



# Cost, environmental impact, and resilience of renewable energy under a changing climate: a review

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## Abstract

Energy derived from fossil fuels contributes significantly to global climate change, accounting for more than 75% of global greenhouse gas emissions and approximately 90% of all carbon dioxide emissions. Alternative energy from renewable sources must be utilized to decarbonize the energy sector. However, the adverse effects of climate change, such as increasing temperatures, extreme winds, rising sea levels, and decreased precipitation, may impact renewable energies. Here we review renewable energies with a focus on costs, the impact of climate on renewable energies, the impact of renewable energies on the environment, economy, and on decarbonization in different countries. We focus on solar, wind, biomass, hydropower, and geothermal energy. We observe that the price of solar photovoltaic energy has declined from \$0.417 in 2010 to \$0.048/kilowatt-hour in 2021. Similarly, prices have declined by 68% for onshore wind, 60% for offshore wind, 68% for concentrated solar power, and 14% for biomass energy. Wind energy and hydropower production could decrease by as much as 40% in some regions due to climate change, whereas solar energy appears the least impacted energy source. Climate change can also modify biomass productivity, growth, chemical composition, and soil microbial communities. Hydroelectric power plants are the most damaging to the environment; and solar photovoltaics must be carefully installed to reduce their impact. Wind turbines and biomass power plants have a minimal environmental impact; therefore, they should be implemented extensively. Renewable energy sources could decarbonize 90% of the electricity industry by 2050, drastically reducing carbon emissions, and contributing to climate change mitigation. By establishing the zero carbon emission decarbonization concept, the future of renewable energy is promising, with the potential to replace fossil fuel-derived energy and limit global temperature rise to 1.5 °C by 2050.

**Keywords** Renewable energy · Renewable costs · Climate change · Decarbonization · Biomass · Solar photovoltaics

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*Disclaimer* The views and opinions expressed in this review do not necessarily reflect those of the European Commission or the Special EU Programmes Body (SEUPB).

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## Abbreviations

LCOE The levelized cost of energy  
IRENA International renewable energy agency

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HECAM II	Hydropower's environmental costs analysis model
ELCC	Environmental life cycle costing

## Introduction

Due to their high energy density, fossil fuels are the primary energy source worldwide; however, fossil fuel combustion produces greenhouse gases; approximately 35% of greenhouse gases are emitted by existing power plants (Maamoun et al., 2020). In addition, China's coal-fired power plants emit 42% of nitrous oxides and 38% of sulfur dioxides, for a total of 40% of the heat-trapping greenhouse gases, thereby increasing global temperature (Yang et al., 2020). Over 300 natural disasters were caused by climate change in 2018, affecting more than 68 million people and causing approximately \$131.7 billion in economic losses, with storms, wildfires, floods, and droughts accounting for 93%. Particularly alarming is the fact that the wildfire's financial losses in 2018 are nearly equivalent to the decade's total losses. Moreover, food, crop yields, water, health, the occurrence of infectious diseases, human habitats, infrastructure, and ecosystems are vulnerable to climate change (Farghali et al., 2022; Fawzy et al., 2020).

It is anticipated that energy demand will increase by 56% by 2040 (Rahman et al., 2022). If the same policy of reliance on fossil fuels is continued, increasing energy demand will increase greenhouse gas emissions. Consequently, mitigating climate change is necessary to avoid these outcomes. Renewable energy sources play a crucial role in achieving carbon neutrality, reducing global warming and climate change, and meeting the Paris Agreements' 2 °C target.

Renewable energy sources are considered to be affordable, sustainable, and free-obtained energy. Figure 1 depicts the various renewable energy sources and their proportional contribution to electricity production.

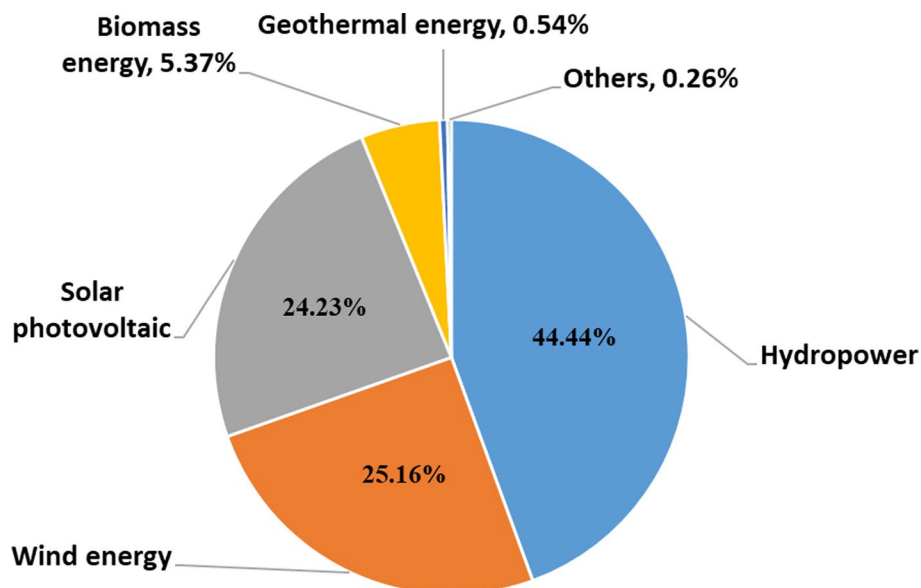
Utilizing renewables is crucial for decarbonizing the energy sector and combating climate change, but solar, hydropower, and wind availability depends on weather conditions and future climate changes. In addition, less research has been conducted on the environmental effects of using renewable energy sources. Therefore, this review was conducted to discuss (i) the most widely used renewable energy sources, (ii) the needs and costs of renewable energy, (iii) the impacts of climate change on renewable energy sources and their future prospective under climate change scenarios, and (iv) the potential environmental impacts caused by renewable energy sources and the most environmentally friendly renewable sources.

## The need for renewable energy

Almost 80% of the global population lives in countries that are net importers of fossil fuels (IRENA, 2022). Due to their dependence on foreign fossil fuels, approximately six billion people are vulnerable to geopolitical shocks and crises (AaH et al., 2021). In contrast, renewable energy sources are available in all nations, but their full potential has yet to be realized. The International Renewable Energy Agency (IRENA) estimates that by 2050, 90% of the world's energy can and should come from renewable sources (IRENA, 2018).

In addition, the excessive use of fossil fuels and non-renewable energy sources contributes to global warming by emitting large quantities of greenhouse gases (Chen

**Fig. 1** Share of renewable energy sources in electricity generation in gigawatt% from a total of 2587.6 gigawatts. The largest contributor to electricity production is hydropower. Solar and wind energy together account for 50% of the total electricity share. Geothermal, ocean, and biomass-based power plants account for slightly more than 6%. Source: Rahman et al., (2022)



et al., 2022a). Controlling greenhouse gas emissions from energy production and consumption is crucial to combating climate change. To achieve the Paris Agreement's goal of limiting global temperature rise to 1.5 °C–2 °C by 2100, energy systems require rapid, immediate, and sustained innovation and the effective use of renewable energy across all sectors (Fawzy et al., 2020). The demand and growth of renewable energy in the transportation, buildings, industrial, and power sectors are summarized in Table 1 based on the critical energy use sectors identified by the IRENA.

The urgency to combat climate change and achieve sustainable development strengthens the global renewable energy transition momentum in an era of global environmental degradation. A sustainable energy future is within reach due to the development of green buildings, green energy and power use in industry, green transportation, decreased costs of renewable energy, increased energy efficiency and continued technological advancements, and informed policymaking. This shift is gaining traction, but it must accelerate to contribute to global sustainable development. According to the development and research on the use of renewable energy in critical sectors (Table 1), the building sector accounts for 70% of the Kingdom of Saudi Arabia's energy consumption. In order to sustain the construction industry, renewable energy is essential. However, the development of renewable energy is hindered by policies, finances, technology, and culture. In addition, India's urgent need for policies promoting the use of renewable energy in the construction industry was demonstrated. According to studies, using renewable energy in the industrial sector can save money and protect the environment from the dangers of fossil fuel emissions. However, government level awareness campaigns regarding the significance of energy conservation are required.

In addition, several studies in China and Europe have demonstrated that even when a high proportion of renewable energy is used in power plants, their capacity utilization is low and that renewable energy exhibits significant monthly variations, resulting in seasonal or even interannual structural imbalances in energy supply. The study concluded that by 2020, Ireland had achieved a 15% contribution of renewable energy in transportation. In Denmark, however, sustainable bioenergy consumption is possible if 100% renewable energy systems are utilized in the transportation sector, which is technically feasible given that the costs are comparable to those of fossil fuel alternatives. Thus, renewable energy can theoretically replace fossil fuels in the four key sectors, but policy and culture influence renewables in practice. In the future, there will also be a need for greater government and relevant authority support for the use of renewable energy, as well as the promotion of energy conservation and renewable energy acceptance campaigns.

This section examines the need for renewable energy in four key sectors across multiple nations. The research demonstrates that policy, technology, finance, and culture influence the use of renewable energy. Therefore, global support for adopting renewable energy and developing policies to promote sustainable development will need to be strengthened in the future.

## Types of renewable energies

Renewable energy is energy that is derived from natural resources. In order to achieve carbon neutrality, the global share of renewable energy is projected to increase from 14% in 2018 to approximately 74% in 2050, requiring an eightfold annual increase. Renewable energy can be evaluated from the perspective of sustainability and its technical characteristics, such as integration with other resources, energy efficiency, and operating costs (Bortoluzzi et al., 2021). These factors assist policymakers in selecting a specific renewable energy source to meet market demand. Identifying the most viable renewable energy source is essential; consequently, defining the renewable energy resource is vital.

Accordingly, renewable energy technologies reported in the literature are categorized, as depicted in Fig. 2, into (i) solar energy, also known as photovoltaic energy, and generated from sunlight (Bortoluzzi et al., 2021; Farrell et al., 2019). Solar energy includes solar photovoltaic grid-connected, solar photovoltaic isolated, and thermal solar energy (Bortoluzzi et al., 2021; Karunathilake et al., 2019; Pang et al., 2022). This energy source is one of the most rapidly expanding clean sources of global energy production (Campos-Guzmán et al., 2019). (ii) Wind energy is the utilization of wind power to generate electricity for residential and industrial use (Konneh et al., 2019; Ren and Lutzen, 2017). A wind turbine is utilized for the conversion of wind energy to electricity. The wind operation can primarily be used as a small-scale wind energy system, which supplies specific regions, and a wind-connected energy grid system, which makes it possible to construct electricity grids similar to wind farms (Bortoluzzi et al., 2021; Yazdani et al., 2018). Wind and solar energies are two sources of clean energy, but they are weather-dependent. Thus, it is essential to consider weather changes when choosing such energy sources (Campos-Guzmán et al., 2019). (iii) Geothermal energy is derived from the earth's heat or the steam of hot rocks (Bortoluzzi et al., 2021). Geothermal energy can provide industrial-scale electricity and heat (Rani et al., 2019). (iv) Biomass energy is derived from both plant and animal sources. The energy is produced through the combustion of wood, agricultural residues such as crop and animal waste, and other organic feedstocks (Osman et al., 2019a). Biomass is incinerated to generate heat and/or electricity or converted into biofuel and

**Table 1** Necessity and growth of renewable energy worldwide. The demand for development and growth of renewable energy in various countries' building, industrial, power, and transportation sectors are mentioned. Multiple sectors, along with the year, country, project description, and key findings relating to renewable energy are reported

Sector	Year	Country/Agency	Project description	Key findings	Reference
Buildings	2012	Kingdom of Saudi Arabia	Renewable energy for the development and future of zero-energy residential buildings	The study indicates that residential buildings account for 70% of energy consumption in the Kingdom of Saudi Arabia. Energy-efficient and environmentally friendly buildings must be constructed and powered by renewable energy to encourage sustainable development. However, several policies, financial, technical, and cultural barriers are impeding the development of renewable energy sources, and the country must develop policies to overcome these obstacles	Alrashed and Asif, (2012)
Buildings	2018	India	Renewable energy technologies for sustainable development of energy-efficient buildings	The project demonstrates that promoting renewable energy technologies to meet the energy needs of buildings is one way to reduce energy consumption from using fossil fuels in building operations. Therefore, policies are required immediately to establish globally integrated renewable energy systems	Chel and Kaushik, (2018)
Industry	2017	International Energy Agency	Renewable energy for industry, from green energy to green materials and fuels	The report examines various current and future options for increasing the use of renewable energy as a potential means of reducing industrial carbon dioxide emissions and reducing energy	Philibert, (2017)
Industry	2012	Pakistan	The need for renewable energy sources	The paper demonstrates that utilizing renewable energy sources reduces expenses and protects the environment from the potential consequences of fossil fuel emissions. The government must conduct energy-saving awareness campaigns to make people aware of the importance of saving energy	Shahzad, (2012)
Power	2017	Europe	An integrated model for variable renewable energy-based electricity supply in Europe	According to the research, even with the highest proportion of renewable energy, conventional power plants can meet between 1 and 8% of demand. Furthermore, capacity utilization is lower, with a large share of renewable energy	Gills et al., (2017)
Power	2021	China	Integration of a high proportion of renewable energy into the electricity system using the customer's energy storage	Studies have shown that renewable energy exhibits substantial monthly fluctuations, resulting in seasonal or interannual structural imbalances in energy supply. Therefore, the power system also requires seasonal flexibility to ensure reliability	Chen et al., (2021)
Transport	2015	Denmark	Smart energy systems for coherent 100% renewable energy and transport solutions	This study demonstrates that a 100% renewable energy system is technically and economically feasible, with costs comparable to fossil fuel alternatives, and can have sustainable bioenergy consumption	Mathiesen et al., (2015)

Table 1 continued

Sector	Year	Country/Agency	Project description	Key findings	Reference
Transport	2010	Ireland	Can we meet targets for biofuels and renewable energy in transport, given the constraints imposed by a policy in agriculture and energy?	This paper examines Ireland's biofuel options concerning a 10% renewable energy target for transportation by 2020, achieving a 15% renewable contribution to transportation energy	Smyth et al., (2010)

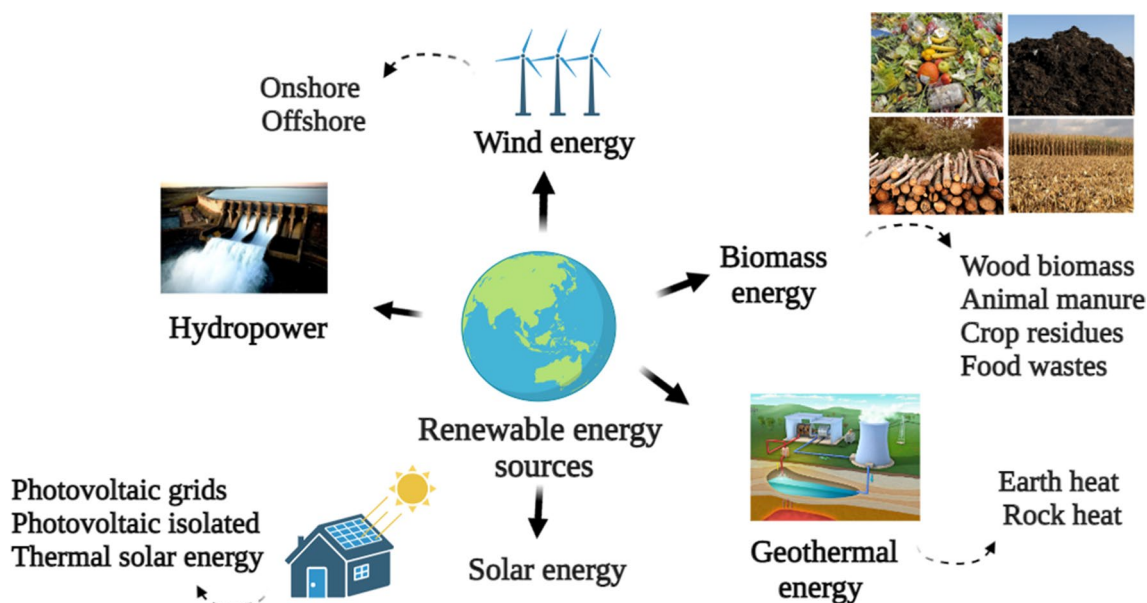
biogas using anaerobic digestion, gasification, or pyrolysis/hydrothermal carbonization (Farghali et al., 2022; Osman et al., 2021a; Rahman et al., 2022). Biomass pyrolysis produces biochar that can be used effectively for climate change mitigation as a readily available negative emission technology; this is in addition to the renewable energy produced from the process in the form of excess heat (Fawzy et al., 2022; Osman et al., 2022). Energy from waste can be considered a subset of biomass energy when waste derived from animal, human, or vegetable sources is considered (Akor et al., 2021; Al-Wahaibi et al., 2020; Osman et al., 2019b). The wastes may be incinerated or anaerobically digested to produce heat and/or electricity (Farghali et al., 2022; Osman et al., 2022, 2021b; Rahman et al., 2022). (v) Hydropower is obtained by converting the potential energy of water into kinetic energy (Çolak and Kaya, 2017). Hydroelectricity is generated by constructing dams on rivers. Water at a greater altitude is precipitated onto the hydroturbine, which generates electricity. Hydroelectricity generates approximately 1150 gigawatts on a global scale and is the largest renewable energy source (Rahman et al., 2022). Table 2 provides a comprehensive listing of the potential renewable energy sources.

### Cost of renewable energies

Renewable energy will soon be the cheapest source of energy in the majority of the world. The costs of renewable energy technologies are falling dramatically, as shown in Table 3. Between 2010 and 2021, the cost of solar energy decreased by 88% (IRENA, 2022). The costs associated with onshore and offshore wind energy decreased by 68% and 60%, respectively. Renewable energy is becoming more attractive everywhere, particularly in low and middle-income countries, where the majority of future energy demand will originate. With prices falling, a substantial portion of the future power supply will probably come from low-carbon sources. By 2030, renewable energy sources could provide 65% of the world's total electricity supply, and by 2050, they could decarbonize 90% of the electricity industry, significantly reducing carbon emissions and assisting in climate change mitigation. Although solar and wind power costs are expected to be higher in 2022 and 2023 compared to pre-pandemic levels owing to overall heightened commodity and freight prices, the International Energy Agency predicts that their competitiveness will improve due to steeper increases in gas and coal prices.

Renewable energy generation capacity introduced in 2021 was 257 gigawatts, which is 41% higher than the 182 gigawatts added in 2019. Renewable generation capacity worldwide increased more than fourfold between 2000 and 2021, from 754 gigawatts to 3,064 gigawatts (IRENA, 2022).





**Fig. 2** Renewable energy types. Various renewable energy sources can be used to produce energy that can replace fossil fuels and as a tool for climate change mitigation strategies. The most common

energy sources are solar, wind, geothermal, hydropower, and biomass. Hydrothermal is the leading energy source, with the capacity to generate 1,150 gigawatts of electricity

**Table 2** Renewable energy technologies. Multiple forms of renewable energy are utilized. Some minor sources, such as geothermal heat pumps and biomass energy, can be used for heat production. Almost primarily, renewable energy sources are used for electricity generation. Source: Karunathilake et al. (2019)

Source	Adopted technology	Energy form	Usage
Wind energy	Onshore	Electricity	Medium
	Offshore	Electricity	Low
Solar energy	Solar photovoltaics—centralized plant	Electricity	Medium
	Solar photovoltaics—building scale	Electricity	Medium
	Concentrated solar power—linear Fresnel	Electricity	Low
	Concentrated solar power—parabolic trough	Electricity	Low
	Concentrated solar power—power tower	Electricity	Low
Hydropower	Large and small hydropower	Electricity	High
Geothermal	Flashing	Electricity	High
	Heat pumps	Heat	High
	Hot dry rock	Electricity	Low
	Binary	Electricity	Low
Biomass and waste energy	Direct combustion	Heat/electricity	High
	Biomass boiler	Heat	High
	Gasification	Electricity	Medium
	Combined heat and power	Heat/electricity	Medium
	Landfill gas	Heat/electricity	High
	Anaerobic digestion—biogas	Heat/electricity	Medium

Thus, renewable energy will become the primary energy source with the lowest cost, especially when combined with the fossil fuel crisis and net-zero emission initiatives (Yang et al., 2022). Solar photovoltaics contributed the most to renewable energy addition in 2021, with an added capacity of 133 gigawatts (IRENAa, 2022). In addition, wind power capacity addition was 93 gigawatts in 2021, of which 72 gigawatts were onshore. In 2021, the generation capacity

of hydropower increased by 23 gigawatts, doubling the 11 gigawatts in 2020.

In 2021, bioenergy power generation grew by an additional 10.3 gigawatts, compared to the 9.1 gigawatts added in 2020. Away from these resources, geothermal power additions were modest in 2021, and only 110 megawatts of concentrated solar power capacity added to the grids. Therefore, the share of renewables growth for the total power

**Table 3** Renewable energy installed prices and levelized cost of electricity. All renewable energy prices were reduced in 2021, except for geothermal and hydroelectric energy. The cost of solar and wind-generated electricity per kilowatt-hour in Europe in 2021 would be four to six times less than that of fossil fuels in 2022. Given the cri-

sis in fossil fuels, the new renewable capacity added in 2021 could reduce electricity generation costs by \$55 billion in 2022. Between January and May of 2022, wind and solar generation alone in Europe prevented at least \$50 billion in fossil fuel imports. Source: IRENAa, 2022

Renewable source	Overall installment cost (\$/kilowatt)			Levelized cost of electricity (\$/kilowatt-hour)		
	2010	2021	Change %	2010	2021	Change %
Bioenergy	2714	2353	− 13	0.078	0.067	− 14
Geothermal	2714	3991	47	0.050	0.068	34
Hydropower	1315	2 135	62	0.039	0.048	24
Solar photovoltaics	4808	857	− 82	0.417	0.048	− 88
Concentrated solar power	9422	9091	− 4	0.358	0.114	− 68
Onshore wind	2042	1325	− 35	0.102	0.033	− 68
Offshore wind	4876	2858	− 41	0.188	0.075	− 60

generation capacity reached 81% in 2021, making renewables account for at least half of all new net energy additions worldwide since 2012 (IRENAa, 2022).

### Cost of solar energy

By 2021, over 843 gigawatts of solar photovoltaic systems had been installed worldwide, representing a 21-fold increase in solar energy since 2010. In addition, 133 gigawatts of newly installed systems were established during 2021 alone, which was a 13% increase from 2020. These new capacity additions were the highest among all renewable energy sources that year (IRENAa, 2022).

Solar energy costs must be quantified to promote the benefits and future of renewable energies. The levelized cost of energy (LCOE) of crystalline and amorphous silicon photovoltaic panels in different local climates was the subject of one study. The LCOE and lifetime of the crystalline silicon panels were \$0.143 (21 years), \$0.138 (32 years), \$0.172 (25 years), and \$0.159 (40 years) for mid-altitude desert, humid subtropical, humid continental, and maritime climates, respectively (Flowers et al., 2016). The amorphous silicon panels had LCOE values and life spans of \$0.141 (17 years), \$0.201 (14 years), and \$0.227 (17 years) for mid-altitude desert, humid subtropical, and maritime climates, respectively. The study identified crystalline silicon panels as the most viable due to their low degradation rates. Another research studied the LCOE of bifacial solar farms considering land and module costs. The research suggested that for places with limited and expensive land, solar panels should be laid flat to maximize land utilization. Additionally, areas with high module costs and latitudes above 300 should tilt the bifacial modules at 100–150, achieving a LCOE reduction of 2–6% (Patel et al., 2019). The authors suggest that a proper choice of photovoltaic panel technology should be implemented to achieve affordable solar energy. IRENAa

(2022) reported that in Europe, crystalline solar photovoltaics costs decreased by approximately 91% between December 2009 and December 2021.

Hybrid energy systems are essential for reducing the overall cost of renewable energy sources. Using NASA (National Aeronautics and Space Administration) and HOMER (Hybrid Optimization of Multiple Electric Renewables) data, researchers in Iran analyzed the cost of 103 hybrid solar–wind systems. The results indicated an 87–100% potential for using solar and wind energy (Jahangiri et al., 2019). The cheapest solar hybrid system at Jask station costs \$0.592/kilowatt-hour and consists of two solar cells, one diesel generator, eleven batteries, and one converter, while the cheapest wind hybrid system at Bandarabbass station costs \$0.586/kilowatt-hour and consists of one wind turbine, one diesel generator, ten batteries, and one converter. The authors emphasized that Iran's renewable energy industry faces obstacles due to the availability of inexpensive fossil fuels and the high dollar exchange rate. Solar concentrating collectors, photovoltaics, a double-effect absorption heat pump, and thermal storage were studied as another hybrid system for heating and cooling buildings. The results indicated that the solar system could provide 31.1% of a hospital's heating and cooling loads while saving 64.2% on energy costs (Chen et al., 2022b). More hybrid systems can be explored here to further reduce solar energy costs. Overall, the global weighted average levelized cost of electricity for solar photovoltaic projects established in 2021 was decreased by approximately 88% from 2010, representing a 13% year-on-year decline, from 0.055 \$/kilowatt-hour in 2020 to 0.048 \$/kilowatt-hour in 2021 (IRENAa, 2022).

In summary, the costs of solar energy are primarily influenced by technology, climate, and national policies; consequently, with advanced technology and favorable renewable energy policies, the costs will continue to decline in the future.

## Cost of wind energy

The offshore wind energy sector is one of the renewable energy sources that can operate without requiring a large amount of land; however, due to construction technology and grid connection challenges, offshore wind farms are more expensive to construct than onshore wind farms (Msigwa et al., 2022). A study was conducted on the costs of offshore wind energy in Southeast Asia, specifically Singapore, where wind conditions are unfavorable. Considering reduction potential of 14% capital costs, 63% submarine power cable costs, and 36.5% operation and maintenance costs, the study found that the LCOE of an offshore wind farm is 32 cents/kilowatt-hour, which is higher compared to solar photovoltaics, which cost approximately 12 cents/kilowatt-hour (Nian et al., 2019). The study suggested that a significant change in the levelized cost of energy (LCOE) of an offshore wind farm in Singapore could be achieved by increasing the wind power plant's load factor, which is only 12%. Enhanced turbine designs and the relocation of turbines as far as 300 km from the coast can increase the load factor. Another study was conducted in Egypt for 7 megawatts of wind turbines at various locations in the Mediterranean Sea with fixed platforms 5 km from the coast and 60 m deep (Abdelhady et al., 2017). The results indicated that capacity factors ranged from 55% to 63%, with LCOE ranging from \$0.075 to \$0.079 per kilowatt-hour, which is competitive with other renewable energies in Egypt and is half the cost of offshore wind energy in Europe. The authors recommend additional research on offshore wind farm technology to bring costs down to parity with onshore wind farms.

Due to technological advancements and favorable renewable energy costs, the wind energy industry has exhibited a declining cost trend. A study of onshore wind energy in the European Union, USA, and Norway between 2008 and 2016 revealed a trend toward larger machines with a decline in capital and financing costs. During the study period, the project capital costs decreased by 10% to €1422/megawatt, and the LCOE decreased by 33% to €48/megawatt-hour, with the decrease attributable to a change in specific power, financing, and capital costs (Duffy et al., 2020). Denmark had the lowest LCOE at €34 per megawatt-hour, while Ireland had the highest, at €68 per megawatt-hour. The price difference between Denmark and Ireland is attributable to Denmark's more favorable renewable energy policies, which reduce the cost of wind energy. Another study on Pakistan wind farms showed that the lifetime LCOE for a windfarm producing 142 gigawatt-hours per year was \$0.11371 per kilowatt-hour and \$0.04092 per kilowatt-hour for 1–10 and 11–20 years, respectively (Hulio and Jiang, 2018). The initial ten years of LCOE are more expensive due to the loan repayment and interest rates that must be paid in full during the initial ten years of the project. According to Table 3, the global

levelized cost of electricity for onshore wind projects established in 2021 decreased by 15%, from \$0.039/kilowatt-hour in 2020 to \$0.033/kilowatt-hour in 2021. In addition, the global average levelized cost of electricity for onshore and offshore wind decreased by 68% and 60%, respectively. IRENAa (2022) reported that the average global levelized cost of electricity for offshore wind decreased by 60% between 2010 and 2021, from \$0.188 per kilowatt-hour to \$0.075 per kilowatt-hour.

The average LCOE for newly constructed projects in Europe decreased by 29% between 2020 and 2021, from 0.092 to 0.065 dollars per kilowatt-hour. Between 2010 and 2021, the global average installed costs decreased by 41%, from \$4876/kilowatt to \$2858/kilowatt. Increasing developer experience, product standardization, industrialization, regional manufacturing and service hubs, and economies of scale have contributed to price reductions. These declines have also been aided by deployment and, in many cases, manufacturing policies that have facilitated growth (IRENAa, 2022).

To summarize, offshore wind energy costs are currently more expensive than onshore. Nevertheless, technological development and favorable policies further reduce costs until they are comparable.

## Cost of biomass energy

Several feedstocks and various technologies can be used to produce energy or electricity from biomass (Al-Mawali et al., 2021). The adapted technology may include biomass pyrolysis and gasification, both of which are still in the developmental phase but are being tested commercially. Direct co-firing, combustion in stoker boilers, anaerobic digestion, landfill gas, municipal solid waste incineration, and combined heat and power systems are established technologies. Available low-cost biomass, such as agricultural by-products, provides highly competitive, dispatchable sources of electricity. However, transportation costs are responsible for the high price of biomass. In Switzerland, research has been conducted on the transport of biomass, including firewood, woodchips, and solid and liquid manure, along various transport chains. The results revealed that transportation costs ranged from 24 Swiss francs/ton of dry matter for the transport of slurry by underground pipe to 340 Swiss francs/ton of dry matter for transporting coniferous wood by farmers (Schnorf et al., 2021). Due to a decrease in volume and an increase in empty trips, the transportation costs for the farmers' chain were higher. In addition, loading and unloading accounted for up to 65% of total manure transportation costs. The author suggested transporting biomass raw materials in large quantities and over short distances to reduce costs.



The cost of harvesting equipment is an additional aspect of biomass energy costs to consider. In Michigan, USA, the fixed-to-machine cost ratios for cut-to-length harvesting systems (30%, 70%, and 100%) ranged between 50% and 60%, whereas those for whole-tree harvesting systems ranged between 30% and 50% (Zhang et al., 2016). Productivity, equipment purchase price, and annual scheduled hours had the greatest effect on harvesting expenses.

Due to its availability and affordability, biomass energy is also employed in cooking. The economic viability of firewood, charcoal, biogas, jatropha oil, and crop residue briquettes was examined in Kenyan and Tanzanian villages. The calculations of life cycle costs revealed that jatropha oil had the highest costs, while firewood burned in efficient stoves had the lowest. The briquettes were competitive with charcoal. In Kitui Kenya, using advanced *maendeleo*, *rocket*, and *envirofit* stoves reduced the life cycle cost per meal by 30%, 55%, and 57%, respectively (Okoko et al., 2018). In Moshi Tanzania, using *kuni chache* and *okoa* stoves reduced the life cycle cost per meal cooked by 49% and 69%, respectively. The charcoal production in Moshi Tanzania was found to be expensive due to royalty fees charged by the government, which account for up to 80% of the cost ranging between \$0.1 and \$0.2/meal. In contrast, charcoal in Kitui Kenya was cheap, ranging from \$0.03–0.04 per meal due to the absence of royalty fees.

In addition to the commercial production of biomass energy, the residential use of biomass energy, particularly in rural areas, is a cost-sensitive; therefore, appropriate incentives are required to promote the use of low-cost biomass energy. Between 2010 and 2021, the average global LCOE of bioenergy for power projects decreased from \$0.078/kilowatt-hour in 2010 to \$0.067/kilowatt-hour in 2021, lower than the cost of electricity from fossil fuel-fired systems. The global installed price for newly commissioned bioenergy is set at \$2353/kilowatt in 2021 compared to \$2634/kilowatt in 2020 (IRENA, 2022). But the cost of bioenergy is varied between countries, with \$0.057/kilowatt-hour in India, \$0.060/kilowatt-hour in China, \$0.088/kilowatt-hour in Europe, and \$0.097/kilowatt-hour in North America. Variations in bioenergy costs are caused by several factors, such as feedstock type, feedstock cost and availability, conversion process, and power production process. Transportation, equipment, technology, and policies significantly impact the cost of commercial and residential biomass energy use.

### Cost of hydropower energy

Hydropower production costs depend on the construction, equipment, operation, and maintenance expenses. Micro-hydropower plants are necessary for rural and underdeveloped areas to have access to electricity. The cost of micro-hydropower plants utilizing locally manufactured equipment

was quantified in Nepal. The results showed that the average price per kilowatt at Crossflow and Pelton sites were \$505/kilowatt and \$605/kilowatt, respectively (Butchers et al., 2022). The generator, penstock, and turbine sub-systems account for almost half of the total costs of the hydropower plant sub-systems. The initial cost of a micro-hydropower plant is around 6 cents/hour, while solar and wind plants cost 10 cents/hour and 7 cents/hour, respectively (Elbatran et al., 2015). The cost of starting up a micro-hydropower plant is divided into civil works (40%), turbine and generator (30%), control equipment (22%), and management cost (8%). The initial costs of construction and equipment for hydropower plants are the highest, and hydropower production at a lower cost requires careful planning.

Another study used the upgraded Hydropower's Environmental Costs Analysis Model (HECAM II) to model the costs of a hydropower plant with the Bakhtiari dam in Iran as a case study. The total cost, revenue, and the benefit-to-cost ratio were \$79.13/megawatt-hour, \$203/megawatt-hour, and 2.57, respectively (Tajziehchi et al., 2022). Another research on the costs of hydropower plants in Ecuador showed that the latest Ecuador hydropower projects of Coca Codo Sinclair, Sopladora, Minas San Francisco, Delsintagua, and Manduriacu had prices that were 79%, 34%, 21%, 12%, and 119% more expensive than the IRENA's averages (Naranjo-Silva et al., 2022). In addition, the cost of hydropower energy was \$2,018/kilowatt, which is 37% higher than the IRENA 2020 cost of \$1,472/kilowatt. Without proper planning from the onset of the project, hydropower can be costly in this situation. In general, the average global levelized cost of electricity of newly commissioned hydropower systems in 2021 was \$0.048/kilowatt-hour—4% higher than the \$0.046/kilowatt-hour recorded in 2020 and 23% higher than the systems commissioned in 2010. However, this cost is still lower than the cost of the newly commissioned fossil fuel-fired systems, which range between \$0.054 and \$0.167/kilowatt-hour (IRENA, 2022).

In conclusion, the initial costs of hydropower plant construction are high relative to operation and maintenance costs; therefore, hydropower projects must be managed properly from the outset to be profitable.

### Cost of geothermal energy

The use of geothermal energy for heating buildings and water is widespread. In Geneva, Switzerland, a geothermal district heating cost analysis was conducted. The LCOE for geothermal energy alone for different decision paths was between 59 and 553 Swiss Franc/megawatt-hour (Pratiwi and Trutnevte, 2022). The lowest LCOE was obtained on the decision path of the annual heat demand of 400 gigawatt-hours/year, geothermal coverage of 40% in a centralized system, linear heat density of 8 megawatt-hours/

(meter-year), and well depth is 2500 meters with a maximum geothermal flowrate per well doublet of 80 liter/second. In contrast, the highest LCOE was on a decision path with an annual heat demand of 100 gigawatt-hours/year and geothermal coverage of 10% with a geothermal flow rate of less than 20 liter/second. Another research in Bangladesh showed that the geothermal energy costs were reduced with increasing capacity and time with a minimum price of €2.8/kilowatt-hour for a 150 megawatts plant. The initial costs of setting up the power plant are \$2500 per kilowatt, with operation and maintenance costs at \$0.01–0.03 per kilowatt-hour with 90% availability. Initial costs for geothermal power plants vary widely, necessitating careful decision-making to ensure that the energy produced is affordable.

Another research studied the environmental life cycle costing (ELCC) for enhanced geothermal systems in Reykjanes, Iceland, and Vendenheim, France. The ELCC for the Reykjanes project was about 14.47–15.78 million euros, with most costs from investment and drilling, while that of Vendenheim was about 91.90–113.97 million euros, with most costs from the plant, well drilling, and operations and maintenance (Cook et al., 2022). The mean LCOE for the Reykjanes project was €16.5/megawatt-hour/year, while that of the Vendenheim project was €45/megawatt-hour/year. In Serbia, the geothermal energy heating price was €0.37/m<sup>2</sup>, which is lower than natural gas and coal ranging between €0.99–1.17/m<sup>2</sup> (Milanović Pešić et al., 2022). Hence, geothermal prices vary widely depending on the type of power plant.

To summarize, geothermal energy prices are competitive with other energy sources and are lower than those of other energy sources; however, the costs of different power plants vary greatly depending on the technology employed.

## Impact of climate change on renewable energies

Using fossil fuels for energy production was the primary cause of climate change and global warming. Renewable energy sources are crucial in preventing carbon emissions and mitigating climate change. However, renewable resources such as solar, wind, and hydropower depend on current weather and future climate variability. Consequently, accurately evaluating the viability of a low-carbon and sustainable energy technology can be made more certain by studying the impact of future climate and estimating the variation in renewable energy sources. Climate changes, such as increasing temperatures, extreme winds, rising sea levels, and decreased precipitation, will be one of the century's greatest societal challenges. This section will examine how climate change affects various renewable energy sources.

## Impact on wind energy

Climate change may alter atmospheric dynamics, affecting wind patterns in terms of spatial distribution and temporal variability, posing a threat to wind power generation (Solaun and Cerdá, 2020). Susini et al. (2022) investigated the impact of climate change on the offshore wind energy sector in the North and Irish Seas by analyzing changes in climate averages and extreme events for the period 2081–2100 under the Representative Concentration Pathway-8.5 scenario. The results indicate a slight decrease in wind energy production and a reduction in all climate indicators (mean and extreme wind speed, wind power density, operating hours, total generation, and capacity factor). Similarly, Doddy Clarke et al. (2021) analyzed wind power generation in the Irish region offshore and onshore under Representative Concentration Pathways-4.5 and Representative Concentration Pathways-8.5 scenarios for 2041–2060 and 2081–2100, respectively. The research results also demonstrate an overall reduction in wind energy (less than 2%) in future climate scenarios. From a seasonal perspective, wind energy is expected to decrease by approximately 6% in the summer and increase slightly by 1.1% in winter. At the same time, under the scenarios that consider greenhouse gas emissions and land use; precisely, the Shared Socioeconomic Pathways-8.5 (intensive emissions) and Shared Socioeconomic Pathways-4.5 (moderate emissions) scenarios, onshore wind energy resources in North America and Canada are expected to decrease. In particular, under the Shared Socioeconomic Pathways-8.5 scenario, wind generation intensity reduces by an overall 15% and up to 40%, respectively in northern regions such as Quebec and Nunavut in Canada and Alaska in the USA (Martinez and Iglesias, 2022).

Russo et al. (2022) estimated the influence of climate change on the future of wind energy generation. The authors found a 20% variation up to 2030, a 40% variation from 2040 to 2060, and a 100% variation from 2070 to 2100. Regionally, South America will be the most vulnerable to climate change, with a 60% expected variation from 2040 to 2060, contrary to Europe, which is more stable. The results in this section show that climate change has a negative impact on wind energy. With the increase in the climate change and severe weather problems, several countries and regions worldwide would have a continuous trend of decreasing wind energy production.

## Impact on solar energy

As solar energy becomes an increasingly important renewable energy source in the future, so it is crucial to investigate the effect of climate change on solar energy's spatial and temporal variability. Oka et al. (2020) analyzed the effect of future climate change on solar energy in Fukushima

Prefecture, Japan, under three representative concentration pathways and seven global climate models. The investigation results showed that photovoltaic power generation is expected to increase under all scenarios (2030, 2050, and 2070) with average annual growth rates of 1.7%, 3.9%, and 4.9%, respectively. Meanwhile, Gil et al. (2018) used a high-resolution model to generate regionalized scenarios of climate change in Spain to study the future solar radiation resource changes in the Iberian Peninsula. The scenario analysis revealed that future solar irradiance would increase, and the solar resource quality is anticipated to improve. Russo et al. (2022) modeled a maximum of 20% variation in solar energy worldwide from 2070 to 2100. The authors emphasized that solar is the least affected energy source by climate change.

Similarly, using data from three different downscaled global climate models, de Jong et al. (2019) predicted that surface solar radiation is expected to increase over most of Brazil between 2070 and 2080 period compared to the end of the twentieth century, with a possible average increase of 3.6% in the northeastern region of Brazil. In contrast, by the end of the century, the annual average solar potential is expected to decline by an average of 4% over much of the African continent and 6% in the Horn of Africa as a direct result of decreasing solar radiation and increasing air surface temperatures, as found through the high-resolution climate experiments (Bichet et al., 2019). Losada Carreño et al. (2020) found that as a result of climate change, direct normal irradiance, global horizontal irradiance, and surface air temperature in Texas increased by 5%, 4%, and 10%, respectively; these changes resulted in an increase in the solar capacity factor from -0.6% to +2.5% for the entire state of Texas. As a result, the solar capacity factor tends to increase in regions with insufficient solar resources, while it tends to decrease in regions with abundant solar resources.

This section specifies that the effects of climate change would generally boost photovoltaic power generation, but there are some areas where solar energy becomes weaker. The research found that solar energy generation is increasing in regions with initially insufficient solar resources, while it is decreasing in regions with abundant solar resources. Therefore, the global impact of climate change on solar energy is predominantly positive, except for a few locations where solar power was originally abundant.

### Impact on biomass energy

Changes in rainfall patterns, temperature, carbon dioxide levels, drought, and air moisture caused by climate change affect biomass productivity, growth, chemical composition, and soil microbial communities (Freitas et al., 2021), thus affecting biomass energy potential. Therefore, the application of biomass energy is directly determined by the impact

of climate change on biodiversity. Nunez et al. (2019) found that the fraction of remaining species and the fraction of remaining area would decrease significantly by 14% to 35% during a global average temperature increase of 1 °C to 2 °C, representing the extinction of many species and thus the scarcity of biomass energy. It is anticipated that climate change will impact all levels of biodiversity, from species to biome, and that continued warming on a global scale coupled with more frequent extreme weather events will put more pressure on all organisms on Earth (Habibullah et al., 2022; Sintayehu, 2018). Under climate change, lignocellulosic biorefineries can be markedly affected, as shown in Fig. 3.

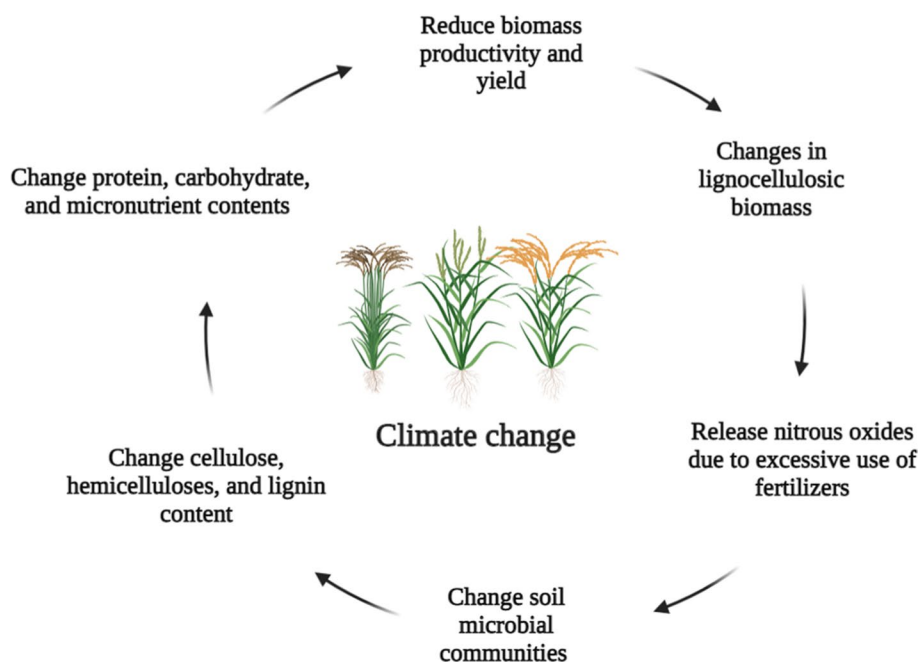
Abiotic stressors and climate change substantially impact cellulosic ethanol yields and other value-added biorefineries by reducing the availability and yield of biomass, such as energy crops or agricultural residues, and by altering the metabolic pathways of plants (Freitas et al., 2021). Zhao et al. (2017) found that a one-degree Celsius increase in temperature could reduce global wheat yields by 6.0%, maize by 7.4%, rice by 3.2%, and soybean by 3.1%. The combined stresses of high temperature and drought decreased maize and wheat photosynthesis rates, leaf, and plant length, total dry weight, and eventually plant yields (Hussain et al., 2019; Sattar et al., 2020). Climate change negatively impacts plant growth and yield, affecting bioenergy potential and food supply.

This section explains that climate change has a negative impact on biomass due to the fact that climate change issues and extreme weather can devastate certain organisms and thus reduce biodiversity. Moreover, biodiversity may restrict the use of biomass, so climate change indirectly has a negative impact on biomass.

### Impact on hydropower energy

Hydropower is an essential renewable energy source, but hydropower may be negatively impacted by climate-related changes in hydrological conditions, such as river flow and reservoir storage. Liu et al. (2016) used 8 global hydrological model simulations under climate scenario data for Representative Concentration Pathways-2.5 and Representative Concentration Pathways-8.5 to predict the future changes in gross hydropower potential and developed hydropower potential in China. The results of the study indicate that the developed hydropower potential would decrease from -2.2% to -5.4% (0.7–1.7% of the total installed hydropower capacity) in 2020–2050 and from -1.3% to -4% (0.4–1.3% of the total installed hydropower capacity) in 2070–2099. Meanwhile, by investigating Representative Concentration Pathways-2.6, Representative Concentration Pathways-4.5, and Representative Concentration Pathways-8.5 conditions, Guo et al. (2021) found that

**Fig. 3** Impact of climate change on biomass. Climate change can have a greater impact on biomass yields. In addition, climate change may negatively impact the carbohydrate–fiber structure of biomass, alter the protein and nutrient content, and negatively impact the food and bioenergy uses of crops. Reduced biomass yields and traits increase the use of chemical fertilizers, resulting in environmental pollution



the near-term hydroelectric power generation decreased by 10.981 megawatts, 12.933 megawatts, and 14.765 megawatts, respectively, and the long-term hydroelectric power generation decreased by 21.922 megawatts, 23.649 megawatts, and 26.742 megawatts, respectively. Similarly, Teotónio et al. (2017) found a potential 41% reduction in hydropower generation in 2050 by assessing the impact of climate change on the Portuguese hydroelectric system.

Precipitation and ambient temperature variations impact hydropower generations (Mello et al., 2021; Turner et al., 2017). Changes in the runoff, rainfall, streamflow frequency, and extended are among the factors affecting hydropower power production (de Jong et al., 2021; Solaun and Cerdá, 2019; Yalew et al., 2020). Russo et al. (2022) estimated that global variations in hydropower potential would fall within  $-5\%$  to  $5\%$ , with the highest effect being mid-to-long term.

This section focuses on the impact that climate change can have on hydroelectric power. Numerous simulation studies have demonstrated that the future efficiency of hydropower energy in many nations will decrease, with a maximum reduction of 41% in hydropower generation.

### Impact on geothermal energy

Geothermal energy exists as heat in the interior of the earth, and the source of this heat is related to the internal structure and physical processes that occur there. Geothermal energy is, therefore, primarily influenced by the structure of the earth's crust. Hence, Adaramola (2017) elaborates on the advantages of geothermal energy in providing base-load

power for daily human life, regardless of seasonal problems or climate change. Thus, geothermal energy can supplement intermittently generated renewable energy sources (such as wind or solar). Geothermal resources are typically located several kilometers underground (Adaramola, 2017). Meanwhile, the World Energy Assessment, the United Nations Development Programme, the United Nations Development in Economic and Social Affairs, and the World Energy Council have worked together to demonstrate that geothermal energy has the greatest potential value among all renewable energy sources. However, geothermal power development lags significantly behind wind and solar photovoltaic power at the present time (Adaramola, 2017).

This section highlighted that geothermal energy will not be affected by climate change, as it is primarily influenced by the structure of the earth's crust and the physical processes within the earth's interior.

### Impact of renewable energies on the environment

According to the World Health Organization, nearly 99% of the world's population breathes unhealthy air, and more than 13 million people die annually from preventable environmental causes, including air pollution (World Health Organization, 2022). Primarily, the combustion of fossil fuels generates fine particulate matter and nitrogen dioxide. In 2018, air pollution from fossil fuels caused daily health and economic losses of approximately \$8 billion (United Nations a, 2018). Switching to renewable energy sources,



such as solar and wind, aids in combating climate change, air pollution, and health problems. Therefore, Table 4 analyzes the positive and negative environmental effects of increasing renewable energy use in various regions.

Increasing environmental degradation and climate instability effectively force the global community to reduce carbon emissions and, as a result, reduce its impact on climate change. Renewable energy sources are one method for combating climate change, which belongs to conventional mitigation technologies. In Egypt, Nassar et al. (2019) have shown that if renewable energy is used as a permanent energy source, by the end of 2022, rocket launchers will reduce carbon dioxide emissions to  $46,405 \times 10^3$  tons of carbon dioxide, generating a price of  $\$433,427.6 \times 10^3$  based on certified emission reduction return and fuel savings would amount to 19,066 kilotons. Furthermore, according to the analysis of the environmental impact of the use of renewable energy in each country in Table 4, we find that the use of renewable energy in BRICS (Brazil, Russia, India, China and South Africa), Europe, the USA, and Japan has a positive impact on the environment, i.e., a reduction in carbon dioxide emissions over the whole life cycle, thus reducing global warming and contributing to sustainable development. In contrast, Table 4 reveals an exponential increase in total carbon emissions after installing renewable energy systems in some remote regions of India. Although studies have shown that renewable energy in remote areas can improve the quality of life of local villagers and create employment opportunities, the increased carbon dioxide emissions have a negative effect on the environment. As given in Table 4, the majority of studies conducted since 2016 indicate that the

use of renewable energy has a positive impact on the environment, which may be a result of the concerted global effort to develop and use renewable energy since the 2015 Paris Agreement to achieve a controlled global temperature rise of 1.5 °C -2 °C. Therefore, in the future, renewable energy sources such as solar, wind, and biomass will also need to be improved.

On the other hand, Rahman et al. (2022) reviewed all the environmental impacts of each type of renewable source, as shown in Table 5. The authors classified the consequences into several classes, including air, soil, water, human-related, and miscellaneous concerns. In terms of air impacts, hydroelectric power plants are primarily responsible for changes in temperature and precipitation caused by greenhouse gas emissions. Solar photovoltaics and concentrated solar power also generate greenhouse gas emissions and ozone depletion. Except for biomass energy, all renewable sources impact nature in aquatic environments. Particularly, hydropower caused eutrophication and an increase in suspended sediments. In addition to drying out rivers, altering lagoons and deltas, causing floods, and altering water temperature and oxygen levels, hydropower plants have an impact on ecosystems. The submerged power plants frequently hinder the movement of sailing vessels and disrupt the defense of the coastline. In conclusion, hydroelectric has the greatest impact on the aquatic environment, while geothermal plants and biomass have the least.

A hydroelectric power plant poses a threat to soil, specifically by causing soil desiccation and soil erosion. The hydropower generated by a dam may cause rivers downstream to dry up, causing soil degradation and further affecting

**Table 4** Environmental impact of increasing renewable energy sources. This table summarizes the environmental benefits and drawbacks of expanding the use of renewable energy in various regions

Project title	Year	Environmental impact	Region	Reference
Heterogeneous impacts of renewable energy and environmental patents on carbon dioxide emission—Evidence from the BRICS (Brazil, Russia, India, China, and South Africa)	2019	+	BRICS (Brazil, Russia, India, China and South Africa)	Cheng et al., (2019)
Social, economic, and environmental impacts of renewable energy systems	2009	–	Uttaranchal state, Tehri Garhwal district, Jaunpur block, India	Akella et al., (2009)
Environmental impacts of high penetration renewable energy scenarios for Europe	2016	+	Europe	Berrill et al., (2016)
Does nuclear and renewable energy improve the environment? Empirical evidence from the USA	2016	+	USA	Baek, (2016)
Impact of renewable energy consumption, globalization, and technological innovation on environmental degradation in Japan: application of wavelet tools	2021	+	Japan	Adebayo and Kirikaleli, (2021)
Economic and environmental benefits of increasing the renewable energy sources in the power system	2019	+	Egypt	Nassar et al., (2019)

and time periods. "+" represents a positive impact, while "-" represents a negative impact



**Table 5** Environmental effects of different renewable energy sources. Hydroelectric power plants are the most damaging to the environment compared to other renewable energy sources. Consequently, the focus of policymakers is required to prevent any upcoming concerns. Solar photovoltaics must be carefully installed to reduce environmental

impact. In comparison, wind turbines and biomass power plants have a negligible environmental impact. Therefore, they are advised to be implemented extensively. In aquatic environments, onshore plants are preferred due to their lower environmental impact. Source: Rahman et al. (2022)

	Environmental impact	Solar	Solar thermal	Wind	Biomass	Geothermal	Hydropower	
Air	Greenhouse gas emission	Moderate impact	Moderate impact	Negligible	Negligible	Moderate impact	High impact	
	Ozone layer depletion	Moderate impact	Negligible	Negligible	Negligible	Negligible	Negligible	
	Air pollution	Moderate impact	Negligible	Negligible	Negligible	Moderate impact	Negligible	
	Air toxification	Moderate impact	Moderate impact	Negligible	Moderate impact	Moderate impact	Negligible	
	Change in air temperature	Negligible	Negligible	Negligible	Negligible	Negligible	Moderate impact	
	Change in air precipitation	Negligible	Negligible	Negligible	Negligible	Negligible	Moderate impact	
Water	Water pollution	Moderate impact	Moderate impact	Moderate impact	Negligible	Moderate impact	Moderate impact	
	Water toxification	Negligible	Negligible	Moderate impact	Negligible	Moderate impact	High impact	
	The mating process of fish	Negligible	Negligible	Moderate impact	Negligible	Negligible	Moderate impact	
	Fish migration	Negligible	Negligible	Moderate impact	Negligible	Negligible	Moderate impact	
	Change in water temperature	Negligible	Negligible	Negligible	Negligible	Negligible	Moderate impact	
	Impact of water flow	Negligible	Negligible	Negligible	Negligible	Negligible	High impact	
	Change in water salinity	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	
	Effect on suspended sediments	Negligible	Negligible	Negligible	Negligible	Negligible	High impact	
	Eutrophication	Moderate impact	Negligible	Negligible	Negligible	Negligible	Negligible	High impact
	Affecting aquatic habitat	Negligible	Negligible	Moderate impact	Negligible	Negligible	Negligible	Moderate impact
	Fish decline	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Moderate impact
	Flooding	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Moderate impact
	Dried up rivers	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Moderate impact
	Water oxygen level	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Moderate impact
	Affecting deltas and lagoons	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Moderate impact
	Fisheries influences	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Moderate impact
Coastline defense	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	
Soil	Land requirement	Moderate impact	Moderate impact	Moderate impact	High impact	High impact	High impact	
	Soil pollution/disturbance	Moderate impact	Negligible	Moderate impact	Negligible	Negligible	Negligible	
	Soil toxification	Moderate impact	Negligible	Moderate impact	Negligible	Negligible	Negligible	
	Desiccated soil	Moderate impact	Negligible	Moderate impact	Negligible	Negligible	High impact	
	Soil erosion	Negligible	Negligible	Moderate impact	Negligible	Negligible	High impact	
	Affecting irrigation	Negligible	Negligible	Negligible	Negligible	Negligible	Moderate impact	
	Mangrove forests	Negligible	Negligible	Negligible	Negligible	Negligible	Moderate impact	
	Affects soil efficacy	Moderate impact	Moderate impact	Moderate impact	Negligible	Negligible	Negligible	
Deforestation	Moderate impact	Negligible	Moderate impact	Negligible	Negligible	Negligible		

**Table 5** (continued)

	Environmental impact	Solar	Solar thermal	Wind	Biomass	Geothermal	Hydropower
Human	Effect on vegetation	Moderate impact	Moderate impact	Moderate impact	Negligible	Negligible	High impact
	Seismic activity	Negligible	Negligible	Negligible	Negligible	High impact	High impact
	Relocation of wild animals	Moderate impact	Negligible	Negligible	Negligible	Negligible	Negligible
	Affecting terrestrial habitat	Moderate impact	Moderate impact	Negligible	Negligible	Negligible	Negligible
	Human health	Moderate impact	Negligible	Moderate impact	Negligible	Moderate impact	Moderate impact
	Disturbance to humans	Negligible	Moderate impact	Moderate impact	Moderate impact	High impact	High impact
	Relocation of native residents	Moderate impact	Negligible	Moderate impact	Negligible	High impact	High impact
	Visual disturbance	Negligible	Moderate impact	Moderate impact	Negligible	Negligible	Negligible
	Unpleasant smell	Negligible	Negligible	Negligible	High impact	Moderate impact	Moderate impact
	Natural esthetic affected	Negligible	Negligible	Moderate impact	Negligible	Negligible	Negligible
Miscellaneous impacts	Tourism potential affected	Negligible	Negligible	Moderate impact	Negligible	Negligible	Negligible
	Archeological places affected	Negligible	Negligible	Negligible	Negligible	Negligible	Moderate impact
	Availability based on time	Moderate impact	Moderate impact	Moderate impact	Beneficial	Beneficial	Beneficial
	Availability based on area	Beneficial	Moderate impact	Moderate impact	Moderate impact	High impact	High impact
	Power reduction after installation	Beneficial	Beneficial	Moderate impact	Negligible	Beneficial	Beneficial
	Dependency on non-renewable energy	Moderate impact	Moderate impact	Moderate impact	Moderate impact	High impact	High impact
	Battery dependency	Moderate impact	Negligible	Negligible	Negligible	Negligible	Negligible
	Installation noise	Moderate impact	Moderate impact	Moderate impact	Moderate impact	High impact	High impact
	Operation noise	Beneficial	Moderate impact	Moderate impact	High impact	High impact	High impact
	Recycling complexity	Negligible	Beneficial	Negligible	Negligible	High impact	High impact
	Chance of accident	Moderate impact	Moderate impact	Moderate impact	Negligible	Negligible	Negligible
	Water for cooling	Moderate impact	Moderate impact	Negligible	Negligible	Negligible	Negligible
	Susceptible to storms	High impact	High impact	Moderate impact	Negligible	Negligible	Negligible
Communication of species affected	Negligible	Negligible	Moderate impact	Negligible	Negligible	Negligible	
Predator inefficacy	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	
Collision or entanglement	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	
Miscellaneous impacts	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	
Impingement	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible	
Biodiversity	Negligible	Negligible	Moderate impact	Negligible	Negligible	Negligible	

vegetation and local communities. Large land areas are also required for biomass, solar, wind, and hydropower, impacting land use for agricultural purposes. Long-term land use diminishes their effectiveness and fertility, affecting wildlife and the demand for deforestation. Moreover, many power plants contribute to air and soil pollution during the installation, maintenance, and removal phases. Hydropower plants cause extreme land impacts.

Some renewable plants are disruptive to animals and people. Except for solar photovoltaics, which is noiseless during operation, almost all power plants produce noise during installation, operation, and maintenance. Wind turbines and concentrating solar power generate visual effects while floating oceanic types can hinder the movement of aircraft and sea transport. The resettlement of the resident is an additional concern. In general, hydropower and geothermal power plants impact human health most.

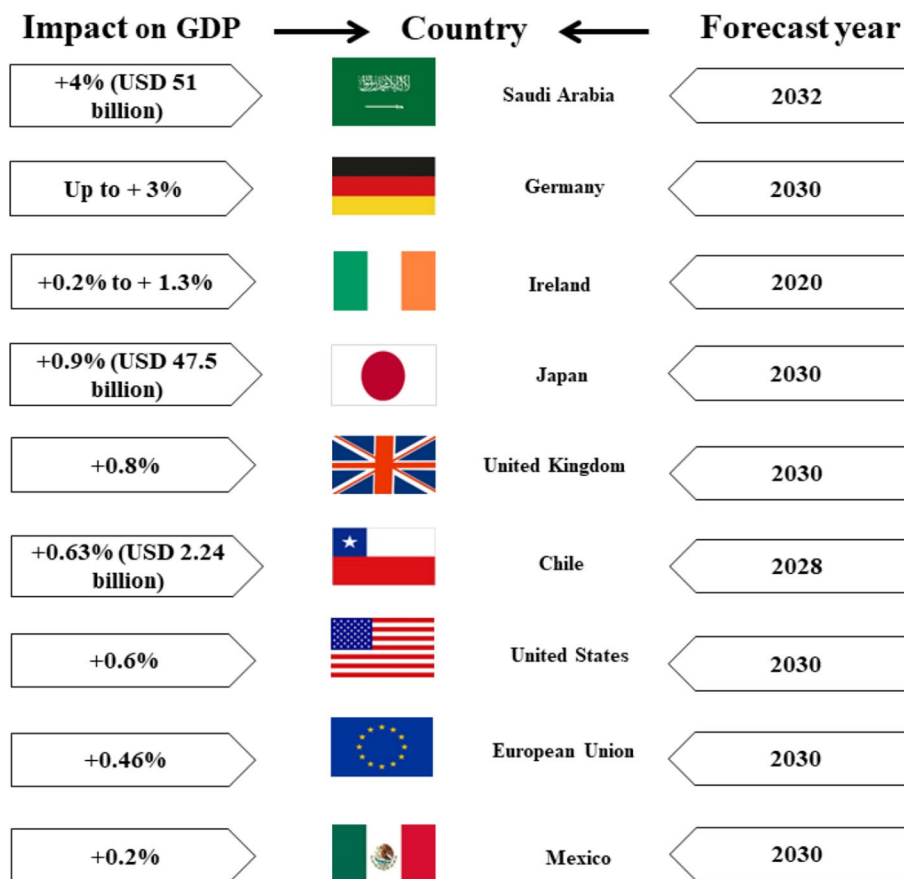
This section examines the impact of renewable energy sources on the environment. The study demonstrates that using renewable energy in most regions and nations positively affects the environment by directly reducing carbon dioxide emissions. However, renewable energy in some remote regions may have adverse environmental impact. To summarize, renewable energy is environmentally friendly and can contribute to sustainable development in the world.

## Economic impact of renewable energy

In 2020, the fossil fuel industry was subsidized to \$5.9 trillion, including explicit subsidies, tax exemptions, and unaccounted for health and environmental losses (Yale Environment, 2021). By 2030, approximately \$4 trillion per year must be spent on renewable energy, including expenditures on technology and infrastructure, to achieve net-zero carbon emissions (International Energy Agency, 2021). The initial cost may be challenging for many nations with limited resources, and many will require financial and technical assistance to complete the transition. However, renewable energy investments will be profitable. Reducing pollution and climate impacts could save the world up to \$4.2 trillion annually by 2030 (United Nations b, 2020). In addition, efficient, dependable renewable technologies may establish a system that is less susceptible to market shocks and increase energy resilience and security by diversifying power supply options. Utilizing renewable energy contributes to economic growth, generates millions of jobs, and improves people's quality of life. Consequently, Fig. 4 examines renewable energy investment and its impact in several countries.

To achieve deep decarbonization of the energy system, such an investment would have enormous socioeconomic

**Fig. 4** Renewable energy from an economic point of view. The figure analyzes the impact of renewable energy use from an economic aspect. GDP refers to gross domestic product, and USD refers to the United States dollar. Data from IRENAC (2016)



benefits and requires approximately \$130 trillion in new investments. The transformation of energy systems could add \$98 trillion to global gross domestic product (GDP) between 2016 and 2050 compared to the business-as-usual scenario, nearly triple the employment in the renewable energy industry to \$42 million, increase energy efficiency-related employment to \$21 million, and increase grid flexibility-related employment to \$15 million (IRENA, 2016). According to Fig. 4, we can observe that Ireland already has a positive impact on gross domestic product from +0.2% to +1.3% in 2020 due to the use of renewable energy. In addition, Chile expects renewable energy to contribute +0.63% to a gross domestic product by 2028, approximately \$2.24 billion. Europe, Germany, Japan, Mexico, the UK, and the USA are expected to positively impact the economy by 2030, contributing +0.46%, +3%, +0.9%, +0.2%, +0.8%, and +0.6% to gross domestic product, respectively. Saudi Arabia is expected to generate a +4% impact on gross domestic product in 2032, approximately \$51 billion. Overall, renewable energy positively impacts most countries' economies, with a relatively significant contribution of 4% to Saudi Arabia's gross domestic product and a relatively small impact of 0.2% on Mexico's gross domestic product. The research demonstrates that using renewable energy will contribute to the growth of national economies.

This section examines the economic impact of renewable energy use in several nations. The study demonstrates that using renewable energy will directly increase gross domestic product (GDP) and improve the economy, with the highest expected growth rate of +4% in Saudi Arabia and the lowest expected growth rate of +0.2% in Mexico.

## Renewable energy and decarbonization by countries

### Asia

China has made significant advances in the research and development of renewable energy technologies, as evidenced by the consistent growth and improvement of low-speed wind power generation technologies, wind power consumption and grid technologies, and energy storage technologies. China provides approximately two-thirds of the world's solar panels and nearly 50% of the world's wind turbines (Liu, 2019). Developing a hydrogen energy system based on a multi-energy complementary system simultaneously increases renewable energy consumption, thereby reducing the negative impact on the grid system (Li et al., 2020). The Chinese government has clearly defined the medium- and long-term development goals and directions in terms of geothermal energy. China will continue to promote geothermal

heating, geothermal water heating, and underground source heat pump technology to meet environmental and water conservation requirements (Hou et al., 2018). India has taken various measures to enhance the use of renewable energy and decarbonization, including improving energy entrepreneurship, democratizing energy trade, allowing private sector participation in energy trade, rationalizing renewable energy procurement, using strict and regulated energy auction procedures, fostering reputable stakeholders, developing and leveraging venture capital, periodically revising tariffs, regulating polluting industries, tracking renewable energy procurement channels in the long term, and incentivizing green energy imports (Thapar et al., 2016). The Japanese government has proposed the concept of "benchmark utilization," which requires power companies to fulfill yearly renewable energy development and utilization obligations. Otherwise, the government will be forced to carry out the enterprise's regular rectification and may even impose a high fine of 1 million yen (Liu, 2019).

This section focuses primarily on the development strategies for renewable energy utilization in China, India, and Japan. China has developed specific technologies for low-speed wind power generation, wind power consumption, electricity grid technology, and energy storage. China also adopts geothermal heating, geothermal water heating, and underground source heat pump technologies as significant development directions. India has taken numerous steps, primarily relating to the renewable energy market and decarbonization policy. The Japanese government has implemented the concept of "baseline utilization" in an effort to expand the use of renewable energy.

### Africa

Nigeria utilizes distributed generation models and smart grids to increase the use of renewable energy and decarbonization. The use of distributed generation will ensure that electricity production is not dependent on a centralized grid that is occasionally disrupted. Connecting distributed generation to the grid creates a smart grid and rationalizes the electrical infrastructure (Ogbonnaya et al., 2019). South Africa offers a range of programs for renewable energy manufacturing and funding mechanisms for renewable energy project development, including the establishment of a Green State Fund and a Memorandum of Agreement with the Development Bank of Southern Africa, the Industrial Development Cooperation Green Energy Efficiency Fund to provide loan incentives, registration of renewable energy technologies with the Clean Development Mechanism, and the possibility of generating carbon credits for market-based carbon financing (Msimanga and Sebitosi, 2014).

This section examines the implementation of renewable energy strategies in the African countries of Nigeria

and South Africa. Nigeria has adopted distributed generation, created a smart grid to increase the use of renewable energy, and optimized the nation's electricity infrastructure. Meanwhile, South Africa offers various renewable energy manufacturing programs and financing mechanisms for renewable energy project development to encourage renewable energy technologies and make solar energy the primary focus of renewable energy technology development.

## Europe

The government of the UK has adopted distributed energy measures to facilitate the integration of renewable energy into the future grid, thereby reducing energy centralization and removing capacity constraints. In addition, the government has provided additional assistance for the private sector to fully integrate distributed energy sources to reduce the complexity of the financial and energy markets (Raybould et al., 2020). Within the UK, the Welsh region has the potential to develop a wide range of marine renewable technologies because of the region's tidal solid content, high tidal energy areas, and limited space for wave energy resources. The UK government has introduced the Tidal and Wave Energy Demonstration Zone to facilitate importing equipment from companies worldwide with the related technologies (Roche et al., 2016). Belgium has the largest scale, composition, and efficiency of public research and development funding invested in European innovation for renewable energy technologies. Green technology research receives 35% of the European Union's total budget of 95.5 billion euros. Belgium has the highest proportion of available public research and development support, at 63%. As a result, Belgium focuses not only on producing renewable energy technologies at the national level but also on the efforts of scientific and technological researchers, allocating a substantial amount of funding to green technology research (Gasser et al., 2022).

This section examines renewable energy initiatives by reviewing the UK and Belgium in Europe. The government of the UK has adopted distributed energy measures to reduce energy concentration and make room for renewable energy development. Simultaneously, the UK has been developing marine renewable energy technologies, and the government has established demonstration zones for tidal and wave energy to attract investment in renewable energy technologies. From the national government to frontline researchers, Belgium is committed to developing renewable energy technologies and has received substantial European Union funding for green technology research.

## Oceania

Australia was the first nation to legislate a renewable energy development target in 2001 when Australia enacted a mandatory renewable energy target. Specifically, Australia has widely implemented incentives such as financial subsidies, tax breaks, and credits in numerous areas of renewable energy use, particularly the transportation sector, which has a high energy demand. Grants of up to a maximum of 20,000 Australian dollars and a reduction of 0.38 Australian dollars per liter of ethanol in the federal excise tax are available to E10 ethanol blend operators (Nelson et al., 2013). The New Zealand government has adopted an energy efficiency policy and has set a target of 90% renewable energy by 2025. The use of distributed generation technologies, the development of battery storage technologies, and the large-scale use of smart grids and electric vehicles are relevant and practical measures that New Zealand is taking to meet renewable energy targets (Verma et al., 2018).

This section examines the actions taken by Australia and New Zealand in Oceania to promote renewable energy development. Australia has implemented numerous incentives, including financial subsidies, tax breaks, and credits, to encourage the growth of the renewable energy sector. In the meantime, New Zealand has developed energy efficiency policies and promoted the use of distributed generation technologies, the development of battery storage technologies, smart grids, and the widespread adoption of electric vehicles.

## North and South America

Policymakers in the USA have increased renewable energy production by encouraging industrial output in the industrial sector with tax credits and subsidies. In addition, policymakers have protected renewable energy producers by establishing dedicated funds for them and proposing market-specific financing schemes (Jamil et al., 2022). The systematic use of energy auctions in Brazil to support public policies has resulted in energy security, improved electricity efficiency, and increased energy supply diversification, particularly for renewable energy. Energy auctions have been incorporated into Brazil's electricity market and can be incorporated into the country's institutional and policy framework (Tolmasquim et al., 2021).

This section summarizes the US and Brazilian renewable energy development strategies. In order to support renewable energy businesses, policymakers in the USA have promoted renewable energy production through tax breaks and economic subsidies and have introduced specific financing schemes for renewable energy markets. Systematically, in Brazil, energy auctions have been used to support public



**Table 6** Cost-effective use of renewables in different countries. The specific strategies for developing renewable energy in different countries and regions are listed. This includes various continents, countries, and cost-effective renewable energy solutions

Continents	Country	Cost-effective solution of renewables	Reference
Asia	China	Using low wind speed power generation technology, wind power consumption technology, grid technology, and energy storage technology Geothermal energy is a priority, and geothermal heating, geothermal water heating, and ground source heat pump technologies are used	Hou et al., (2018); Li et al., (2020); Liu, (2019)
	Japan	Introduced the “baseline utilization” concept	Liu, (2019)
	India	Encourage private renewable energy markets and track renewable energy procurement channels Standardize energy procurement process and auction process Update and revise tariffs on the renewable energy industry to restrict polluting industries and encourage renewable energy imports	Thapar et al., (2016)
Africa	Nigeria	The adoption of distributed electricity generation and the establishment of smart grid systems	Ogbonnaya et al., (2019)
	South Africa	A range of renewable energy manufacturing schemes and financing mechanisms are available for renewable energy project development Developed solar energy as a long-term policy and energy roadmap for developing renewable energy use	Msimanga and Sebitosi, (2014)
Europe	UK	Distributed energy measures have been adopted Development of marine renewable energy technologies, and the government has launched tidal and wave energy demonstration zones to attract investment for renewable energy technologies	Raybould et al., (2020); Roche et al., (2016)
	Belgium	The Renewable Energy Technology Research Group was established and received significant funding from the European Union for renewable energy technology research	Gasser et al., (2022)
Oceania	Australia	Incentives such as financial subsidies, tax breaks, and credits are implemented to support the development of the renewable energy sector	Nelson et al., (2013)
	New Zealand	Develop energy efficiency policies and promote the use of distributed electricity generation technologies, the development of battery storage technologies, and the large-scale use of smart grids and electric vehicles	Verma et al., (2018)
North and South America	USA	Develop tax breaks and economic subsidy policies to promote renewable energy production Introduce specific financing schemes for the renewable energy market	Jamil et al., (2022)
	Brazil	Systematic use of energy auctions as a tool to support public policies	Tolmasquim et al., (2021)

policy and promote the diversification of renewable energy supply.

Based on the development of renewable energy and decarbonization strategies for various nations, we have compiled Table 6 as a summary. The survey results indicate that the specific measures for developing renewable energy in each nation are divided into government policy support and research on renewable energy technologies, which can provide guidance for nations that have not yet developed renewable energy use. Reducing taxes on renewable energy can be an effective incentive for companies to expand their renewable energy projects. At the same time, improving renewable energy laws and regulations can better regulate

the energy trade market and strengthen the capital injection mechanism. Since each country has a unique geographical location, each nation's renewable energy advantages vary, and other regions must concentrate on developing renewable energy with inherent advantages.

## Conclusion

Here, we reviewed the potential of renewable energy sources in decarbonization policy and the impact of climate change on the expansion of renewable energy sources. About 80% of the world's population resides in net importers of fossil

fuels, leaving approximately 6 billion people susceptible to geopolitical shocks and energy crises. In contrast, renewable energy sources are available in all nations, but their full potential is not being realized. By 2050, approximately 90% of the world's energy will come from renewable sources. Excluding geothermal and hydropower-derived energy, renewable energy technology costs have decreased significantly since 2010. In Europe, the cost of solar and wind-generated electricity per kilowatt-hour in 2021 was four to six times less than that of fossil fuels in 2022. Between January and May of 2022, wind and solar generation alone in Europe prevented at least \$50 billion in fossil fuel imports. With prices declining, new power supply has a significant portion of the future to supply 65% of the world's total electricity by 2030 and to decarbonize 90% of the electricity industry by 2050, thereby drastically reducing carbon emissions and contributing to climate change mitigation.

Understanding the effects of climate change on producing renewable energy is crucial for achieving a sustainable future. Wind, hydropower, biomass, and geothermal energy were found to have the greatest effects, while solar energy had the least. Long-term climate change has a greater impact than short and medium-term climate variations. In addition, future decarbonization efforts are necessary for expanding and establishing renewables to reduce reliance on fossil fuels, save the environment from pollution and climate change, and reduce dependence on fossil fuels. Future research should emphasize increasing climate model estimates to evaluate the entire energy generation system rather than focusing solely on a single energy source to identify decarbonization strategies.

In this review, the environmental effects of renewable energy sources have also been thoroughly investigated. Consideration is given to all renewable energy sources, including solar, wind, hydropower, geothermal, and biomass. Each renewable energy source has different environmental impacts depending on the renewable energy source type, location, scale, and implementation method. However, these effects can be mitigated through careful choice and utilization of renewable energy sources. Using a building's rooftop, for instance, the impact of solar power on land can be significantly mitigated. Considering the severity of the environment, hydropower plants are the most harmful renewable energy source. Future actions should be taken to prevent hydropower plants and restore typical rivers once dependence on fossil fuels is eliminated. Wind and biomass energy are the most environmentally friendly energy sources.

To achieve net-zero emissions by 2050, renewable energy sources must be established by 2030 at the cost of \$4 trillion annually. The initial expense may be prohibitive for many nations, which may require financial and technical assistance to complete the energy transition. However, by achieving net-zero carbon emissions, renewable energy investments

will be profitable and could save up to \$4.2 trillion annually. Additionally, renewables are less susceptible to market shocks and increase each country's energy security. Understanding the role of renewable energy implementation in all nations to reduce reliance on fossil fuels and mitigate climate change will aid policymakers and decision-makers in promoting the widespread use of renewable energy sources, particularly environmentally friendly ones.

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