was generated in 2019 [4]. The European Union produces an estimated 118.2 billion cubic meters, exports an estimated 93.75 billion cubic meters, and imports an estimated 420.6 billion cubic meters of natural gas annually [58]. The European Union receives 40.1% of their natural gas from Russia, 18.5% from Norway, 11.3% from Algeria, 4.5% from Qatar, and 25.6% from others [8]. As of 2017, it is estimated that the European Union has 1.3 trillion cubic meters of proved reserves [6].

Nuclear Energy

Nuclear policy with the European Union largely depends on the member states themselves. There are currently 13 countries within the European Union that have nuclear power: Belgium, Bulgaria, the Czech Republic, Finland, France, Germany, Hungary, the Netherlands, Romania, Slovakia, Slovenia, Spain, and Sweden. Additionally, Lithuania and Poland both have proposed reactors [11]. There are currently 106 nuclear power plants with a total capacity of 104,000 MWe. From this, 2,290,270 GWh of electricity was generated in 2019 [4]. This accounts for over a quarter of the electricity generated across the European Union, with over half of this nuclear energy being produced in France [11]. While there are some nuclear plants undergoing construction in Finland, France, and Slovakia, nuclear is set to decline over the coming years. It is estimated that by 2050 the total nuclear capacity in the European Union will level out between 95,000 and 105,000 MWe [11]. The European Union received a uranium delivery in 2018, where 28% of the uranium came from Canada, 16% from Niger, 15% from Australia, 14% from Russia, 14% from Kazakhstan, and 8% from Namibia [11].

Renewable Energy Generation

Photovoltaics (PV)

In 2019, the EU had 9000 MW of installed photovoltaic capacity [12]. From this, 118,645 GWh of electricity was generated in 2019 [13]. Currently, the largest solar power plant is the Núñez de Balboa photovoltaic plant in Badajoz, Spain, built by a subsidiary of the Iberdrola group. The Núñez de Balboa plant began operation in April 2020 [14]. The average solar irradiance across the European Union varies depending on the geographic location. The southernmost member states receive an average daily irradiance of 4.5 kWh/m^2, while the more northern member states receive an average daily irradiance of 2.7 kWh/m^2 [15]. It is estimated that solar could meet 20% of the energy generation needs of the EU by 2040 [16].

Wind

In 2019, the EU had a total installed wind capacity of 192,000 MW [17]. From this, 363,143 GWh of electricity was generated in 2019 [13]. The largest wind farm in the EU is the Fântânele-Cogealac Wind Farm in Romania. This wind farm began operation in 2012, has a capacity of 600 MW, and is owned by CEZ Romania [18]. It is estimated that the EU could have 350,000 MW of wind power by 2030 [19]. The EU put forth plans in November 2020 to increase offshore wind capacity from the current 12,000 MW to a minimum of 60,000 MW by 2030 and to a further 300,000 MW by 2050 [20].

Hydro

As of 2019, the EU had 150,000 MW of hydropower capacity [21]. From this, 334,449 GWh of electricity was generated in 2019 [13]. The largest hydroelectric plant in the EU is the Iron Gate I Hydroelectric Power Station jointly owned by Romania and Serbia. This dam, initially opened in May 1972, has a total installed capacity of 2280 MW [22]. It is estimated that there is 658,000 GWh/year of technically feasible hydropower in the EU [22].

Ocean

As of 2020, the EU had 247 MW of ocean energy capacity [23]. From this, 498 GWh of electricity was generated [4]. In the EU Strategy on Offshore Renewable Energy, the EU is planning to implement 40,000 MW of ocean energy (and other technologies like floating wind and solar) by 2050 [20].

Geothermal

Italy is home to most of the EU's geothermal capacity, with a capacity of 915 MW that generated 5700 GWh of energy in 2019 [24, 25]. It is estimated that by 2050 the EU could achieve 2,570,000 GWh of geothermal power [26]. While the EU officially supports geothermal energy, it is largely up to the member states to commit to its usage. There are some projects such as GEOTHERMICA that aim to promote research and innovation in geothermal energy, with the help of the European Commission [27].

Biomass

As of 2017, the EU had 32,000 MW of solid biomass electricity-generating capacity. From this, 1,483,598 GWh of electricity was generated [4, 28]. It is estimated that the total bioenergy capacity of the EU could reach 52,000 MW by 2030, producing around 360,000 GWh [29].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

In the EU, pumped hydro storage makes up the vast majority of the energy storage, with a capacity of 25,264 MW [23]. Such as with other aspects of the EU's energy system, implementation is largely up to the member states.

Country's Future Storage Direction

However, the European Parliament voted positively to adapt an energy strategy that heavily promotes energy storage. This is a nonbinding policy, although it does provide political pressure by displaying the direction the Parliament wants to go [30].

Carbon Footprint

Most Recent Carbon Output

In 2019, the EU had a greenhouse gas (GHG) emission of 3749 Mt CO_2 equivalent [31].

Historical Trends of Carbon Footprint

The EU has had a steady decline in greenhouse gas emissions over the past 10 years. There was a slight increase around 2015; however, the EU has still achieved an overall downward trend (Fig. 4).

Types and Main Sources of Pollutants

The majority of GHG emissions from the EU come from fuel combustion, at 53%. Transportation emissions account for 25%, agriculture 10%, industrial processes 9%, and waste management 3% [32].

Air Quality

According to the European Environment Agency, the majority of the EU (where data are available) is considered to have a good-to-fair air quality. This means that the concentration of $PM_{2.5}$ (particles <1.5 μm) is from 0 to 20 μg/m^3, the concentration of PM_{10} (particles <10 μm) is from 0 to 40 μg/m^3, the concentration of nitrogen dioxide (NO_2) is from 0 to 90 μg/m^3, the concentration of ozone (O_3) is from 0 to 100 μg/m^3, and the concentration of sulfur dioxide (SO_2) is from 0 to 200 μg/m^3 [33].

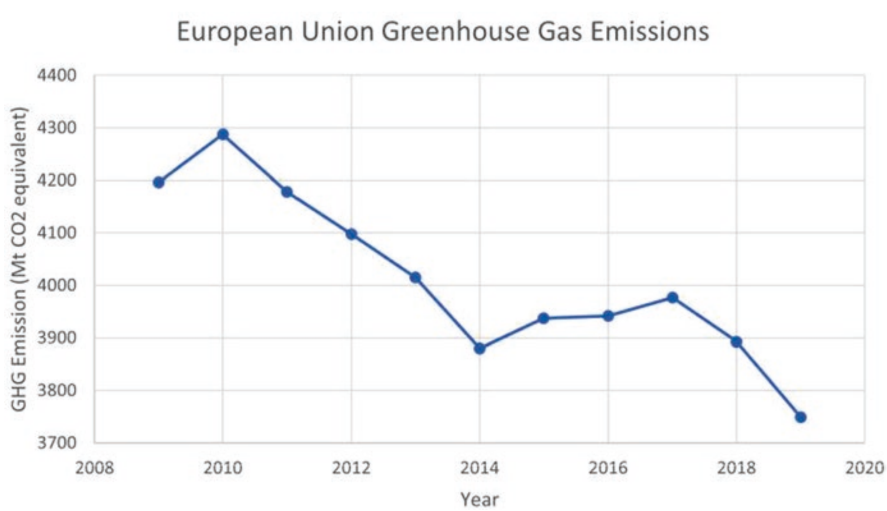

Fig. 4 Annual emissions of the European Union for the past 10 years

Energy Resiliency

Electrical Grid

The majority of the EU is serviced by the synchronous grid of Continental Europe. This grid is the largest synchronous electricity grid in the world. As of 2009, this grid was brought under the European Network of Transmission System Operators for Electricity (ENTSO-E). As of 2018, the European power grid has 474,700 km of transmission lines from 110 kV to 400+ kV [34].

Climate and Natural Disasters

This section talks about climate and natural disasters with the following information: commonalities for specific geographic locations, that is, hurricanes, earthquakes, and fires; resources; pollution; and other contributing factors exacerbating a country's climate and climate change impact on renewables.

Grid Resiliency

The European grid generally has a high stability, although, with the size of the grid, small issues can lead to cascading problems. An example of this occurred on January 8, 2021, when a substation in Croatia experienced a failure resulting in a redirection of the electricity, and more failures resulting in the load being shifted to neighboring transmission lines. This redirection resulted in further tripping that resulted in cascading trips from the border of Romania and Ukraine down to the Mediterranean Sea. These trips resulted in the European grid being split into two, the northwest area and the southeast area, in an effort to avoid even more cascading blackouts. This is because the northwest area ended up having a lower frequency than the southeast area. The splitting of the grid was required to help stabilize the frequency before resynchronization could commence [35]. The EU is prone to flooding, extreme weather, wildfires, earthquakes, and droughts. An increase in the global temperature can cause the EU to experience rising sea levels, droughts, heat waves, and wildfires [36].

Geopolitical Circumstances

Reliance on Foreign Fossil Fuels

The EU has a moderate dependency on foreign fuels for their energy production. In 2018, foreign energy sources accounted for 58% of the EU's energy needs [8].

Relations with Global Community/ Socioeconomic Influence

In 2020, the EU updated its Nationally Determined Contribution (NDC) under the Paris Agreement to reducing emissions by a minimum of 55% by 2030 from 1990 levels [37]. The EU is an enhanced permanent observer within the United Nations. Normal observers are not allowed to speak or vote within the United Nations, but in 2011 the EU acquired the enhanced observer status, which grants them speaking rights. While the EU is an enhanced observer, all of the EU's member states have full United Nations' membership status [38]. While the EU does not have any outstanding political conflicts, there are a few notes of importance. Due to North Korea's nuclear and ballistic missile-related activities, the EU puts forward sanctions against North Korea in 2020 [39]. While the EU has had good relations with China for many years, in 2021 the EU moved to reduce dependency on Chinese suppliers and limit companies supported by foreign subsidies to purchase EU businesses [40]. Finally, while the EU and Russia have had an agreement known as the Partnership and Cooperation Agreement since 1997, with the annexing of Crimea by Russia, some of the dialogues between the EU and Russia have been suspended [41]. Of additional note is the United Kingdom leaving the EU in what is known as Brexit. While it is yet to be seen how this will affect the EU in the long run, the United Kingdom made up 13% of the EU's population and was one of the major military powers, meaning that there will likely be ideological and power shifts over the coming years [42].

Summary

Current Energy Situation

This part will summarize the generation methods and energy trends of the country.

Future Energy Situation

The EU, and Europe in general, is very focused on clean energy, with the goal of becoming the first climate-neutral continent by 2050. This is the goal of the European Green Deal [43]. The EU is posed to meet this goal, with over 20% of their electricity generation coming from renewable sources. Whereas each member state is largely responsible for their own energy mix, the EU has taken steps as a whole to increase energy efficiency and decrease the reliance on fossil fuels through the European Green Deal, which puts forth an action plan to help all member states improve their energy mixes [3].

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Macedonia

Slobodan Petrovic, Isidora Janeva, and Stefan Stefanoski

National Energy Introduction

The Republic of Macedonia (hereafter Macedonia) is a landlocked country in Southeast Europe, bordering Greece to the south, Serbia to the north, Bulgaria to the east, and Albania to the west. It gained independence in 1991 after the secession of former Yugoslavia. The population of the country is 2.083 million, with Skopje as its capital city. Macedonia has been a candidate for joining the European Union (EU) since 2005, a process that has been slowed down due to political issues, such as the naming dispute with Greece (source: Washington Post).

Fossil fuels dominate the energy portfolio of Macedonia. The principal energy source is coal (63%), followed by hydropower (34%). Efforts have been made to increase the renewable energy contribution to this portfolio, even though a slow progress has been made in this direction in the past decade. This is consistent with the slowly growing economy of the country, as well as the slow adjustment to the EU legislation. Key strategies remain to be drafted in support of a sustainable economic growth and in line with the EU legislation, as well as the global requirements for reducing the carbon footprint. The Republic of Macedonia adopted the 2040 National Strategy for Energy Development (NSED) in December 2019, highlighting scenarios for reducing carbon emissions and crafting policies with specific renewable energy commitments and targets.

The 2022 energy crisis, preceded by the COVID-19 pandemic, has forced the country to import high-priced electricity from international markets due to the lack of domestic production. Macedonia is a full member of the Union for the Coordination of Production and Transmission of Electricity (UCPTE), which ensures interconnection compatibility with European electric power systems.

Despite some investments in modernization, domestic production of electricity has decreased by 25% in the last 10 years, and electricity imports have risen to 36% of the total consumption. The total annual production of electricity in 2018 was 5447 GWh, which provided 69% of the total domestic electricity needs.

Macedonia's state-owned power company was unbundled and partially privatized in the 2000s. Austrian utility company EVN has been responsible for the electricity distribution in Macedonia since entering the market in 2006. State-owned MEPSO is the country's electricity transmission system operator. Elektrani na Severna Makedonija (ESM; Powergeneration Plants of Macedonia, formerly known as ELEM) is Macedonia's state-owned electricity producer.

Breakdown of Energy Generation and Consumption "Mix"

Energy Generation Mix

The energy generation mix of the Republic of Macedonia is dominated by fossil fuels. In 2017, coal (predominantly lignite) had an estimated reserve of 332 million tons and remains the largest source of domestic energy generation. In total, 2.06 GW, or 63% of the generated power, comes from thermal power plants. After coal, the power generation mix is represented by renewable energy sources, mostly hydropower, but also wind, biomass, and solar. About 34% of the generated power comes from small and large hydropower plants. Numerical data from 2019 provide a detailed breakdown of the generated energy by source: coal (42,979 TJ), hydropower (4189 TJ), oil (44,134 TJ), biofuels and waste (8570 TJ), wind, solar, and others (653 TJ), and natural gas (10,221 TJ) (see Fig. 1).

Other renewable energy sources contribute with only 3% to the energy mix. There has been a steady increase in the use

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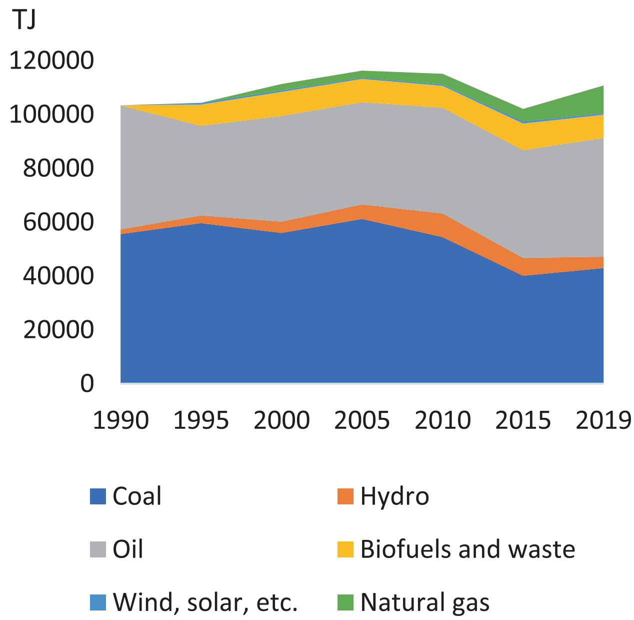

Fig. 1 Total energy supply by source for the Republic of Macedonia. (Source: IEA World Energy Balances)

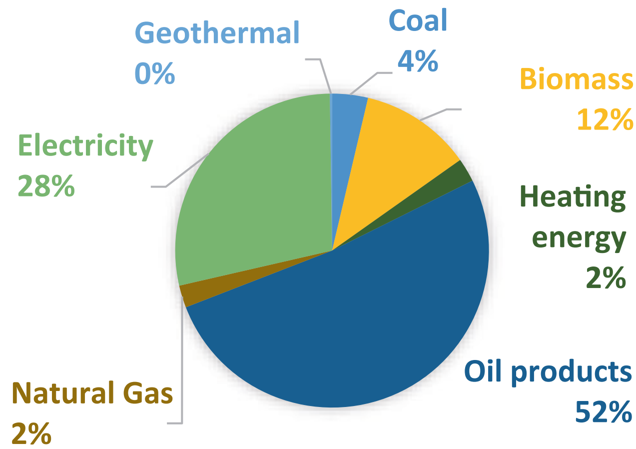

Fig. 2 Energy consumption by energy sources in 2020

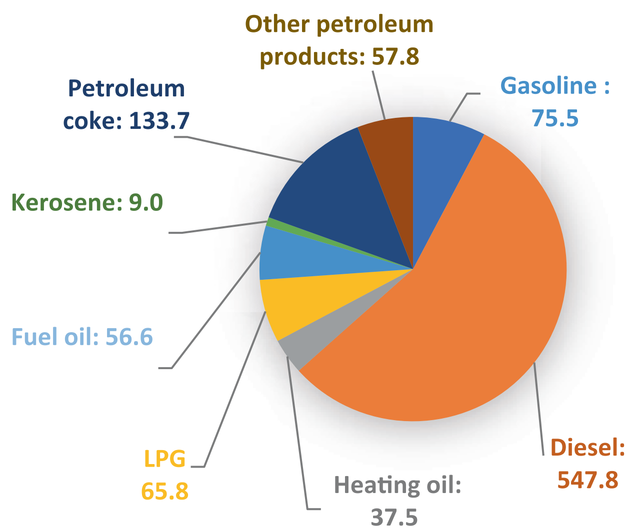

Fig. 3 Final energy consumption of petroleum products in kt for 2020

of this type of energy sources in the past decade. In 2018, 25% of the total electricity production in Macedonia, excluding hydro, was made up of renewable energy sources (De-risking Investments in North Macedonia, International Renewable Energy Agency IRENA).

Energy Consumption Mix

The total energy consumption in Macedonia for March 2022 amounted to 798,667 MWh. The consumed resources range from 44.74 million m^3 of natural gas, 446,801 tons of coal, and 100,788 tons of oil products (source: Serbia Energy). The State Statistical Office offers a breakdown of the energy consumption by source (see Fig. 2). Oil products account for 51.5%, electricity for 28.4%, and biomass for 11.5% of the total consumed energy. By sector, the final energy consumption looks like this: transportation 35%, households 27%, industry 25%, and the commercial sector 10%. Agriculture has a minor participation in the energy consumption mix and amounts to just over 1% in the final energy consumption (North Macedonia Energy Balance, 2022).

Fossil Fuels

Oil

The oil consumption in Macedonia was reported to be 19,946 barrels per day in December 2020, according to the data categorized under the World Trend Plus's Association: Energy Sector – Table RB.BP.OIL: Oil Consumption. Macedonia utilizes a 213-km pipeline linking the Hellenic Petroleum's facilities at the port of Thessaloniki in Greece to the OKTA refinery outside of Skopje. The pipeline is capable of carrying 2.5 million tons of crude oil annually, thereby reducing transportation costs and providing security of supply to the region. The total cost for the project was $105 million (€213 million) and was financed by the European Bank for Reconstruction and Development (EBRD) (source: EBRD).

According to the "North Macedonia Energy Balance for the year 2022," the main petroleum products the country uses are diesel, gasoline, petroleum coke, liquefied petroleum gas (LPG), fuel oil, heating oil, as well as a small amount of kerosene. The largest consumption is seen with diesel (547.8 kt), followed by petroleum coke (133.7 kt) and gasoline (75.5 kt) (Fig. 3).

Most of the petroleum products used in domestic consumption are imported, with the most notable imports being

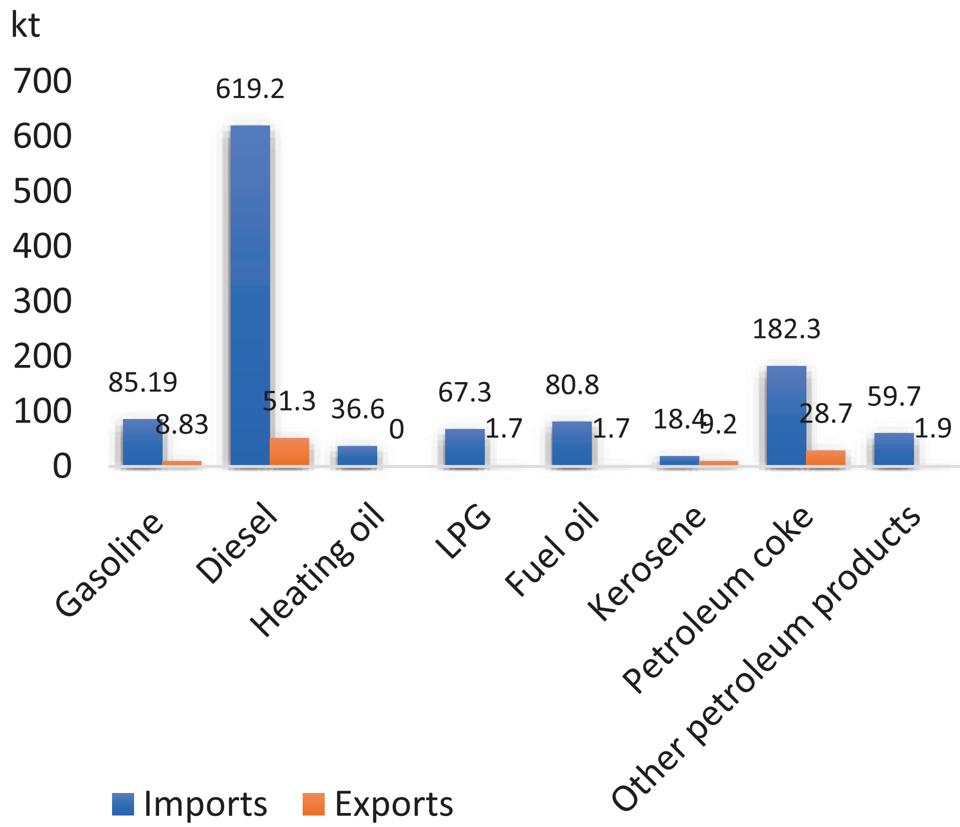

Fig. 4 Petroleum products: import and export in 2020

for diesel. The largest exported petroleum product in 2020 was also diesel, followed by petroleum coke (North Macedonia Energy Balance, 2022) (Fig. 4).

Coal

Coal participates with 30% in the country's energy consumption. Other solid fuels in Macedonia include lignite (which includes coal, dark coal, and peat), sub-bituminous coal (imported lignin with higher calorific value), and coke and coal (which includes anthracite, coke coal, and bituminous coal) (North Macedonia Energy Balance, 2022).

Coal is a fundamental part of the electric power production system in Macedonia. This system is comprised of several different means of production, with the largest production achieved by two thermal power plants with a total installed capacity of 800 MW. These two facilities account for over 70% of the country's total generated electricity. The smaller thermal power plant "REK Oslomej" (with an installed capacity of 125 MW) is not in operation, and its obsolete equipment is in urgent need of modernization. There is an intention to convert the plant's boiler to burn high-caloric coal. The modernization of the second thermal plant "REK Bitola" (with an installed capacity of 675 MW) was completed in 2017; however, its equipment is still largely obsolete. In comparison, the third largest power plant in the country, TEC Negotino, is a heavy oil-fired plant with an installed capacity of 215 MW. It has resumed its operation after being dormant since 2009. The efforts are made by the government to convert this plant to a natural gas-fired power plant.

The total coal reserves, including the potential from the Kicevo and Pelagonija Basins, are estimated to be 2.5 billion tons. Macedonian coal is predominantly lignite with a relatively low caloric value and high content of damp and ash from the geological Pliocene and Miocene ages. The coal in Macedonia is exploited in two types of mines. The first type produces coal for electricity production, and the second type produces coal as fuel (Source: ESM). The country has two open-pit lignite mines, SM Suvodol and SM Oslomej, with a combined capacity of 7 million tons per year and estimated deposits for the next 15–20 years (North Macedonia – Energy, Privacy Shield Framework). With an annual production of 6.5 million tons of coal, the Suvodol Coal Mine, which is located in the Bitola Municipality, Pelagonia Basin, is the biggest in the country. The coal reserves of the mine are estimated to be 175 million tons of lignite, and it is considered as one of the largest coal reserves in Europe and the world. Authorities in Macedonia are committed to switching to renewable energy as part of the government's plans to meet the EU goals on reducing carbon dioxide emissions. They have also announced that the REK Bitola and REK Oslomej thermal power plants will be closed by 2030 as part of the efforts to switch to renewable energy and reduce the air pollution (Dimitrievska for bne.eu).

Natural Gas

Natural gas has seen continuous growth throughout the years. The needs for natural gas for 2020 were estimated to be 339,497 thousand Nm^3. Macedonia has one functional natural gas transportation pipeline, which is operated by Gasification Macedonia (GA-MA). The natural gas transmission system in the Republic of Macedonia is part of the Russian transit natural gas pipeline, which passes through Ukraine, Romania, and Bulgaria. Consumer countries for this gas include Turkey, Greece, Serbia, and Montenegro. This pipeline carries gas from the connection point at the Bulgarian border, an area called Deve Bair. The main gas transmission pipeline has a length of 98.197 km and a pipe diameter of 530 mm. It has been designed for an intended capacity of 800 million Nm^3 natural gas and a working pressure of 40 bar (source: GA-MA). The Russian company Gazprom supplies the gas in its entirety. The gas pipeline runs only through selected cities, primarily large industrial centers, such as Skopje and Kumanovo (North Macedonia – Country Commercial Guide, trade.gov) (Table 1).

Nuclear Energy

Nuclear power in Macedonia is unavailable for production and consumption. The potential for the construction of a nuclear power plant was explored back in the 1970s. According to this study, Mariovo in the central region of the country would be the most optimal location for the construction of a nuclear power plant. This stems from several factors, most notably the geographical advantages of the area. Mariovo is seismically the most stable area in Macedonia, with access to abundant water resources, which is a vital for the operation of a nuclear power plant. The nearby river Crna Reka can be used to cool the nuclear reactor. Another factor that places a positive score on Mariovo is its less population. Mariovo is the least populated area in Macedonia, which reduces the consequences of a possible nuclear disaster. In terms of the effects on the economy and the economic growth of the country, the construction of a nuclear power plant would potentially create thousands of new jobs in different areas and promote strategies for the development of the region (analyticamk).

The first serious idea about building a nuclear power plant in Macedonia came into the spotlight in 2011. The three primary arguments against the construction of the plant were the high cost of the project, the lack of space for the storage of nuclear waste, and the lack of trained staff who would operate the plant.

Table 1 Natural gas outlook in 2020

Natural gas in 2020	Nm^3
Consumption	52,688
Energy transformations	285,665
Losses	1144
Total energy needs	339,497
Gross primary production	0
Import	339,462
Export	0

Macedonia attempted to join the Belene Nuclear Power Plant (BNPP) Project. BNPP was a planned nuclear power plant in northern Bulgaria, near the Danube River. This project was intended as a substitution for the decommissioned reactors of the Kozloduy Nuclear Power Plant, which was decommissioned as part of the prerequisites for Bulgaria to join the European Union. Macedonia pulled out from this project in 2020, and Bulgaria abandoned the project soon afterward (source: V. Dimitrievska for bne.eu). The 2040 energy strategy, according to which Macedonia is moving to a greener energy future, does not include any plans for the construction of a nuclear power plant.

Renewable Energy Generation

As a country-candidate for the EU accession, Macedonia is on the path of a greener energy future. This necessitates a proactive incorporation of diverse renewable energy sources into its mix. Under its Energy Community commitments, Macedonia is working on the increase of the share of renewable energy in its mix. The set target for 2020 was that 28% of the final gross energy consumption should be renewable energy (the energy sector in North Macedonia, bankwatch.org). As a consequence of the economic crisis in 2022, following the COVID-19 pandemic, this target has not been achieved.

Renewable energy sources participated in the total energy needs with 349 ktoe. Of these, 217 ktoe was biomass, 109.8 ktoe hydropower, 10 ktoe wind power, 2 ktoe solar power, and 5.1 ktoe biogas (Fig. 5). The share of renewable sources in the total energy was 18.5% and in the total energy needs 13.5% (North Macedonia Energy Balance, 2022).

Large and small hydropower plants, solar power plants, and plants fueled by biogas and biomass have a combined capacity of 795 MW. In total, they have produced 1662 GWh of energy in 2021, or 31.4% of the country's total electricity output, according to the annual report by Macedonia's energy regulator, Energy Regulatory Commission (ERC) (Balkan Green Energy News).

Solar Photovoltaics (Solar PV)

According to the data from Weather & Climate, the annual average number of sun hours in Macedonia is 2356 hours or 98 days. This fact plays into the expectation that renewable energy from solar PV should be highly utilized in the country's energy mix. However, the reality is quite different. Solar PV energy in Macedonia is underutilized, even though there

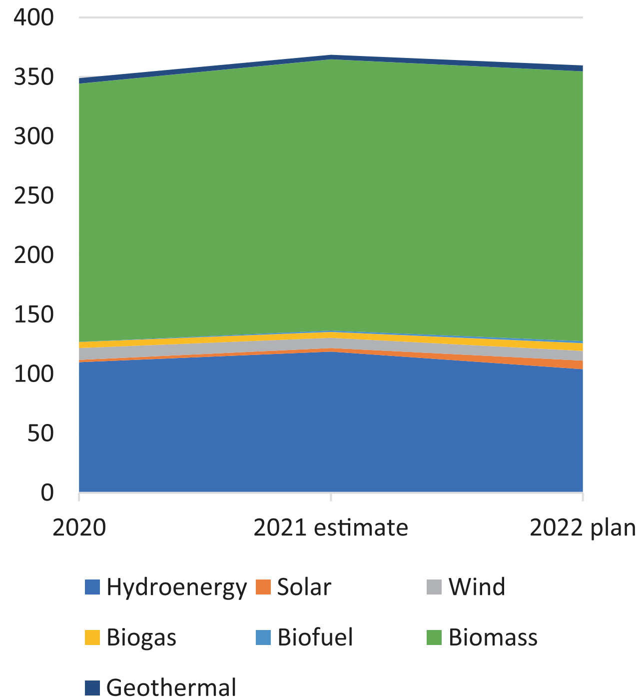

Fig. 5 Renewable energy sources in Macedonia, in ktoe. Realized, estimated, and planned needs

have been steps in the right direction to amend this problem and harness the power of the sun.

The first large-scale solar plant in Macedonia is Oslomej 1. It was built on the site of the Oslomej lignite coal mine with a capacity of 10 MW. It was built with the support of the European Union, Western Balkans Investment Framework (WBIF) bilateral donors, and the European Bank for Reconstruction and Development (Source: EBRD). The construction was carried out by the public company of JSC Elektrani na Severna Makedonija (ESM) and was the company's first solar plant in Macedonia. It is currently connected to the power grid and producing clean electricity. This particular plant was developed with an intention to diversify energy sources and support the ongoing decarbonization efforts, in line with the country's strategy for a greener energy future.

The Oslomej 1 solar PV power plant is expected to produce around 15 GWh of electricity annually, while displacing almost 12,000 tons of CO_2. This particular power plant is one of the 21 flagship projects completed in the Western Balkan region, which were selected for funding by WBIF (Western Balkans Investment Framework, EBRD). In 2020, solar power plants provided 2 ktoe of the total energy needs of Macedonia (North Macedonia Energy Balance, 2022).

Wind

Wind energy participates with 36.8 MW of installed power of a wind farm near Bogdanci in the southeastern part of the country. It accounts for 10 ktoe of the total energy needs of the country (North Macedonia Energy Balance, 2022). Macedonia was the first country in the Western Balkan region to put into operation a sizeable wind facility. The development of a feasibility study for this renewable energy infrastructure was supported by the Western Balkans Investment Framework (WBIF), a joint initiative of the EU, financial organizations, bilateral donors, and beneficiaries. It was aimed at enhancing the investments for socioeconomic development of the region and reinforcing the European perspective of the Western Balkans. There are reportedly plans for two more wind farms that would be built in the next 5 years, bringing the total wind capacity to around 86 MW (bankwatch).

Hydropower

The hydropower potential of Macedonia is estimated to be 5500 GWh. However, only about 1500 GWh is currently utilized for electricity generation, which represents a total installed capacity of 674 MW. The majority of the operational hydropower plants in Macedonia are located in the mountains of the northwest region. There are eight operational larger-scale hydroelectric power plants, with installed capacities ranging from 42 to 150 MW. The two largest plants are HE Vrutok and HE Tikveš, with installed capacities of 150 MW and 116 MW, respectively.

Since 2010, a total of 80 small hydropower plants have gone online. There is a boom in the interest for energy generation from hydropower. Five small hydropower plants were opened in 2015 in the Tikveš region, near the city of Kavadarci. The capacities of these power plants range from 1.4 MW to 2.8 MW, with a combined capacity of 10.9 MW (HydroPower.org). This particular project also includes an irrigation system on the Bosava River.

In 2020, hydropower plants provided 109.8 kto of the total 349 kto energy created by renewable energy sources (North Macedonia Energy Balance, 2022). The Energy Development Strategy recommends that a total of 998 MW of new hydropower capacity should be added before 2040 (The Energy Sector in North Macedonia, bankwatch.org).

Ocean

Macedonia is a landlocked country without a potential for harvesting energy from the ocean.

Geothermal

Macedonia utilizes low-temperature geothermal energy, while the medium- and high-temperature geothermal energy potential has not yet been explored. There are 18 known geothermal fields in the country (Fig. 6), which include boreholes, wells with hot water, and more than 50 thermal springs with a discharge capacity of about 1000 l/s and temperatures between 20 and 79 °C. Hot waters are mostly of the hydro-

Fig. 6 Main geothermal fields in Macedonia (Popovski, 2001)

carbonate type, according to their dominant anion, mixed with traces of Na, Ca, and Mg (Geothermal Energy Use, Update for 2018).

According to the 2020 statistics in the National Energy Balance Report, the consumption of geothermal energy resources amounted to 1.464 million m^3. No major changes to this consumption rate are expected in the future (North Macedonia Energy Balance, 2022).

Power generation from geothermal energy is currently absent. There are indications of foreign interest to explore and utilize such potential. The utilization of thermal waters in Macedonia today consists of seven geothermal projects and six spas. All of these projects, including Istibanja, Kocani (Podlog or Geoterma), Bansko, and Smokvica, had been completed before and during the 1980s. The Istibanja geothermal project includes the heating of a 6-hectare greenhouse complex in combination with a heavy oil boiler for peak loadings. The Smokvica geothermal system used to be the largest geothermal system in Macedonia. It provided heating for 32.5 hectare of greenhouses. Today, only three of the seven wells are exploited with a total flow of 90 l/s and temperatures between 63.9 and 68.5 °C. This energy is used to heat around 10 hectare of greenhouses, 6 hectare of glasshouses and 4 hectare of plastic houses. The Kocani Geothermal Project is the largest geothermal project in Macedonia. It consists of a complex of greenhouses of nearly 18 hectare and space heating of public buildings in the center of the town.

The most notable spas include Negorci (Gevgelija), Katlanovo (Skopje), Kezovica (Stip), and Bansko (Strumica). All of these spas are in need of renovation and modernization and therefore domestic or foreign investors who would sponsor these improvements.

Table 2 Biomass key indicators for 2022

Biomass in 2020	ktoe
Gross domestic production	164.6
Import	58.3
Export	0.2
Total needed energy	217.3
Consumption in the energy sector	0.0
Industry	18.0
Households	192.7
Agriculture	1.6
Other sectors	5.0

Biomass

Biomass in Macedonia is used in the traditional sense, that is, mostly as firewood for heating. In this sense, and in terms of heating and cooling usage, the share of renewable energy sources in the energy mix of Macedonia exceeded 31% in 2018. As the majority of stoves and biomass-based boilers currently in use are rather obsolete, this process is fairly inefficient (De-risking Investments in North Macedonia, IRENA).

The needs for firewood in 2020 were met mostly by domestic production. In total, 979.1 thousand m^3 of firewood was produced domestically, and only 36 thousand m^3 was imported. In the same year, the consumption of wood waste, such as briquettes and pellets, amounted to 123 kt. These needs were met mostly by imports of 129.4 kt, as compared to a domestic production of only 12 kt. The household consumption of wood from orchards or vegetable wastes was estimated to be 24.9 thousand m^3 (North Macedonia Energy Balance, 2022) (Table 2).

Biofuels

Biodiesel is the only available biofuel in Macedonia. The overall need for biofuel amounted to 0.1 kt in 2021 and was met by imports (North Macedonia Energy Balance, 2022). There is only one biofuel refinery in Macedonia, which is owned by Makpetrol AD Skopje. The refinery started production in 2007, with an annual capacity of 30,000 tons. Biodiesel is produced by the exploitation of unrefined oil from rapeseed, purchased by import (Energy and Water Services Regulatory Commission of the Republic of North Macedonia).

Energy Storage Technologies

There are currently no available data on any large-scale energy storage facilities in Macedonia, including pumped storage hydropower, compressed air, or battery storage power stations. Strategies for future employment of such technologies include electric vehicles and pumped storage hydropower, which would also provide a better grid management (De-Risking Investments in North Macedonia, International Renewable Energy Agency IRENA).

Greenhouse Gas Emissions

As the World is moving toward a CO_2-neutral lifestyle, Macedonia is slowly transitioning with its energy production strategies to reach its strategic climate goals, including the reduction of greenhouse gas emissions. Macedonia has a problem with air pollution, most notably during the heating season in the capital city of Skopje. It is one of the most polluted cities in the world, which contributes to larger than average number of premature deaths. An average of 2574 people die every year as a result of air pollution, according to a report by BreatheLife, a joint campaign by the World Health Organization, UN Environment, and the Climate and Clean Air Coalition (CCAC) (Air pollution in Skopje: how citizens spurred policymakers towards the change, CORDIS.EU).

Greenhouse gas emissions in 2020 were measured at 7157 kt of CO_2. Most emissions came from the combustion of lignite used in electricity generation, amounting to 49% of the total CO_2 emissions (Fig. 7). The second largest source of emissions, producing around 1865 kt CO_2, is the diesel fuel used in transportation. This is followed by other types of fuel, which account for about 1800 kt of CO_2 emissions (North Macedonia Energy Balance, 2022).

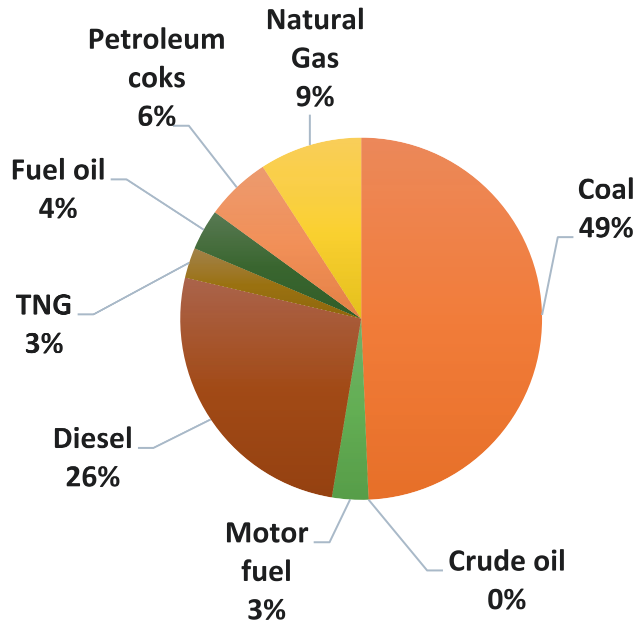

Fig. 7 Macedonia's greenhouse gas emissions per energy source for 2020

Energy Resiliency

Macedonia's Electric Grid

The Macedonian transmission grid is operated by a joint stock company that is fully state-owned and called the MEPSO Electricity Transmission System Operator of North Macedonia. Established in 2005, the main activities of MEPSO include the regulation of electricity transmission via the high-voltage network, the control of the electric power systems, the supply of electricity to industrial clients, and the regulation of the low-voltage grid of EVN Macedonia.

The Macedonian transmission grid has a large number of rings (contours) at two voltage levels: 110 kV (black) and 400 kV (red) (see Fig. 8). It consists of transmission lines, transformer substations, and the overall accompanying primary and secondary high-voltage equipment. The total length of the transmission lines is 2021 km (MEPSO Investment and Development Sector, "TEN YEARS NETWORK DEVELOPMENT PLAN).

The 400-kV transmission lines are the basis of the Macedonian transmission grid. They form a 400-kV ring comprised of three transmission lines. These lines connect the largest electrical consumers located in the northern part of the country. The largest production facilities are located in the southeast region of the country. These 400-kV transmission lines are used for the interconnection between the neighboring power systems.

The transmission grid of 110 kV is the most widespread and the most developed grid in Macedonia. It connects the thermal power plants, the large hydroelectric power plants, the larger populated areas, and the industrial parks.

The interconnection between the 400-kV and 110-kV transmission networks is done at five substations: SS Skopje 5, SS Skopje 4, SS Dubrovo, SS Shtip, and SS Bitola 2 (Fig. 8). The Macedonian power network is connected to that of the neighboring countries via 400-kV interconnections (MEPSO Investment and Development Sector, "TEN YEARS NETWORK DEVELOPMENT PLAN).

Climate and Natural Disasters

Macedonia's climate is characterized by warm and dry summers and autumns and relatively cold winters with heavy snowfalls. Macedonia is an elevated plateau, consisting of mountains, deep basins, and valleys. The Dinaric Alps extend down into Macedonia. It has three major lakes, and River Vardar is the longest river in the country. As a result of its geographical location and features, Macedonia's territory is prone to a range of natural hazards such as earthquakes, floods, landslides, droughts, and heat waves, to name a few. Historically, two major natural disasters took place in Macedonia: the 1963 Skopje earthquake, and the 1962 Skopje flood. The earthquake had a 6.1 moment magnitude and killed over 1070 people, injured between 3000 and 4000, and left more than 200,000 people homeless in a city that was 85% destroyed. The most recent disaster was in 2016 when at least 21 people were killed in a flash flood in the Skopje region.

The Republic of Macedonia is part of the South-East European Multi-Hazard Early Warning Advisory System (SEE-MHEWS-A) that benefits the National Meteorological and Hydrological Services of the World Meteorological Organization (WMO) members from the region (source: WMO/North Macedonia). According to the WMO, flash floods, which account for 85% of all flooding disasters, are among the world's deadliest natural disasters with more than 5000 lives lost annually.

Geopolitical Circumstances

Some of the key efforts in the energy market developments in Macedonia include the construction of an internal gas distribution network, continued liberalization of the electricity market, and increased regional cooperation for electricity and gas interconnections. A new Energy Law was adopted in

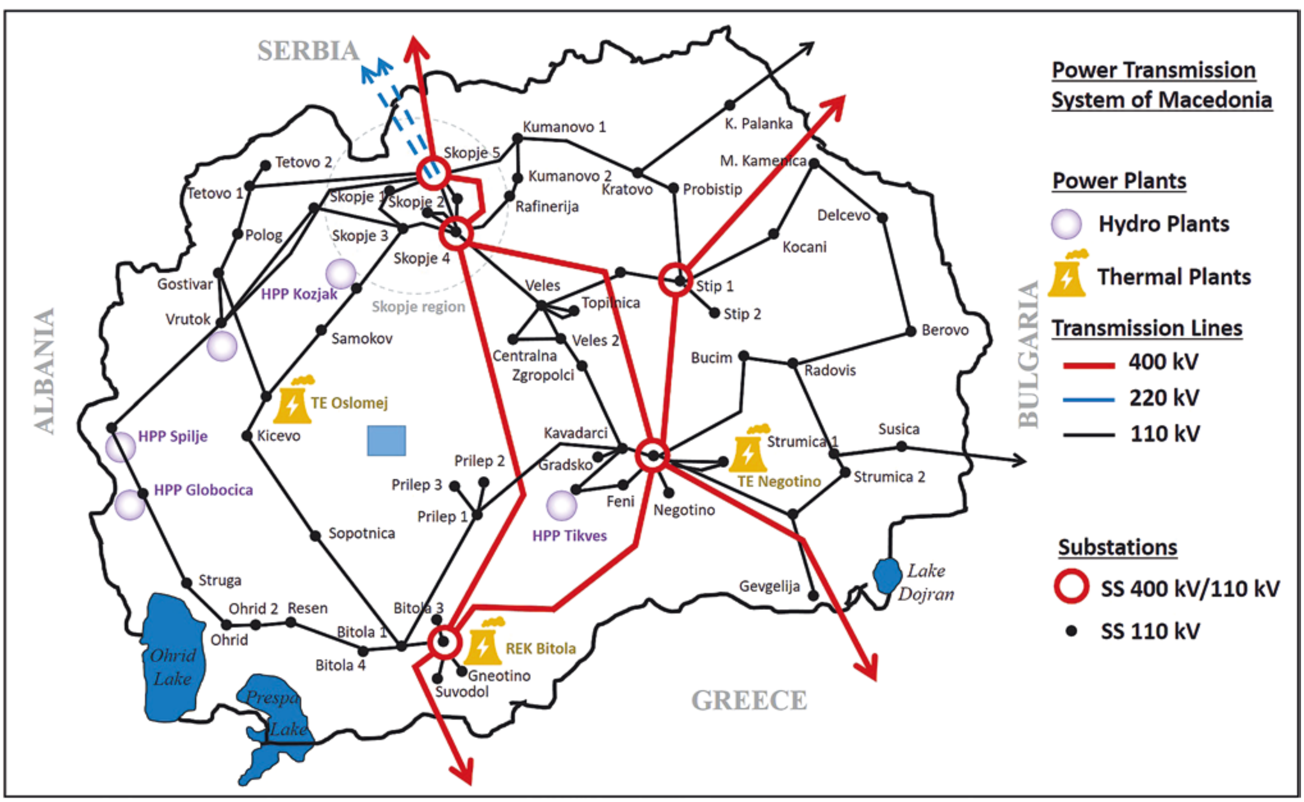

Fig. 8 Topology of the Macedonian transmission grid, 2020 (MEPSO Investment and Development Sector, "TEN YEARS NETWORK DEVELOPMENT PLAN)

June 2018, harmonizing its energy legislation with the EU Energy Community's Third Energy Package. Consistent with the Nationally Determined Contribution (NDC) submitted to the United Nations Framework Convention on Climate Change (UNFCCC), the Republic of Macedonia adopted the 2040 National Strategy for Energy Development (NSED) in December 2019, highlighting three possible scenarios for reducing carbon emissions. In April 2021, the government submitted the enhanced NDC to the UNFCCC Secretariat and a draft of the National Energy and Climate Plan (NECP) to the Energy Community Secretariat. These national strategies placed the energy-related policies and actions at the center of decarbonization efforts, including commitments to specific targets for renewable energy for power, heating, and cooling,

Education

The only university that offers specific energy-related studies at both undergraduate and graduate levels in Macedonia is the University of St. Cyril and Methodius in Skopje. Specifically, the Faculty for Mechanical Engineering offers a 4-year undergraduate program in Energy and Ecology. The same faculty also offers a 1-year graduate program on Sustainable Energy and the Environment (Faculty of Mechanical Engineering at UKIM, Skopje).

Funding for equipment and research is still needed to enhance the training capacity at the universities across the country. There is a necessity to boost the existing and to create new and proactive collaborations between universities and the private sector, in order to provide opportunities for practical experience for students in the country, as well as abroad.

Summary

The energy market developments in the Republic of Macedonia are centered on the three main areas: construction of an internal gas distribution network, continued liberalization of the electricity market, and increased regional cooperation for electricity and gas interconnections. Some of these efforts have been stalled due to the 2020–2021 COVID-19 pandemic, which had a significant negative impact on the economy of Macedonia, including the energy sector.

Macedonia welcomes investments in the energy sector. The government invites companies to design, build, and operate new large and small hydro power plants. One such concession has been extended to private investors for a public–private partnership with the state-owned electricity producer ESM, for the construction of a hydro power plant with a capacity of 440 MW. Even though the feasibility study has already been completed, a call for bidders has not yet been issued. Companies can also apply for tenders to construct sections of the national gas distribution network.

The government wants to increase the solar energy capacity from the current 20 MW to 200 MW. It plans to switch from offering a feed-in tariff to a premium tariff, while also offering free land and free connection to the electricity grid. In addition, the government intends to introduce a net metering system, allowing households to produce electricity via solar PV (source: Privacy Shield Framework: North Macedonia Energy). In addition to installing a new 14-MW capacity to the existing wind park, the government plans to increase the country's wind power capacity to 100 MW by tendering projects to prospective private investors.

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Switzerland

Slobodan Petrovic and Nathan Margoshes

National Energy Introduction

Energy Policies

The primary energy policy currently going on in Switzerland is the Revised Energy Act. Following the Fukushima nuclear disaster, Switzerland decided to move away from nuclear energy entirely, resulting in the creation of this act. As nuclear energy is the second biggest source of electricity in Switzerland, this act aims to improve the efficiencies of current energy sources and expand their renewable portfolio.

Domestic Resources

Switzerland is a landlocked mountainous region in Central Europe. As Switzerland does not have any exploitable fossil fuel reserves, they have to rely on imports and renewable energies. Luckily, Switzerland's geography is ideal for hydropower, resulting in over half of their generated electricity coming from hydropower.

Breakdown of Energy Generation "Mix"

Energy Generation Mix

There are two statistics to look at when examining Switzerland's energy situation: the electricity generation mix and the total energy breakdown. The electricity generation mix looks at all the electricity generation methods and how they are compared with each other in usage (Fig. 1).

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Energy Consumption Mix

The total energy breakdown looks at the total energy consumption. This takes into account all the different ways the energy is consumed by the people such as electricity, motor fuels, and biomass for cooking (Fig. 2).

Fossil Fuels

Oil

Fossil fuels play a decently large part in Switzerland's energy mix. The largest source of energy consumption is through motor fuels at 36%. As Switzerland does not produce crude oil, 57,400 bbl/day of crude oil is imported. From this, 61,550 bbl/day of refined petroleum products is produced. Switzerland has two refineries that are majorly owned by the private sector and have a combined output covering 45% of the domestic demand for petroleum products. Crude oil is imported mainly through pipelines [1, 2].

Coal

Like oil, Switzerland does not have any coal reserves. Thus, they must import any coal they wish to use. However, currently, Switzerland does not generate any electricity through the use of coal.

Natural Gas

For natural gas, 3.681 billion m^3 is imported. Switzerland does have reserves of natural gas, but they are mostly too small to be worth exploiting. In total, 95% of the natural gas consumed in Switzerland comes from the Netherland, Russia, Norway, Germany, and Algeria; 40% of the gas used is for households and 33% for the industrial sector. There are

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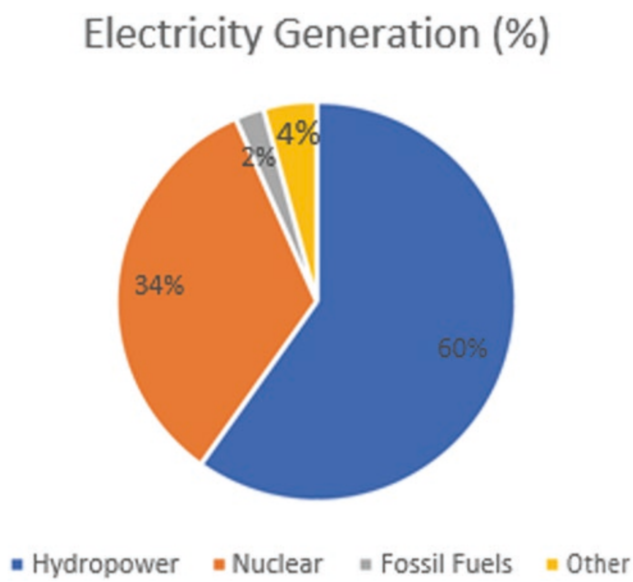

Fig. 1 Electricity generation breakdown [1]

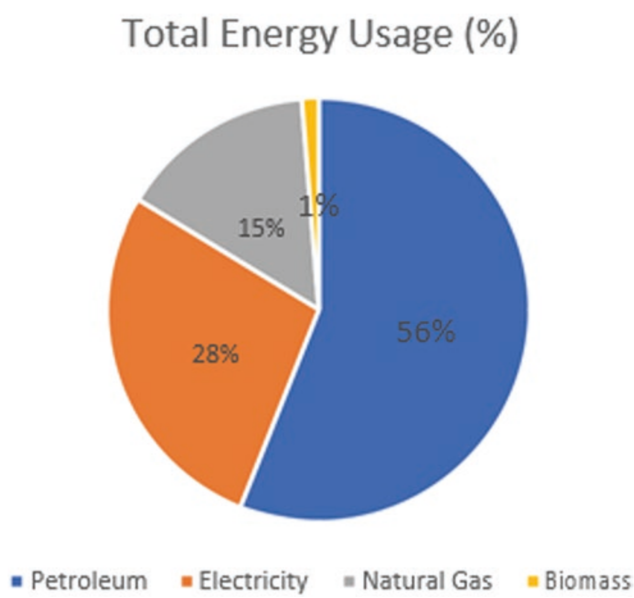

Fig. 2 Total energy breakdown [1]

over 600 km of high-pressure pipelines run by Gaznat for natural gas transportation [3].

Nuclear Energy

Switzerland is in an interesting phase regarding nuclear energy. Currently, the nuclear energy accounts for up to 40% of Switzerland's energy production; however, they have enacted a plan to totally phase out the nuclear energy following the Fukushima nuclear disaster [2]. Switzerland's largest nuclear plant is the Leibstadt plant, which is a 1220-MW plant first utilized in 1984.

Renewable Energy Generation

Photovoltaics (PV)

Switzerland uses a large amount of renewable energy. Currently, the majority of their generated electricity comes from renewable sources. There is 2172 MW of solar power installations in Switzerland, providing 3.4% of the electricity consumed, almost all of which are mounted on buildings. A study shows that solar panels could be fitted to 55% of Switzerland's total rooftop areas [4]. Assuming all of this real estate was exploited, it could cover 40% of Switzerland's electricity demand. It is estimated that Switzerland has only tapped into 10% of its potential. It has an average global horizontal irradiance between 3.2 and 4.0 kWh/m^2, meaning a decent potential.

Wind

As of 2017, Switzerland had 37 large wind turbines with a combined capacity of 75 MW, which produce 132 GWh of electricity. This accounts for 0.2% of the country's electricity demand. As Switzerland is a very mountainous region, the wind speeds vary greatly depending on the elevation. The flat lands have around 3 m/s, and the mountains have 9 m/s. This allows for great wind potential on mountains. Due to this, Switzerland is home to the highest wind farm in Europe [5, 6].

Hydro

Switzerland's geography makes it an apt location for hydropower. Therefore, almost 60% of Switzerland's generated electricity comes from hydropower. There are 672 hydropower power plants that have a capacity of at least 300 kW. They generate a maximum output of 15,510 MW and have an annual production potential of 36,567 GWh. The largest producers are Valais and Graubünden with a combined output of 17.70 TWh, which supply almost half of Switzerland's hydropower. Any future hydropower plants revolve around glacial runoff. The seven leading future plants have the potential to achieve the goal of removing nuclear energy from Switzerland's energy mix [7].

Ocean

As Switzerland is a landlocked country with no access to any oceans, there is no usage or potential for wave or tidal energy.

Geothermal

Switzerland is a leader when it comes to shallow geothermal energy. However, these come in the form of heat pumps, which are not used for generating electricity, but for heating. The main factor that is inhibiting the adoption of geothermal for electricity generation is the lack of knowledge about the conditions deep underground; due to this, there have been multiple projects set up for researching geothermal since 2018 [8, 9].

Biomass

Biomass has a fairly large role in Switzerland's energy situation. Biomass is largely used for heating and electricity generation. Biomass combustion makes up 12% of the total heating. For electricity generation, biomass accounts for 11.94 TWh [10]. It is estimated that Switzerland has a potential to produce 58.06 TWh from biomass alone [11]. Switzerland's largest biomass power plant is the Domat/Ems wood-fired power plant. Opened in 2006, the Domat/Ems plant has an annual heat production of 120,000 MWh and an annual electricity production of 100,000 MWh [12].

Biofuels

Biofuels make up 3.4% of Switzerland's motor fuel usage. In 2018, 158.1 million L of biodiesel was used, and 56.3 million L of bioethanol was used. Additionally, 2.8 million kg of upgraded biogas was used as transport fuel. In total, 12.5 million L of biodiesel was produced domestically, and the remaining 145.5 million L was imported, primarily from Germany. Switzerland does not have any domestic bioethanol production, so it is imported from Poland, Norway, Sweden, Germany, Holland, and Italy [13].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

Switzerland currently makes use of pumped hydro storage facilities to store energy. The Linth–Limmern Power Stations are a set of hydroelectric power stations located in the canton of Glarus. The Limmern Power Station is a 1000-MW pumped storage component that was added to the facility in 2017 [14, 15]. Another pumped hydro facility has recently been constructed in caverns between the Emosson and Vieux Emosson reservoirs. The 900-MW facility, known as the Nant de Drance project, has recently passed their final rounds of dry safety tests. It is expected that this facility will be operational from 2021 [16].

Country's Future Storage Direction

In addition, in 2019, a large battery storage system was installed. This 18 MW, 7.5 MWh is to be used primarily for primary frequency reserve [17]. This is currently Switzerland's largest battery installation.

Energy Resiliency

Electrical Grid

Switzerland has a very advanced power grid. The grid is around 6700 km long and has 141 substations. To ensure stability, the grid is mapped across 40,000 metering points, which record around 10,000 values within seconds. This has led to having one of the most stable electrical grids in the world [18, 19]. One of the things that ensure the constant flow of electricity are Switzerland's cross-border lines. These cross-border lines allow Switzerland to sell off excess energy or bring in energy when they have a deficiency. This allows for Switzerland's renewable energy-dominated generation mix to work so effectively.

Climate and Natural Disasters

Switzerland is mostly free of extreme natural disasters. They do suffer from storms though, which can always pose a threat to grid stability, although there have not been any major issues in the recent years. As mentioned, Switzerland is in a unique position where climate change is leading to more renewable energy potential. Due to rising temperatures, the glacial runoff is increasing. This is resulting in plans to harness this runoff for more hydropower.

Geopolitical Circumstances

Relations with Global Community/ Socioeconomic Influence

Due to Switzerland's unique stance of neutrality, there are no outstanding issues with surrounding countries. In fact, maintaining good relationships is important to their energy supply, as vast amounts of energy are sent to and from their neighboring countries of France, Germany, Italy, and Austria.

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Ukraine

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National Energy Introduction

Ukraine (Ukraina) is the second largest country in Europe by land area, bordering Russia, Poland, Romania, Moldova, and a long coastline along the Black Sea. Ukraine regained its independence with the dissolution of the USSR on August 24, 1991. Its total area is estimated to be 603,550.00 km^2, and the capital city is Kyiv (Kiev). The country's population was estimated to be 43.9 million as of July 2020 [1]. Ukraine has a wealth of natural energy resources, including coal, manganese, natural gas, oil, magnesium, nickel, graphite, timber, fertile agriculture land, and potential for hydroelectric power and bioenergy production.

Electricity generation in 2020 totaled 149 terawatt-hours (TWh) [2]. In 2019, nearly 65% of Ukraine's total energy demand was met by domestic production [3]. A significant portion of the energy generation capacity comes from nuclear sources. In 2019, Ukraine was the world's seventh highest producer of nuclear energy with 83 TWh [3]. Reducing consumption of imported fuels is a priority for Ukraine. It is a net importer of energy mostly from Russia, Belarus, and Kazakhstan. Importing less natural gas from Russia and exporting more biofuels would better secure Ukraine's energy profile.

Energy Policies

Ukraine has many policies governing fossil fuels, renewables, and other forms of energy. A focus of these energy goals is to reach complete energy independence from foreign nations including Russia. Many of Ukraine's more current policies show a shift away from fossil fuels toward more renewable sources. The law in Ukraine covering the electricity market [Information of the Verkhovna Rada (VVR), 2017, (No. 27–28, p. 312)] is a policy outlining the use of alternative energy resources. The energy strategy for the development of renewables until 2020 includes legislation for increased bioenergy development.

On March 23, 2021, the decree of the president of Ukraine number 11/2021 declared climate change a threat to national security and set priority measures in place to neutralize them. The decree outlines policies related to air protection, pollution emission control, water quality, purification of mine waters, preservation of soil and its fertility, marine environmental strategy, low carbon development, and a climate action plan up to the year 2030 [4]. This is an important energy policy because it regulates energy production by adding tariffs and penalties for pollution and increased criminal action.

The Energy Strategy of Ukraine 2035 outlines the nation's energy roadmap through 2035. Ukraine set a goal of generating 25% of its total energy mix from renewable sources by 2035. This is a significant portion of the nation's energy generation capacity and the policies discussed above make this goal a realistic possibility.

Domestic Resources

Ukraine has many domestic natural resources, including coal, natural gas, wind, solar, minerals, and arable land. Roughly 66% of all renewable generation is located within 5 major regions in southern Ukraine: Odessa, Zaporizhzhia, Mykolaiv, Kherson, and Dnipro regions. These regions have the most wind resources and receive the highest amount of sunlight [5]. Natural graphite is a valuable mineral used in the production of batteries and photovoltaic (PV) cells [6]. In 2020, 15,000 tonnes were mined making up 1.7% of total global production [2]. Ukraine has the world's second largest known gas reserves second only to Norway. Ukraine has a low annual reserve rate usage of around 2% [7]. This means that they may have a much larger natural gas reserve than estimated due to limited exploration of new fields.

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Large areas of arable land may be considered Ukraine's greatest resource with 3,000,000 hectares of unoccupied agricultural land. 4 billion m^3 of natural gas was replaced by bioenergy in 2018 [8]. These lands can be used to grow crops that can be used to grow biomass feedstock for power generation. Growing energy supply plants on 1 million hectares could replace half of all imported gas [8]. Bioethanol and biodiesel can also be obtained from bioenergy crops from the available land.

History of Energy

With the collapse of the Soviet Union in 1991, Ukraine gained independence coupled with an economic collapse. Electricity generation capacity decreased from 296 TWh in 1990 to 170 TWh in 2000. A significant portion of this decrease was from coal and gas [9]. Ukraine had a long period of economic growth from 2000 to 2007 in part due to its low gas prices, strong national currency, and high demand and price of steel exports. Ukraine joined the World Trade Organization in 2008 [3].

Breakdown of Energy Generation "Mix"

Energy Generation Mix

In 2020, the primary per capita energy consumption was estimated to be 3.31 EJ or 75.8 GJ. This was a 3.35 EJ reduction in energy consumption from 3.42 EJ in 2019 [2] (Figs. 1 and 2).

Energy Consumption Mix

Data on total energy consumption from 2012 to 2017 show a decreased consumption of 30.9 Mtoe in the agricultural, residential, service, industrial, and construction sectors [12]. In 2019, the industrial sector was the largest consumer of energy at 32.7% of the country's total energy consumption. This was followed by 28.4% for the household sector and 20.4% from the transportation sector [13] (Fig. 3).

Fossil Fuels

Oil

Fossil fuels including crude oil still play a key role in Ukraine's energy resiliency. In 2016, total electricity production was 153.6 billion kWh and electricity consumption was 133.2 billion kWh. In 2016, 65% of the total installed electricity capacity was generated from fossil fuels [1]. In 2020, Ukraine generated 0.70 TWh of electricity from oil [2] and 0.45 EJ of energy from oil was consumed for roughly 232 BBL/D/1K of energy production [2]. This shows that although a significant portion of electricity generation capacity comes from the burning of fossil fuels, the percentage of energy generated from fossil fuels is decreasing.

In 2018, 2.3 Mtoe of crude oil was produced [3]. A 2019 report by Baker Hughes showed that Ukraine led Europe with the most active oil rigs. Ukraine operated 84 of Europe's 186 active oil rigs including 44 offshore platforms [12]. Although Ukraine is not a large exporter of oil, it has one of the largest oil transportation networks in Europe and Eurasia. UKRTRANSNAFTA is a public joint stock company created in 2001 from the state-owned joint stock company with Druzhba. UKRTRANSNAFTA operates and maintains Ukraine's main oil pipelines. There are 19 main pipelines running a length of 4767.4 km. The inflow capacity is 114 million tonnes per year, and the outflow capacity is 56.3 million tonnes per year [13]. The main pipeline network also includes 28 oil pumping stations, 176 pumping units, and 79 operated reservoirs.

Ukraine imported 10.4 Mtoe of oil products, which was roughly 83% of total oil consumption in 2018 [3]. Belarus supplies Ukraine with most of its refined products. Ukrainian crude oil production averaged 53.50 BBL/D/1K during 1993–2021. In 2020, Ukraine produced approximately 46 BBL/D/1K with an oil refinery throughput of 68 BBL/D/1k. At the time of this writing, crude oil production in 2021 was 42 BBL/D/1k with a total refining capacity of 250 BBL/D/1k [2].

Oil and gas production plays a key role in maintaining Ukraine's energy independence. Three regions in Ukraine account for most of its oil and gas production: the Dnipro-Donetsk basin, the Carpathian region in western Ukraine, and the Crimea region and Black sea in the south of Ukraine. The Dnipro-Donetsk basin accounts for approximately 90% of all Ukrainian hydrocarbon oil and gas production [14]. In 2018, it was estimated that Ukraine had 395 million BBL of crude oil reserves.

Coal

Coal is still a primary fuel source for heating and electricity generation in Ukraine. In 2020, the country consumed 0.98 EJ from coal to meet its primary energy consumption needs [2]. In 2018, Ukraine generated 0.42% of its GDP from coal production revenue, and at the time it was ranked 14th in the world in coal production [1]. Recorded coal production for 2020 was equivalent of 0.54 EJ making up roughly 0.3% of global coal production [2]. In

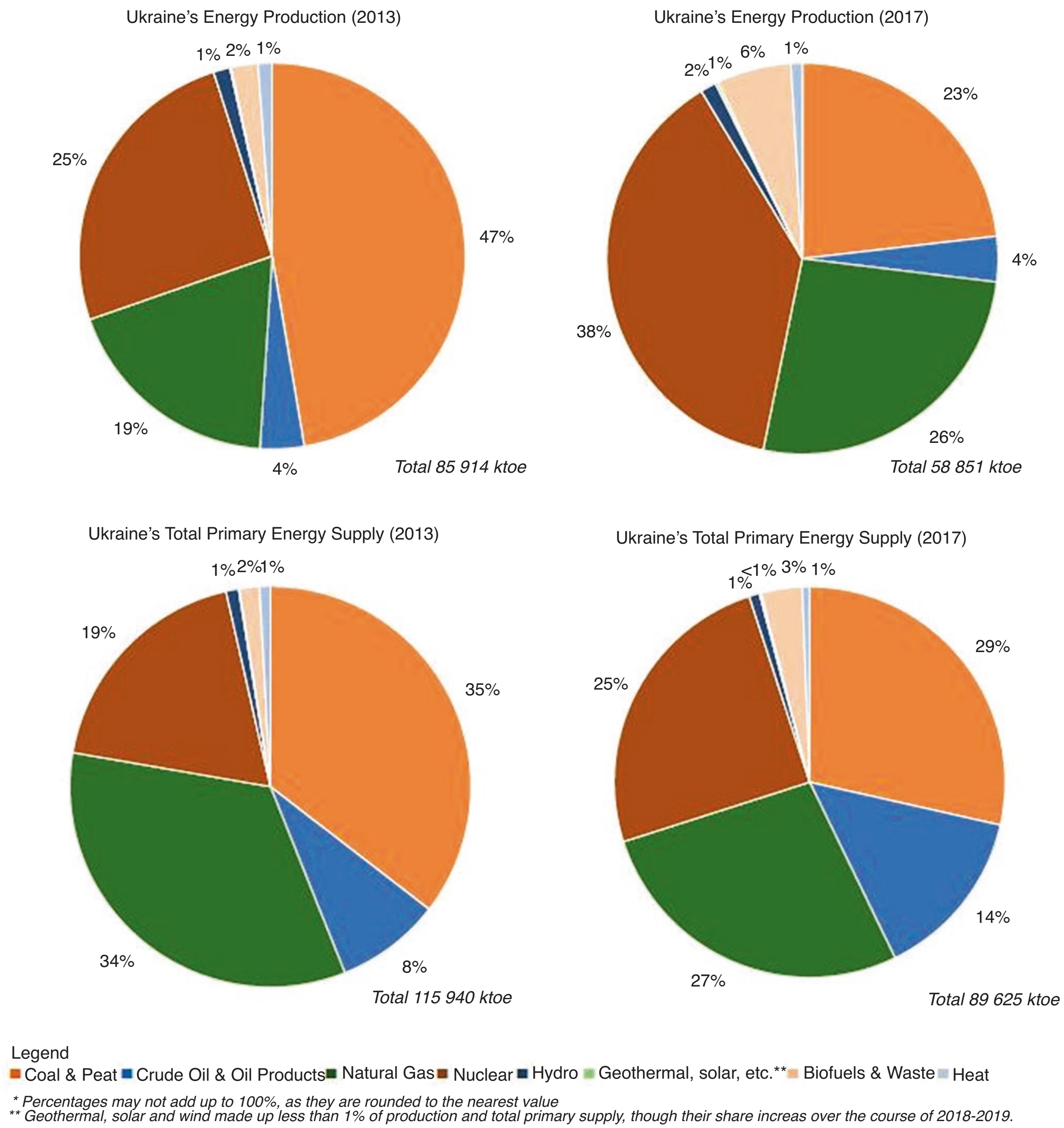


Fig. 1 Ukraine's energy generation and consumption mix 2017 [10]

2018, 14.4 Mtoe equivalent of coal was produced [3]. Another report estimated that in 2018 Ukraine imported 13.8 Mtoe of coal which was approximately 50% of the country's coal consumption [3]. Around 41.2 TWh of electricity was generated from coal in 2020 [2]. Ukraine has an estimated total proven coal reserves of 34,375 million tonnes, making up roughly 3.2% of total global coal proven reserves [2].

Natural Gas

Natural gas production and consumption play a significant role in Ukraine's energy profile. In 2020, an estimated 29.3 billion m^3, roughly 1.06 EJ, of energy was consumed from natural gas resources [2]. About 13.9 TWh of electricity was generated from natural gas [2]. Most of the gas produced in Ukraine is run by state-owned companies: PJSC

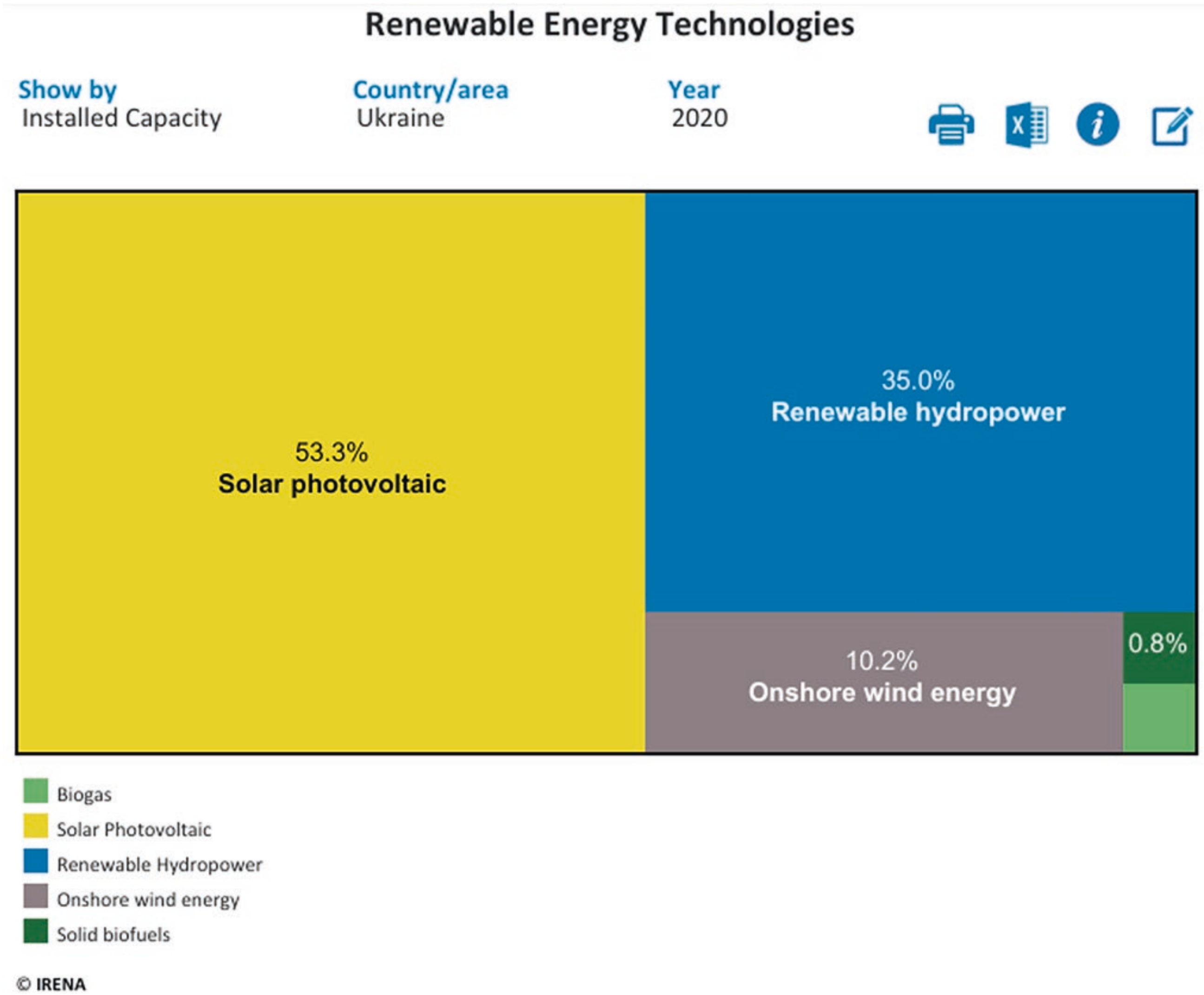
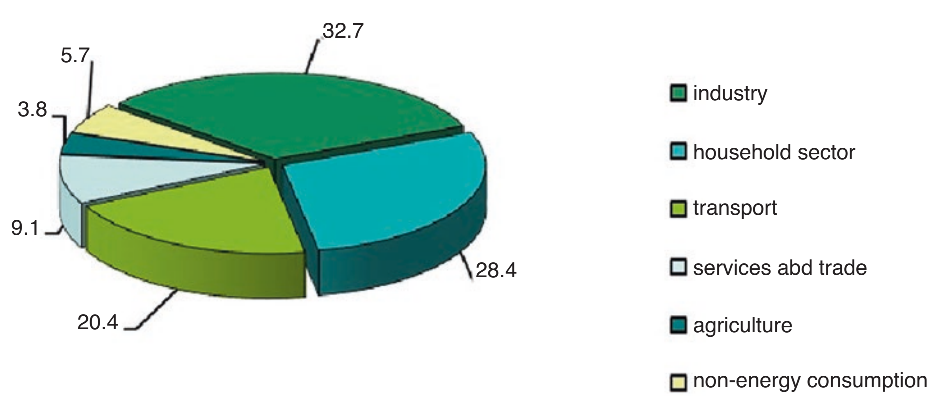


Fig. 2 Ukraine's renewable energy mix [11]

Fig. 3 Ukraine final energy consumption mix (in %) 2019 [13]



UkrGasVydobuvannya with 72% and PJSC Ukrnafta with 5%. The remaining production comes from six major private Ukrainian companies and 45 small private gas producers [14].

At the time of this writing, Ukraine was the largest transporter of natural gas in the world [3]. Ukraine is not an exporter of natural gas but it does play a significant role in the transit of natural gas from Russia to the European Union (EU) and other nations across Europe and Eurasia. In 2017, natural gas production was estimated to be 19.73 billion m^3 and the national consumption was 30.92 billion m^3 [1].

In 2020, natural gas production showed a slight decrease from 2017 with 19.0 billion m^3, roughly 0.68 EJ, of energy, making up 0.5% of total global natural gas production [2]. This decrease in production is a direct correlation to the reduction of energy consumption due to the global corona virus pandemic. Similar to crude oil, the Dnipro-Donetsk basin, the Carpathian region in western Ukraine, and the Crimea region and Black Sea in the south of Ukraine account for the majority of natural gas production.

Ukraine has a significant amount of natural gas resources with an estimated 0.6% of the world's total natural gas reserves. In 2020, it was estimated that Ukraine has 38.5 trillion cubic feet of natural gas reserves with a reserve-to-production ratio of 57.5% [2]. Another report by the International Trade Association in 2021 estimated that Ukraine has 900 billion m^3 of proven natural gas reserves ranking second in Europe [14]. This very high reserve ratio shows that Ukraine has a wealth of untapped natural gas resources. With many of its current policies moving away from fossil fuels and into renewable sources, this may remain the case for some time. Ukraine would also be able to extract more natural gas using newer fracking techniques; however, these techniques can be controversial and may have a negative impact on the local environment, water supply, and wildlife.

Nuclear Energy

Energy from nuclear sources has a long and mixed past with a large percentage of electricity generation capacity being a part of Ukraine's energy profile since the introduction of the technology. The Chernobyl nuclear disaster occurred on Saturday April 26, 1986, at the number 4 reactor. The reactor was located near the city of Pripyat in the north of the Ukrainian Soviet Union. The accident was a result of a flawed reactor design operating with insufficiently trained personnel. The lack of a safety culture at the time and Cold War isolation were directly related to the accident. The explosion and fires released radioactive materials into the environment. It was one of only 2 nuclear accidents in history to receive the highest disaster rating of 7 on the International Nuclear Events scale [9]. This disaster had a significant impact on nuclear policy and led to increased safety guidelines.

In 2012, the Ukrainian energy strategy to 2030 was revised, proposing 5000–7000 MWe of additional nuclear generation capacity, at a cost of US$25 billion. When Ukraine signed the Ukraine–EU energy bridge in 2015, it marked a shift in the policy to increase nuclear energy production and grid integration. These policies are expected to help generate capital for new nuclear capacity and will allow the sale of excess capacity to energy partners in the EU [9].

Ukraine produces a significant portion of its energy needs from nuclear power. Currently, there are 15 active nuclear plants with plans to build two more plants to meet the 2030 energy production goals. Operable capacity at the time of this writing was 13,107 Mwe. Operable capacity of the proposed reactors is estimated to be 27,070 Mwe [9]. In 2020, 76.2 TWh of electricity was generated form nuclear facilities [2]. In the same year, 0.68 EJ of energy was consumed from nuclear power sources [2]. Currently, most of Ukraine's nuclear fuel and nuclear services come from Russia. Ukraine is reducing its dependency on Russia by purchasing fuel from Westinghouse [9].

At the time of this writing, the current nuclear capacity of Ukraine was not ascertainable due to the ongoing Russian invasion of Ukraine. DTEK has reported the loss of 1.3 GW of nuclear generation capacity from the shutdown of the Zaporizhzhia nuclear power plant due to shelling and bombings by the Russian army.

Renewable Energy Generation

There are several companies within Ukraine, both state-owned and foreign investment, which contribute to the renewable energy market in Ukraine. Power generation from renewable sources in 2020 totaled 9.7 TWh [2]. Multiple types of renewable energy resources and investments have been in the growing renewable energy consumption mix. Large-scale projects through the nation's history include solar, wind, hydroelectric, geothermal, and biomass. By increasing renewable energy generation, Ukraine will increase its energy resiliency.

Photovoltaics (PV)

Solar power sources generated 6.2 TWh of energy in 2020, with a growth rate of 56.6% from 2.9 TWh in 2019 [2]. The increased economic periods of growth during 2000–2007 and the current policy are expected to increase solar production to meet energy use demands for the 2035 goals.

The largest solar plant in Ukraine is the Nikopol solar power generation facility with a total capacity of 200 MW. The plant is located on a former quarry site on unproductive land. The arrays include 750,000 photovoltaic panels. Construction was completed jointly by the Ukrainian company DTEK and the Chinese company CMEC. Construction was completed in under a year [15]. The total solar capacity in 2020 was estimated to be 7.3 GW [2].

KNESS is a Ukrainian company that constructed a 200 MW factory in Vinnitsa in 2019. It has plans to add an additional 200 MW of generation capacity [16]. The KNESS PV plant not only generates electricity but also gives Ukraine the ability to manufacture its own solar components, including panels, inverters, electrical equipment, and metal frames [16]. This gives Ukraine the ability to manufacture and sell PV cells. This is a technological advantage that increases the resiliency of Ukraine's energy profile.

Wind

Wind energy resources generated 10.2% of Ukraine's total renewable energy generation mix. These resources help to diversify the country's energy profile making its system more robust. Ukraine generated 3.2 TWh of energy from wind resources in 2020. This was an increase of 110.3% from 2.0 TWh in 2019 [2]. Installed wind turbine capacity was estimated to be 1.4 GW in 2020 [2]. A joint venture between the Ukrainian company WindFarm and Chinese company Power China was awarded a US $1 billion contract to build an 800 MW wind farm. The wind project will be located in the eastern Donetsk Oblast, close to the towns of Manhush and Nilolske. At the time of this writing, it was expected to be the largest wind farm in Europe [17].

Hydro

Hydroelectric power is one of the oldest renewable energy generation resources used in Ukraine. It was estimated in 2017 that 8% of the total installed generation capacity came from hydroelectric plants [1]. In 2020, Ukraine consumed 0.06 EJ of energy generated from hydroelectric sources [2]. The Kyiv hydroelectric station is located on the Dnieper River in Vyshhorod Ukraine. The dam is 288 m long and creates the Kyiv reservoir. Hydroelectric generation capacity is 418.8 MW from 16 20.5 MW and 4 22.7 MW turbines. Annual generation is approximately 683 GWh [18].

The Dnieper hydropower plant has been in operation since 1939 and Andritz was contracted to rehabilitate and expand capacity of the plant. The Dnipro 2 expansion will bring capacity of the dam to 1500 MW while improving performance, efficiency, and reliability. Construction was estimated to be completed in late 2021 [19].

Ocean

Ukraine has a long coastline along the Black Sea and has potential for multiple types of tidal energy generation resources.

Geothermal

As of 2019, Ukraine had a total of eight geothermal plants with a total installed capacity of 11.2 MW. Conditions for geothermal generation in Ukraine are average. The youngest geological structures are the Carpathian mountain folds and the Crimean mountains. Forecasted potential geothermal resources were estimated to be 50 Mtoe a year [20]. Geothermal generation capacity is expected to increase to help meet the 2035 energy objectives.

Biomass

Some of Ukraine's many biomass facilities are for the production of heat and electricity. Bioenergy makes up approximately 70% of all renewable sources in Ukraine [21]. In 2018, 4 billion m^3 of natural gas was replaced by bioenergy [21]. Energy crops include local quick-growing trees and plants, including willow, poplar, and silvergrass (Miscanthus). Biomethane is also produce by upgrading biogas facilities or through the gasification of biomass solids. Some of these crops also make the land more fertile over time; for example, growing willow over 20 years makes marginal lands fertile [21].

Biomass is a more cost-effective replacement for coal and natural gas. According to the Bioenergy Association of Ukraine, the energy potential from biomass is 23 Mtoe. Plant residues make up 10 Mtoe, roughly 44% of total biomass potential, and energy crops make up 7.5 Mtoe, which is roughly 32% of total biomass potential [8]. According to preliminary expert estimates, renewable energy technologies may reach 65% of Ukraine's total energy sector [21]. With bioenergy accounting for more than half of all renewables in Ukraine, this makes bioenergy a significant part of the energy strategy. The large amount of arable land combined with policies that promote the use of renewable energies and reduction of greenhouse gases shows that Ukraine has a wealth of untapped bioenergy and biomass. Ukraine has the biomass potential to replace all gas, coal and, gasoline imports [21]. Ukraine can increase its energy resiliency by increasing production of biofuels to export to other EU nations. Ukraine already has extensive pipeline networks for transportation (Figs. 4 and 5).

Biofuels

Ukraine is the second largest country in Europe with approximately 70% of its land area being arable agricultural land. Large areas of arable land allow Ukraine to produce an abundance of biofuel resources including lignocellulosic feedstocks [23]. Energy crops commonly grown include rapeseed

Type of biomass	Theoretical potential, Mt	Potential available for energy	
		Share of theoretical potential, %	Mtoe
Straw of grain crops	32.8	30	3.36
Straw of rapeseed	4.9	40	0.68
By-products of grain corn production (stalks, cobs)	46.5	40	3.56
By-products of sunflower production (stalks, heads)	26.9	40	1.54
Secondary agricultural residues (sunflower husk)	2.4	100	1.00
Wood biomass (firewood, felling residues, wood processing waste)	8.8	96	2.06
Wood biomass (dead wood, wood from shelterbelt forests, pruning)	8.8	45	1.02
Biodiesel (rapeseed)	-	-	0.39
Bioethanol (corn and sugar beet)	-	-	0.82
Biogas from waste and by-products of agricultural sector	1.6 bln m³ CH_4	50	0.68
Landfill gas	0.6 bln m³ CH_4	34	0.18
Sewage gas (industrial and municipal wastewater)	1.0 bln m³ CH_4	23	0.19
Energy crops: willow, poplar, miscanthus (1 mln ha*)	11,5	100	4.88
Energy crops: corn for biogas (1 mln ha*)	3.0 bln m³ CH_4	100	2.58
TOTAL	-	-	23

44% (straw of grain crops to secondary agricultural residues)

32% (energy crops)

*In case of growing on 1 mln ha of unused agricultural land.

Source: UABIO calculations

Fig. 4 Biomass potential of Ukraine [22]

Fig. 5 Bioenergy growth in Ukraine [8]

and sunflower for biodiesel, corn and sugar beet for bioethanol, and corn for biogas. A 2018 report by the UABIO states that Ukraine has enough biomass to replace all gas, coal, and gasoline imports. Ukraine has 4,000,000 hectares of unoccupied agricultural land suitable for growing energy crops. As of 2018 0.1% is used for the production of bioenergy [21]. Ukraine has enormous potential for increased production of biofuels. It is estimated that during the period 2020–2050 the use of wood biomass will remain constant, whereas straw stalk, sunflower husk, agricultural residues, energy crops, biofuels, and solid waste energy production will increase. Combined biofuels have potential to reach 23 Mtoe annually by 2050 [8]. Many policies in Ukraine promote increased production of bioenergy and biofuels. Directive 2009/28/EC on the promotion of the use of energy from renewable sources, Directive 2009/30/EC regarding the quality of transportation fuels, and the bioenergy sustainability policy are expected to help guide Ukraine toward reaching its energy goals by utilizing its massive potential [22].

Energy Storage Technologies

Country's Current Implementation of Energy Storage Techniques

Ukraine has large underground gas storage facilities with a capacity of more than 31 bcm. This is a very significant amount of storage considering the approximate storage capacity of the EU is 100 bcm [7]. This massive storage capacity can be combined with the resources to increase the production of biofuels and extensive natural gas reserves.

Country's Future Storage Direction

In July 2020, DTEK signed a contract with Honeywell for a 1 MW 2.25 MWh lithium ion battery storage system. May 20, 2021, officially became the first energy storage day launching the first large-scale industrial energy storage facility in Ukraine. The storage site is located in the city of Enerhodar near the Zaporizhzhia nuclear power plant [24]. At the time of this writing, it is not known whether the battery storage facility is intact and operating due to the current conflict and Russian invasion of Ukraine.

Carbon Footprint

Most Recent Carbon Output

Methane emissions were estimated to be 38.2 Mtonnes in 2016. Nitrous oxide emissions in 2016 produced CO_2 equivalent of 35.99 Mtonnes. An additional source estimated Ukraine's CO_2 to be 223.23 million tonnes in 2019 [25]. With per capita CO_2 of 5.07 tonnes, in 2019, Ukraine's annual CO_2 emissions were 0.61% of global CO_2 emissions. In the same year, the USA's global share of CO_2 emissions was 14.50%. Ukraine experiences several periods of great economic growth that explain the sinusoidal decreasing emissions from the year 2000 until the time of this writing [26].

Historical Trends of Carbon Footprint

Ukraine has had a steady increase in CO_2 emissions from 1900 peaking in 1987 with 707.34 million tonnes. This decreasing trend continued until the year 2000 when annual CO_2 emissions began to increase again. Ukraine has shown a significant reduction in CO_2 emission nearly every year since 2009. In 2009, 302.5 million tonnes was produced decreasing between 3.4 and 51.9 million tonnes per year [2]. A UABIO 2018 report stated that 8 million tonnes of CO_2 was not released into the atmosphere due to the use of bioenergy [21] (Fig. 6).

Types and Main Sources of Pollutants

Ukraine is a member of the Paris Accord and has made commitments to decrease its carbon footprint. One of the measures is a commitment to a reduction in CO_2. The majority of CO_2 emissions historically and until the time of this writing was produced from burning fossil fuels. Emissions were produced in the following order of magnitude by different fuel types: coal 115.18 Mtonnes, oil 37.32 Mtonnes, gas 61.81 Mtonnes, flaring 2.4 Mtonnes, and other industries 2.81 Mtonnes [26]. CO_2 emissions were approximately 177.4 million tonnes in 2020 [2].

Air Quality

In 2018, the Eco City project was started by students in the city of Ivano-Frankivsk, Ukraine, to monitor public air quality. From this project, Eco City expanded air quality monitoring across the country. Large cities including Kryvyi Rih, Zaporizhzhia, Dnipro, Kharkiv, and Mariupol were covered. Results from the study show that air pollution is the highest near the largest cities, including Kyiv. Higher amounts of air pollution were shown in the Donetsk and Dnipropetrovsk regions [27]. A more recent air quality report taken from live air quality data maps shows that the air quality around the city of Kyiv improved from October 2021 to April 2022 with the average air quality of 64 on the air quality index [28]. The data show a decrease in air pollution around Kyiv which typically has the worst air quality in the country. Air quality

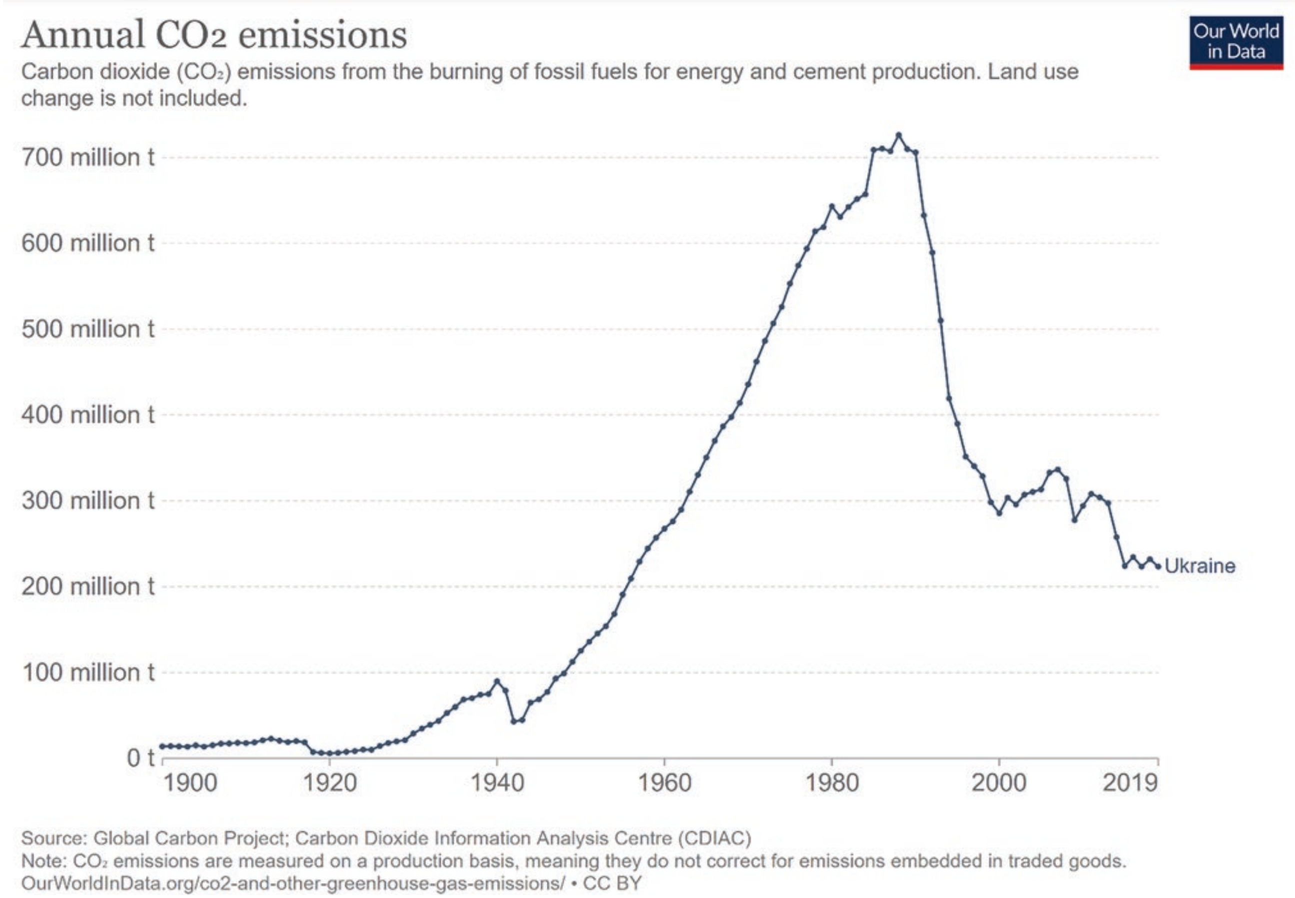


Fig. 6 Ukraine's annual CO_2 emissions [25]

data taken from Ukraine is difficult to correctly interpret after February 2022 because of Russia's invasion of Ukraine. These geopolitical circumstances destroyed and impacted cities, the electrical grid, and air quality sensors across the country (Figs. 7 and 8).

Energy Resiliency

Electrical Grid

Ukraine signed an agreement in June 2017 with the European Network of Transmission System Operators for Electricity (ENTSO-E) appointing the state-run utility company Ukrenergo to synchronize its electrical grid with that of the continental European synchronous area (CESA) by 2026 [29]. The European Union contributed 9.0 million euro of the estimated total 53.4 million euro budget for the project. This project will restructure Ukrenergro transmission network and make the necessary upgrades to achieve grid synchronization. Additionally, nine substations will be upgraded and automated in the southwestern power grid of Ukraine [29]. These policies will help to give the transmission system the upgrade it needs to allow more renewables to connect to the grid. A report was published in the Ukrainian news wire on March 1, 2022, that the technical synchronization for the grid interconnection will take approximately 2 weeks. The European Union has been providing technical support and the necessary energy products. Ukraine showed tremendous resiliency in completing the synchronization of its energy grid to the EU energy grid in approximately 2 weeks. On February 24, the Ukrainian power grid was disconnected from the Russian power grid. Shortly after the grid disconnection, Russia invaded Ukraine. Its grid showed tremendous resiliency in being able to keep energy flowing throughout wartime. According to a news report from the *Fortune* magazine, the Ukrainian power grid was successfully synchronized with the EU grid on March 16, 2022 [33].

Grid Resiliency

Many of the electrical systems and components are still vulnerable to cyber-attacks. It was suspected in 2016 that portions of the electric grid in Ukraine were brought down by a Russian state-approved cyber-attack.

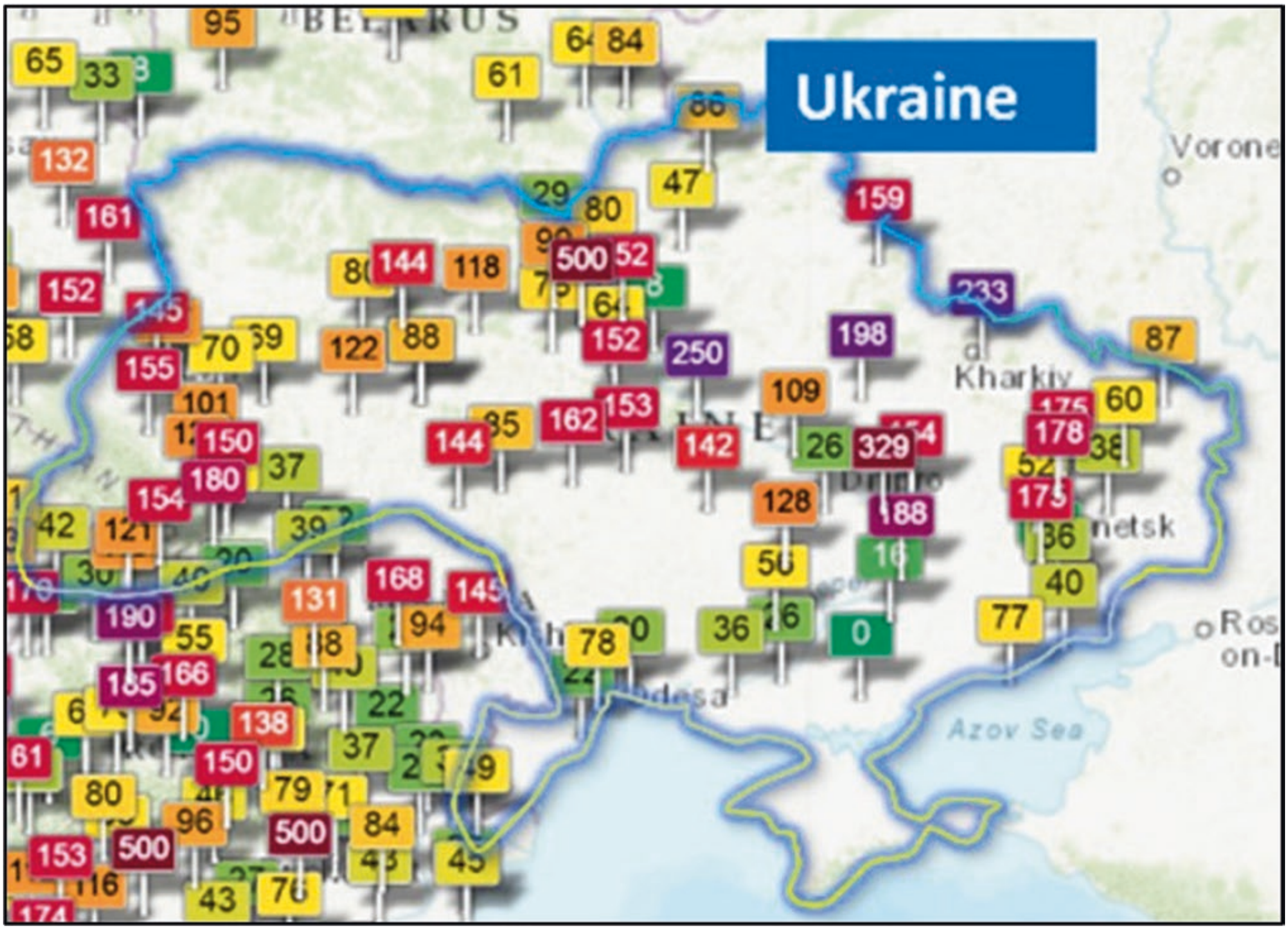


Fig. 7 Real-time air quality map (October 30, 2021) [27]

Education

Ukraine has focused a great deal of attention to research and development of its nuclear energy sector. This research includes materials science, nuclear safety, and computer simulation software. Ukraine participates in co-funded research with other EU countries under the Euratom framework programs. They also participate in the International Atomic Energy Agency (IAEA) and the International Project on Innovative Nuclear Reactors (INPRO) [27]. Ukraine has many technological universities across the country with an average of 140 masters students graduating every year with degrees in nuclear energy [27].

Summary

Current Energy Situation

Ukraine has a diverse energy profile with energy generation from fossil fuels and renewables. It has large amounts of coal, natural gas, and crude oil reserves. At the time of this writing, current natural gas and crude oil consumption exceeded production. Still it consumes more petroleum products and crude oil than it produces. Ukraine has a large nuclear energy generation capacity. Much of its energy generation capacity currently comes from nuclear power.

Ukraine has a diverse mix of renewable energy resources. About 53.2% of total capacity is generated by solar power in 2020. Hydropower is the next largest source with 35%. Wind farms add robustness to the system by adding additional capacity at night. Their extensive agricultural resources have tremendous potential to increase the nation's energy resiliency. The production of biomass and biofuels across the country plays a critical role for heating homes and buildings. Biofuels like biodiesel and bioethanol help to supplement the nation's dependency on imported oil.

The country's energy resiliency is moderately high. Its extensive and diversified resources add to the resiliency. Many parts of its electrical grid need to be upgraded to synchronize with the EU power grid. The upgrade to the power grid is a significant investment. Currently its grid is under a high risk of cyber-attack with successful attacks on energy systems in 2015 and 2016.

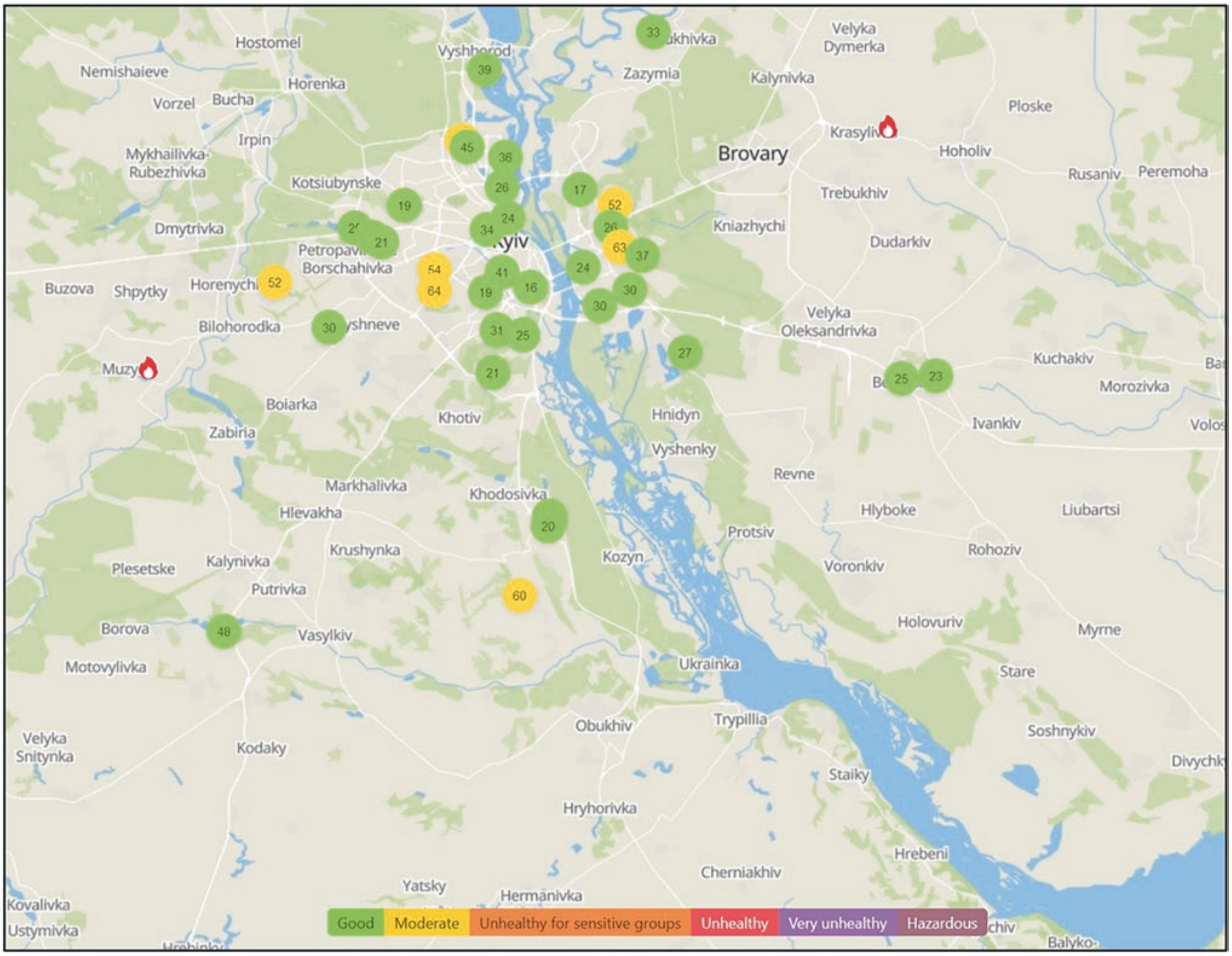


Fig. 8 Air quality map of Kiev (April 28 2022)

Future Energy Situation

Ukraine is on its way to reshaping its energy future and greatly increasing its energy resiliency. Many partnerships have already been entered into to increase energy generation capacity with multiple renewable technologies including solar, wind, hydroelectric, geothermal, nuclear, and bioenergy. Bioenergy may be the most underexploited resource across Ukraine. With a large area of arable land, Ukraine has potential to meet a majority of the its fuel needs from biofuels and sell surplus production to increase its GDP. With extensive pipeline connections it would have the ability to sell the surplus biofuel to EU countries with low tariffs.

The Energy Strategy of Ukraine 2035 and the Climate Action Plan 2030 have been designed to transform Ukraine's energy profile while strengthening grid resiliency. Synchronization of its electrical grid with that of EU and the much-needed grid upgrade are expected to greatly increase its grid resiliency. Investment in multiple technologies is poised to make Ukraine an energy exporter by 2050.

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