Strategies for Sustainability

Francisco J. Lozano
Alberto Mendoza
Arturo Molina *Editors*

Energy Issues and Transition to a Low Carbon Economy

Insights from Mexico

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Editors

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Editors
Francisco J. Lozano
Tecnológico de Monterrey
Toluca, Mexico state, Mexico

Alberto Mendoza
Tecnológico de Monterrey
Monterrey, Nuevo León, Mexico

Arturo Molina
Tecnológico de Monterrey
Mexico City, Mexico

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For the support of my wife Luz María, son Rodrigo and daughter Fabiola, the latter two being my future generation that needs a sustainable world for their well-being; also, to the memory of my late father, who fostered the education betterment of their sons and daughters.

Francisco J. Lozano

To my wife Silvia, daughter Monserrat and son Julio

Arturo Molina

To my wife Gabriela and daughters Fernanda and Miranda

Alberto Mendoza

Foreword

Eppur si muove!

(Albeit it does move!)

Attributed to Galileo Galilei

Against continuing fossil fuels use, antagonising renewable energy

On fostering and promoting renewable energy sources and efficiency for the future

Never give in, never give in, never, never, never, never—in nothing, great or small, large or petty—never give in except to convictions of honour and good sense.

Winston Churchill

This book is dedicated to future generations of Mexicans, all of whom deserve a better world, with safe and sound energy, from renewable sources, but without the deleterious environmental and social costs inherent in burning fossil fuels. That is, despite the false ideological discourse from the government, denigrating renewable energy sources and blocking their widespread use.

Anno Domini 2020

Francisco J. Lozano
Tecnológico de Monterrey, Campus Toluca,
Mexico state, Mexico

Preface

Present-day economies function effectively by using vast amounts of energy derived from various sources, mainly fossil fuels. Minimising climate change and its associated risks for a transition to low-carbon economies, relying strongly on renewable sources, is a moral imperative, as well as a surviving and sustainable strategy.

Mexico and the USA share a long border where trade, people travelling, as well as energy are exchanged. The energy reform in Mexico that was approved in December 2013 allows both countries to participate closely in the energy market between them.

Energy has to be approached in a systemic frame of reference, where many human knowledge disciplines come together; hence, there is a need to consider them as an interconnected web, understanding their resonance; also, developing in-depth knowledge for each discipline is a necessity. Complexity in energy generation, its use and management, as well as their social and environmental impacts, has to be considered in any country. In addition, present-day economies, in an era of globalisation, need to foster collaboration between nations regarding energy issues.

Hence, the chapters of this book aim at presenting a systemic approach regarding energy, within the encompassing frame of reference provided by sustainable development. First, we consider the historical context discussion on energy from different sources, as well as their main uses. Public policy provides the laws and regulations that support collective action in countries, as well as the interaction between them; hence, this issue is discussed linked to environmental policy and the relation of both to economic development.

For transitioning towards a low-carbon economy, a *sine qua non* condition is increasing fossil fuel use efficiency to attain thermodynamic and material limits using present-day technologies. At the same time, we shall witness a market evolution wherein renewable sources need to be considered.

Energy markets will evolve in two ways: First, grid interconnection between different countries will be needed, with respect to AC and DC currents; second, distributed renewable source penetration will appear increasingly as economies deepen their transition.

From the policy, economic and technical points of view, considering electricity generation through distributed renewable sources and its proper management to avoid brownouts and blackouts will require a newer systemic outlook. The latter will include proper grid planning that considers this type of generation, along the appearance of electric transport and corresponding charging node infrastructure, wherein micro-grid design, devices deployment and maintenance are part of the transition to a low-carbon economy.

Besides, the need to assess the use of residual biomass from agricultural and forestry produce, considering their spatial and time distribution in order to generate either electricity or thermal energy, is taking shape nowadays.

Upon formulating the policy, regulations, economic feasibility and technical issues, a proper decision-making tool needs to be generated for those in charge of the decision-making.

Collaboration between Mexico and the USA for the aforementioned energy transition is addressed in some of this book's chapters to strengthen and set the foundations for a common border energy market, as well as to suggest a policy frame of reference that takes into account the respective commonalities, and differences, for each country. The actual research effort themes come from the Binational Laboratory for the Smart Management of Energy Sustainability, where funding has been provided by the Mexican Ministry of Energy and the National Council for Science and Technology (CONACYT).

Toluca, Mexico — Francisco J. Lozano
Monterrey, Mexico — Alberto Mendoza
Mexico City, Mexico — Arturo Molina

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An Insight How to Read the Book

The present book conveys a systemic approach to sustainable energy in Mexico, and several knowledge disciplines have contributed to the task.

Some readers might be inclined to delve preferably in certain disciplinary approaches.

First, and those with specific disciplinary interest, this summary is intended to help the readers make their choices.

A simplified concept map is shown in Fig. 1, where the interconnected complexity for the book chapters is presented.

Chapter 1 presents a short historical context for energy, emphasising at the end the energy mix used presently in the world economy, underlining the importance of energy intensity as a measure of wealth generation and energy efficiency.

Public policy is addressed in Chap. 2, linking energy and environmental policies and the way they interact to foster economic development and growth.

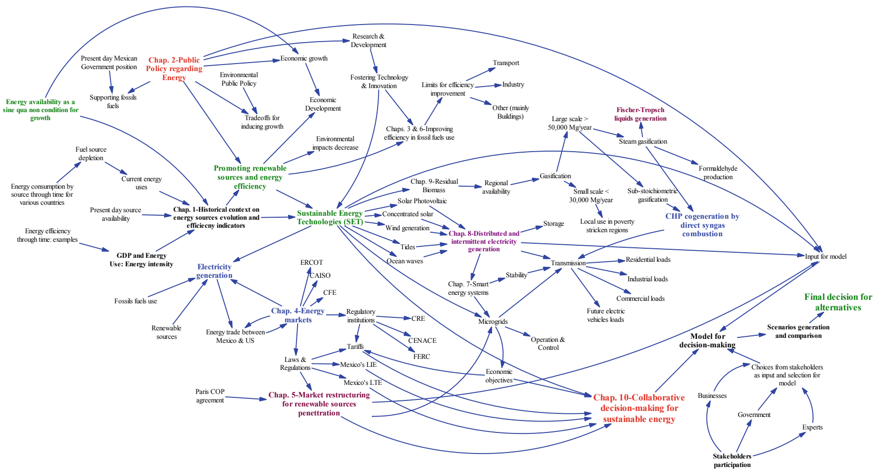

Fig. 1 Simplified concept map for book content

Chapter 3 provides and overall view for efficiency in three main economic sectors: industry, transport and buildings

The economic stance is presented in Chaps. 4 and 5. First, Chap. 4 comments on differences between submarkets in Mexico's northern region and California and Texas regions. By comparing regulations, prices, installed generation, transmission lines extension, renewables pe rcent, while Chap. 5 develops markets restructuring needs to incorporate renewable sources as a frame of reference for a sustainable future. Furthermore, discussing Mexico's Energy Law (LIE) and the Energy Transition Law (LTE), as well as the technology drivers to foster the transition.

Present-day importance of fossil fuels use implies the relevant issue for their efficient use. Converting the largest ratio of energy embedded in the fuels to usable power. Chapter 6 discusses this efficiency with a detailed discussion for energy efficiency in Mexico regarding the transport sector.

Electricity generation from renewable sources and the trends and challenges are presented in Chaps. 7 and 8. The relevance of intermittency and the need to use microgrids for a sustainable approach to renewables are in Chap. 7, as part of smart systems. Their inherent implications for operation and control are presented, along their environmental, economic and technical objectives. In Chap. 8 the trends and challenges facing the sustainable generation, transmission and distribution for electricity are presented; the role played by several renewable energy sources is discussed.

The potential to use residual biomass from several crops in Mexico to generate electricity or Fischer–Tropsch liquids is in Chap. 9, where a geographic information system (GIS) is used as a basis to allocate the biomass to specific processing sites to maximise profit.

Finally, Chap. 10 provides a decision-making approach through a collaborative approach to select between different scenarios, taking into consideration the knowledge presented in the previous chapters. Different stakeholders can participate in the process, wherein their specific points of view can be incorporated as input in the model.

Contents

Chapter 1
Historical Context and Present Energy Use in the Global Economy

Arturo Molina, Alberto Mendoza, Francisco J. Lozano, Luis Serra-Barragán, and Alejandro Ibarra-Yunez

Abstract This chapter will provide a starting point; covering a brief evolution of energy sources through time and considering the intensive use of fossil fuels and the increasing use of several renewables associated with scientific and technical revolutions. The chapter will describe the main current energy uses, their relationship with specific resource availability in different countries, the geopolitical strategic contexts, and main market trends. With the present focus on sustainability, the book's first chapter sets the basis for all contributions to this edited book, and for the following chapter that deals with economic and environmental policy. Sustainability's three main tiers will also be addressed in the book's chapters, emphasising the systemic approach to energy.

A. Molina
Tecnologico de Monterrey, Campus Ciudad de Mexico, Calle Puente 222, Coapa, Arboledas del Sur, Tlalpan, 14380 Ciudad de México, Mexico
e-mail: armolina@tec.mx

A. Mendoza
Tecnologico de Monterrey, Campus Monterrey, Av Eugenio Garza Sada 2501, Colonia Tecnológico, 64849 Monterrey, NL, Mexico
e-mail: mendoza.alberto@tec.mx

F. J. Lozano (✉)
Tecnologico de Monterrey, Campus Toluca, Avenida Eduardo Monroy Cárdenas 2000 San Antonio Buenavista, 50110 Toluca de Lerdo, México, Mexico
e-mail: fjlozano@tec.mx

L. Serra-Barragán
Escuela de Gobierno y Transformación Pública, Sede Mixcoac, Tecnológico de Monterrey, Av Revolución 756, Segundo Piso, Nonoalco, Benito Juárez, CDMX, 03700 Ciudad de México, Mexico
e-mail: luisalberto.serra@tec.mx

A. Ibarra-Yunez
EGADE Business School Monterrey, Tecnologico de Monterrey. Rufino Tamayo y Eugenio, Av. Eugenio Garza Lagüera, Valle Oriente, 66269 San Pedro Garza García, NL, Mexico
e-mail: aibarra@tec.mx

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Abbreviations

GDP	Gross Domestic Product
IEA	International Energy Agency
OPEC	Organisation of Petroleum Exporting Countries
SE4ALL	Sustainable Energy for All
UK	United Kingdom
USA	United States of America
WWII	World War Two

1 Energy Sources

Nowadays, our economies rely on large material and energy flows to accomplish their economic aims. The main flows are concentrated on the energy sector. Without energy there would be "no well-functioning economy", and there might be an "onset of social upheavals in our societies", or, with easily available energy, social development will be fostered. Our societies are "energivorous", if we are allowed to use this neologism, meaning that they devour energy.

Illustrating the latter, Table 1 presents some energy and material flows for the year 2017, for which widespread data are available. It is obvious from the data that energy flows are the largest worldwide; oil, coal, and natural gas (fossil fuels), with 4,622; 3,732; and 3,156 million tonnes oil equivalent (Mtoe), respectively. While phosphate rock, potash, and nitrogen are one or two orders of magnitude lower; considering that these latter materials are used to produce food for humans and livestock, the relevance of energy flow through fossil fuels is paramount.

Table 1 Total material and energy flows worldwide for 2017

Material	Amount	Units	Type	Year
Oil	4,622	10^6 tonnes oil equivalent	Consumption	2017
Oil	98.5	10^6 barrels daily	Consumption	2017
Coal	3,732	10^6 tonnes oil equivalent	Consumption	2017
Natural Gas	3,156	10^6 tonnes oil equivalent	Consumption	2017
Cement	4,050	10^6 tonnes	Production	2017
Iron ore	2,430	10^6 tonnes	Production	2017
Phosphate rock	263	10^6 tonnes	Production	2017
Potash	42	10^6 tonnes as K_2O	Production	2017
Nitrogen	150	10^6 tonnes as N	Production	2017
Copper	19.7	10^6 tonnes	Production	2017

Sources BP (2018), USGS (2019)

According to Ayres et al. (2013): "... *in industrial economies for energy the output elasticity is significantly larger than its cost share, whereas for labour the opposite is the case*". But presently, if policy decisions are guided by energy's cost-share in the economy, decision makers will tend to disregard its importance. Citing (Kümmel 2013); "*Energy conversion moves the world. In modern economies, the output elasticity of energy far outweighs its small share of costs, while for labour just the opposite is true*", the latter emphasising Ayres et al. proposition. Energy output elasticities for USA, Germany and Japan (between 1960 and 1999) are 0.35, 0.47 and 0.73 respectively (Kümmel et al. 2010; Lindenberger and Kümmel 2011).

There is also a relationship between social evolution and energy, as stated by L. White "*culture evolves as the amount of energy harnessed per capita per year is increased, or as the efficiency of the instrumental means of putting the energy to work is increased*" (White 2007). The latter is discussed at length in Energy and Civilization (Smil 2017), underlining social and economic issues in relation to energy.

Then present importance of sustainability is needed, encompassing, among others, the economic, social, and environmental dimensions with time changes. Considering the generations' future well-being, allows considering energy issues as crucial and basic for humanity.

A brief discussion on energy before the First Industrial Revolution is pertinent. Wood in the Classical world (a period comprising Greece and Rome predominance) was the fuel of choice, and in the Mediterranean basin mining for silver, copper, iron and tin for bronze was a widespread activity (Williams 2006). This needed large amounts of wood to produce charcoal that was used to produce various metals. As an example, producing a Mg of copper, 300 Mg of charcoal was needed. Comparing iron production using charcoal and coal, Fig. 1 presents the material efficiency, implying the energy efficiency as well, between both methods in producing 1,000 kg of iron.

2 Historical Context

Europe had economic expansion and growth between 1000 and 1300 but never on the scale following the Industrial Revolution. Until the nineteenth century, development was constrained by land availability due to energy sources, where 9/10 parts were provided by animals or plants (Cipolla 1994). During the Middle Ages main fuel types were wood, charcoal, and residual biomass from agriculture. Also, during 1500–1600, wood was the fuel of choice and, indirectly, charcoal. A similar situation pertained in other parts of the World. Using wood implied clearing forests.

In the Middle Ages using streams as energy sources resulted in the appearance of waterwheels, either horizontal or vertical, applying their power for grinding, water pumping, lifting, pounding, pressing, brewing, blast furnaces (Gies and Gies 1994).

The growth above mentioned was linked to population growth happening between 700 and 1300, almost doubling (see Fig. 2). Afterwards the bubonic plague (1347–1353) that spread throughout Asia and Europe, resulting in a decreased in population

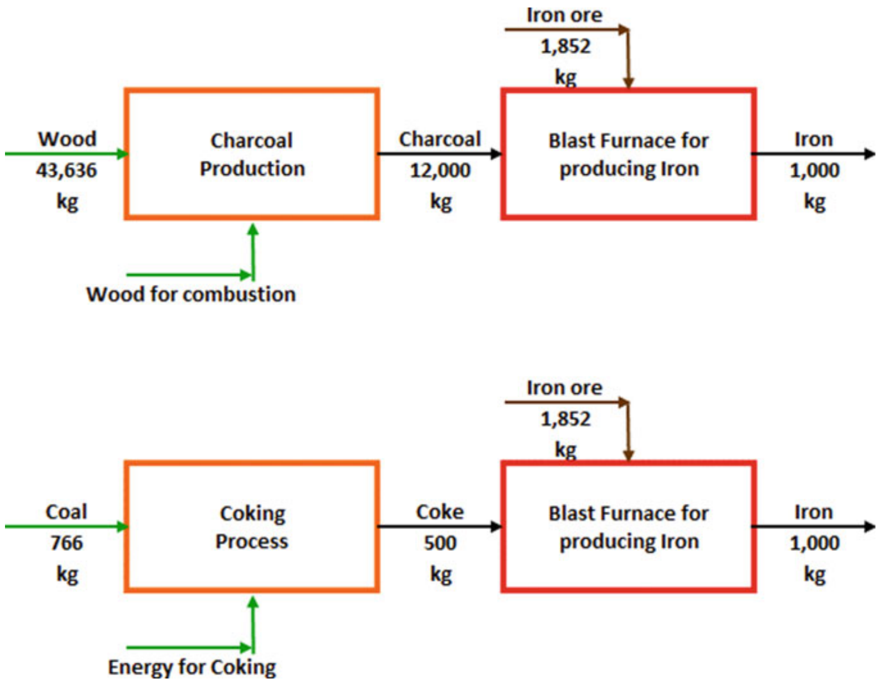

Fig. 1 Energy efficiency in Iron production using charcoal and coal

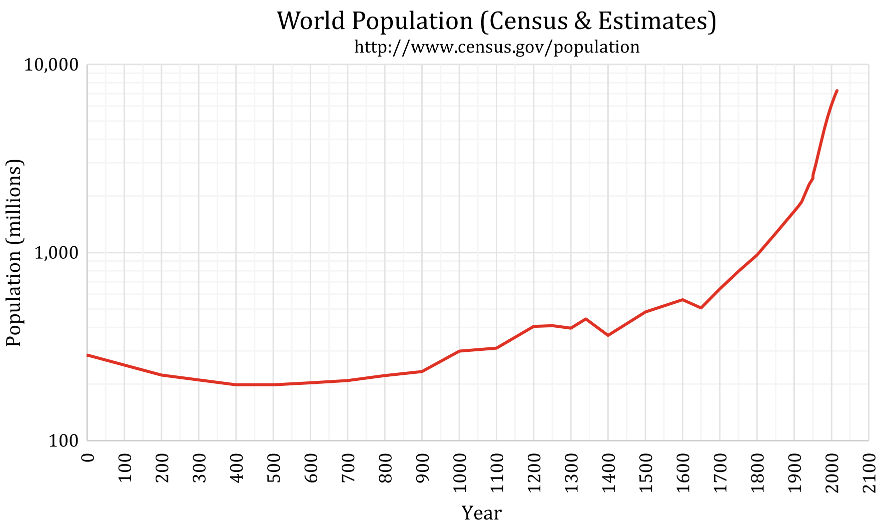

Fig. 2 World population during the Christian era

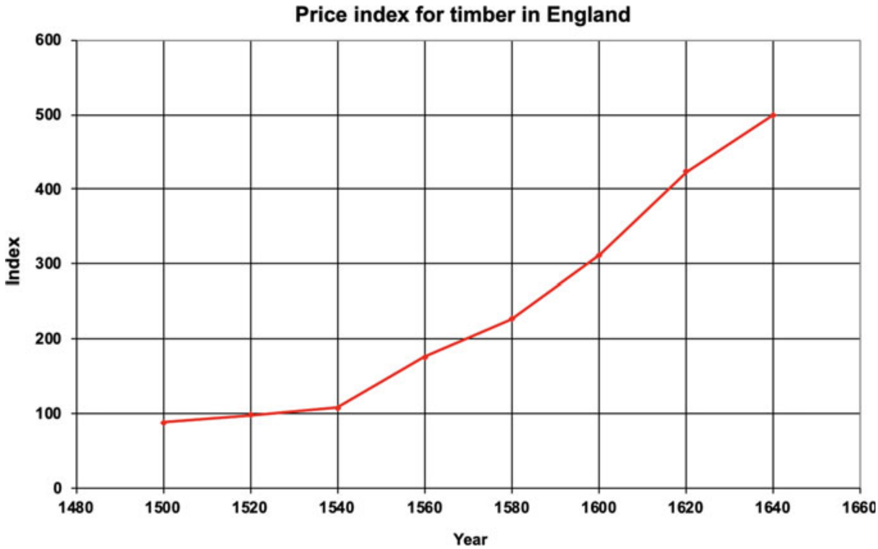

Fig. 3 Timber price index in England (Cipolla 1994)

(Livi-Bacci 2012). Population growth implied an increasing resource demand, either from material or energy sources. An increase in agriculture activities also implied clearing forests for cultivation. A demand for minted coinage, then grew for commercial activities, implying an increase in mining activities, thereby pushing up wood demand for mine shoring and smelting (Agricola 1950; Williams 2006).

The increase in wood demand generated shortages, that implied a price increase for wood and charcoal as can be seen in Figs. 3 and 4, as discussed by Cipolla (1994). Wood scarcity faced a 5 times price increase in a century and a half. A more detailed discussion regarding firewood price increase is given by Williams (2006) related to agricultural clearing, population increase and iron making.

Deforestation was not only particular to Europe, but also in Asia, mainly in populated China and Japan. With European arrival to America and the colonisation events, a purposeful deforestation happened in North and South America, as well as the Caribbean.

Normally older data pertaining fuel use as well as their composition are not easily obtained. For the case of England and Wales there is data covering 1560–2001 (Warde 2007). The source evolution from 1560 to 1730 is presented in Fig. 5 wherein there is an important increment in coal use, from around 10 to 55% of total, a diminishing use of firewood and draught livestock; and a marginal contribution from wind and water. Underlining this trend, it looks a communal response to scarcity in wood linked to an increasing energy demand in that period. Figure 6 presents England's population for 1086–1800, the bubonic plague impact appears in the fourteenth century, but the population recovery is clear, showing a four-fold increase from 1400 to 1801.

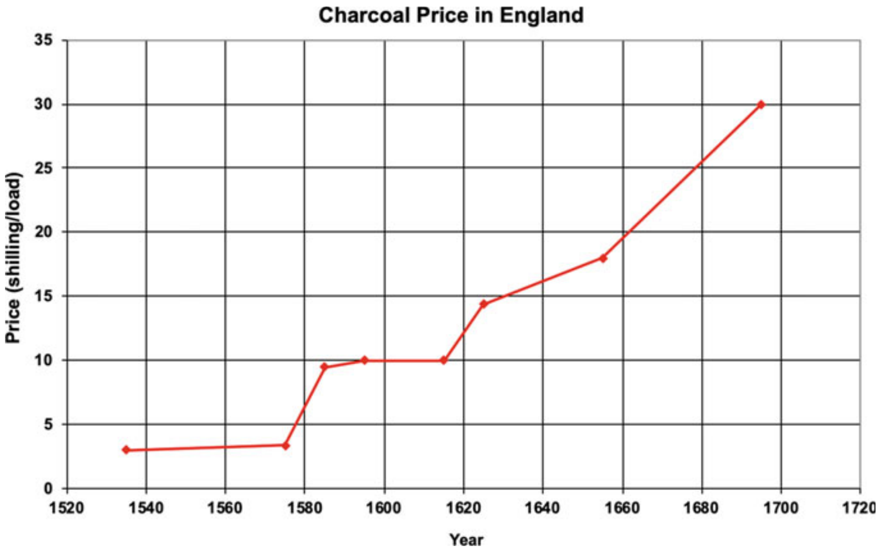

Fig. 4 Charcoal price increase in England

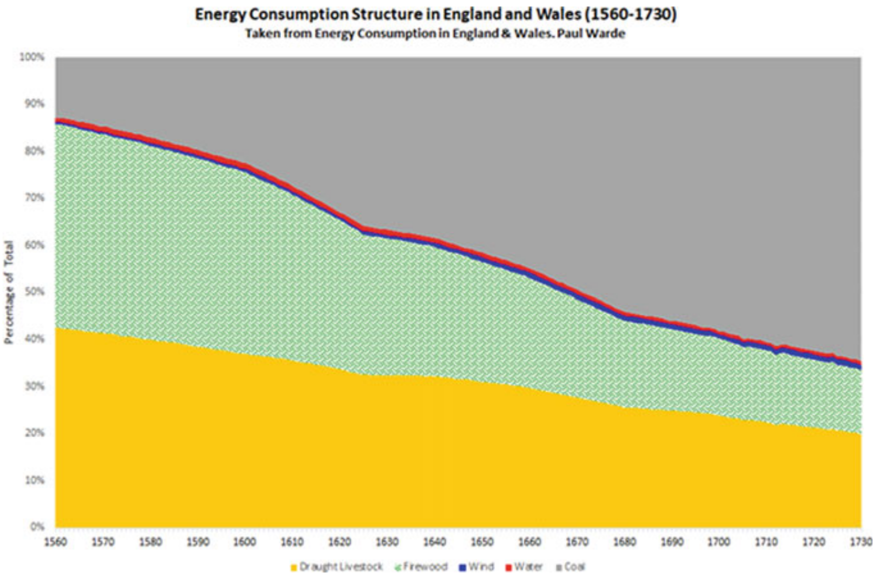

Fig. 5. 16th and 17th centuries' energy consumption in England and Wales

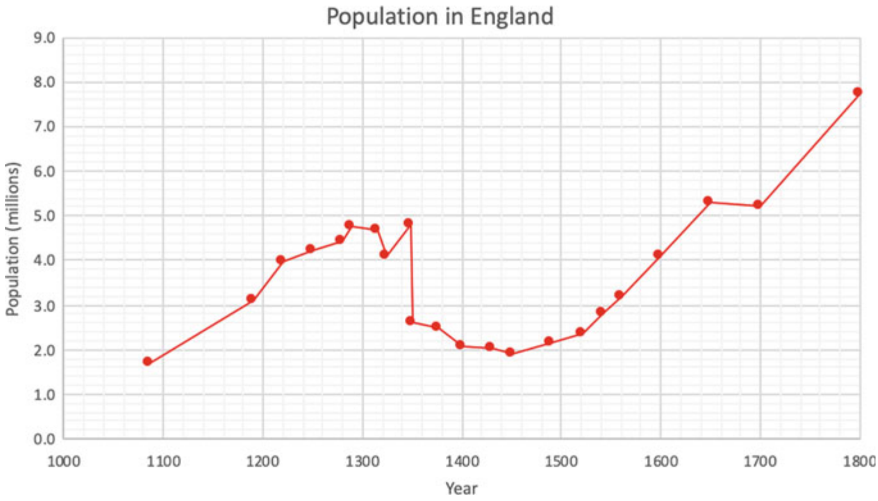

Fig. 6 England's population from 1086 to 1801

A similar trend occurred in the United States regarding energy sources. Figure 7 shows the energy source structure from 1775 to 2018, it is by the end of the nineteenth century that wood was no longer the main energy source and during the twentieth century coal, oil and natural gas became the principal sources.

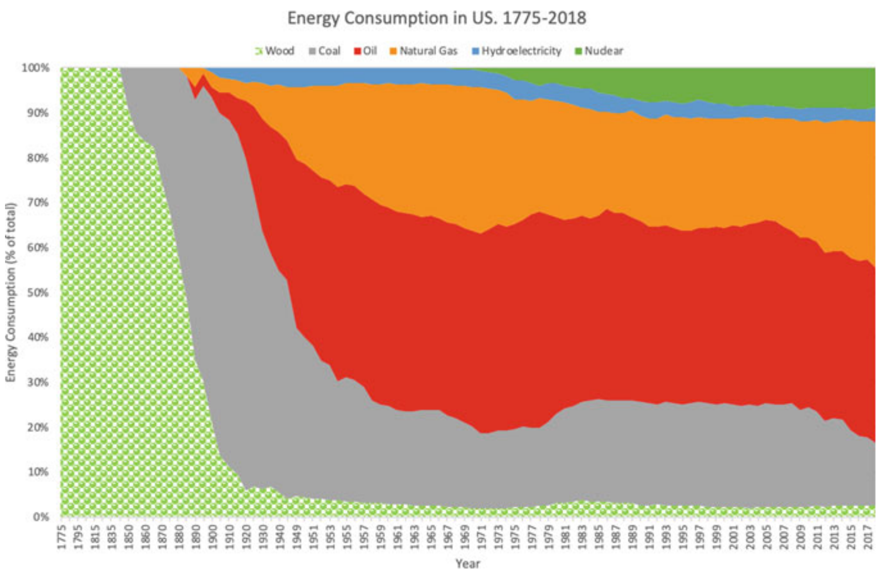

Fig. 7 Energy consumption structure in the USA from 1775 to 2018. *Source* EIA

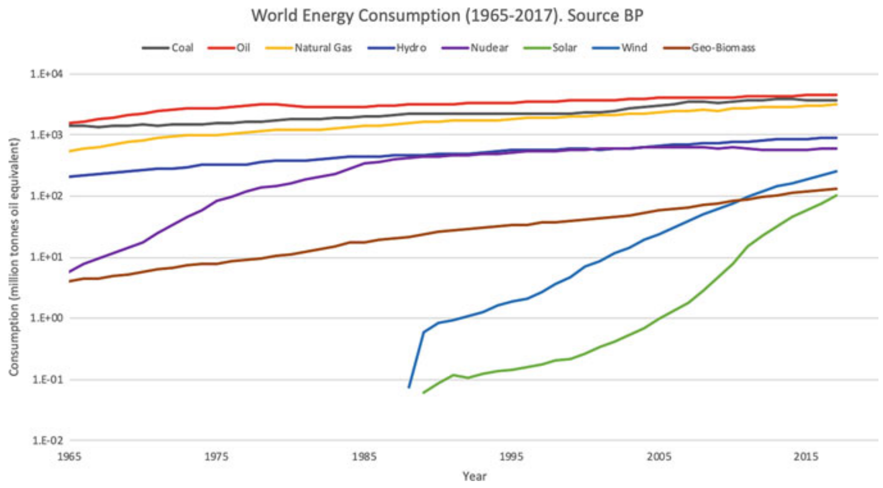

Fig. 8 World energy consumption from 1965 to 2018 [semilog scale] (BP 2018)

The dawn of the First Industrial Revolution at the end of the eighteenth century is a milestone regarding energy source and communication technologies, such as the telegraph. As Ayres has analysed the historical disjunctive of continuing wood use as a fuel source was evident when shifting to coal (Ayres 2001). The former would have increased deforestation and ecological stress at the time, while the latter sparked off the present-day economies, the burgeoning of technological discoveries, as well as scientific development.

World's energy sources evolution (from 1965 to 2017) is shown in Fig. 8 with data taken from (BP 2018). The sources mixture in present-day world's energy still makes fossil fuels predominant; oil, coal and natural gas contribute with 34.2%, 27.6% and 23.4% respectively; while solar, wind, geothermal and biomass barely reach 3.6% for 2017.

3 Source Depletion, Source Evolution and Link to Economic and Scientific Development: Long Cycle Trends in Energy Primary Resources

Material scarcity is linked to high demand in our open economies, where throughput from cradle to grave is prevalent. Copper content in ore has decreased from 1.5 to 2% weight at the beginning of twentieth century to 0.3–0.5% weight at the beginning of the twenty-first century (Mudd 2009; Crowson 2012; Prior et al. 2012; Henckens et al. 2016; Rötzer and Schmidt 2018).

A similar decline in copper average yield for its ore is presented in Fig. 9 for England (1850–1885), and for USA (from 1890 onwards); presently a value around

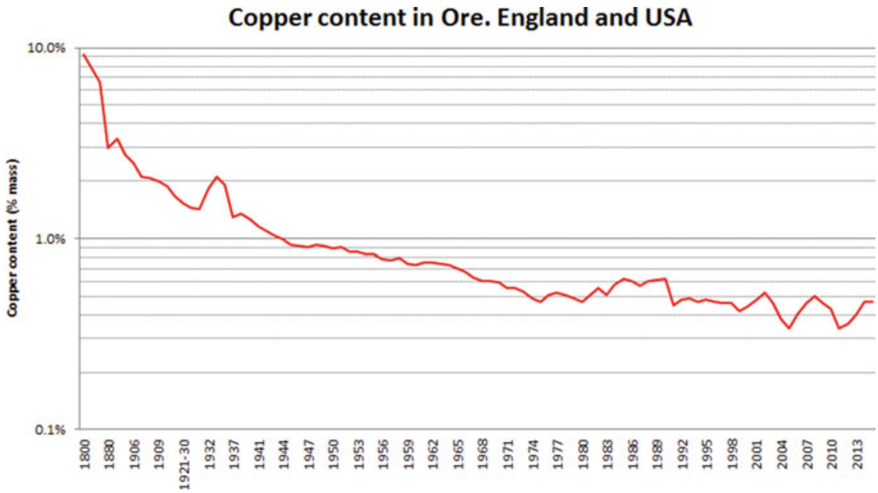

Fig. 9 Average copper ore yield in England and USA [semilog scale]

0.5% weight is typical for USA copper ore. That of course implies increasing capital and production costs for mining copper with a higher energy use, inherently increasing environmental impacts as a result of higher tailings volume.

Oil production for Mexico and the UK is shown in Fig. 10, where the peak production and its subsequent decline, for both countries, can be noted. Conventional oil exploitation deficiencies caused that decline to happen. In Fig. 11 oil production in the USA is shown, where the decline started in 1985. But around 2009 the widespread use of fracking technology started to be used, making the USA an important oil

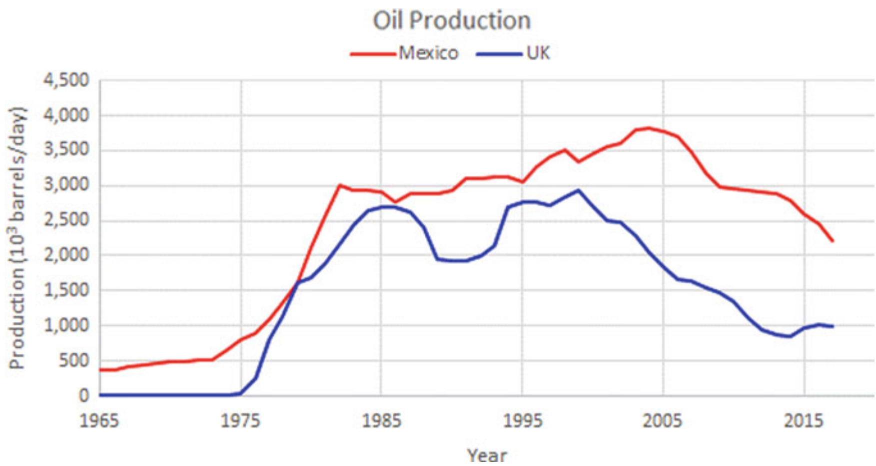

Fig. 10 Oil production in Mexico and UK between 1965 and 2017

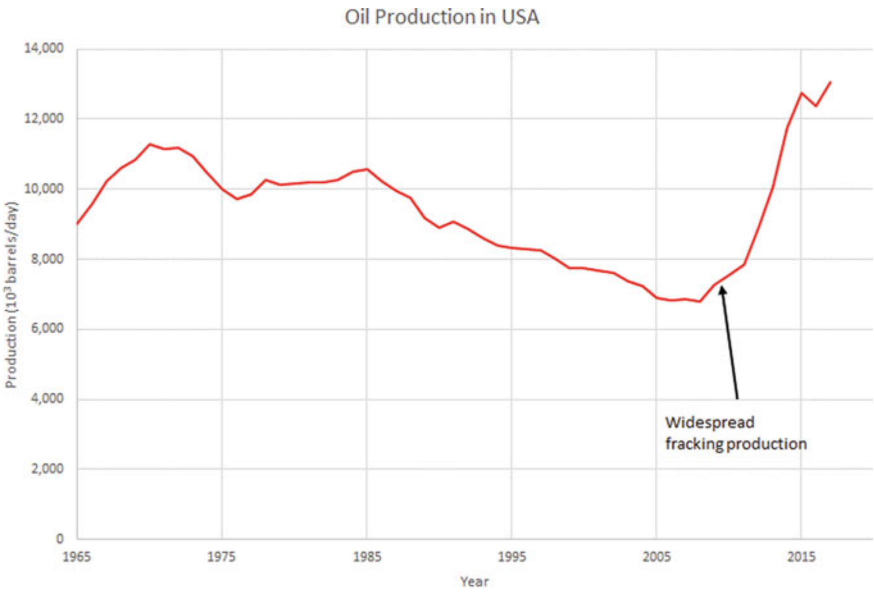

Fig. 11 Oil production in USA from 1965 to 2017, showing onset of widespread fracking exploitation

producer once again, wherein this fracking technology change contributed to the production increase. In the UK there was much opposition to fracking, on the grounds of pollution of the water table, and a fear of local earthquakes.

As noted above, the use of a not-so-new technology, fracking, with improvements in the USA has made possible the increase in oil production.

The above-mentioned examples regarding oil production in Mexico and the UK, where the conventional oil extraction implies lower available resources; in a similar fashion coal production is shown in Fig. 12 for Germany, UK, and Spain, exhausting such resource. For a specific and longer-term view Fig. 13 shows coal production in UK from 1700 to 2017, showing clearly the top peak production in 1913, and its decline onwards.

Then the use of a not so new technology, fracking, with improvements in the USA has made possible the increase in oil production. For a thorough discussion on oil peak and decline Smil (2017), lays out a proper discussion on oil scarcity and production decline, which is beyond the present book intent.

The crossroads before the First Industrial Revolution, as discussed by (Ayres 2001), where one option as energy source was continuing exploitation of timber, with its implication for deforestation impacts; as opposed to the other option of using coal as an energy source, which generated the foundations for our present day Society. Hence presently, that path chosen has made our economies possible, but not exempt from their own environmental and social issues. Presently, our societies face a similar milestone, where we can continue using extensively fossil fuels as

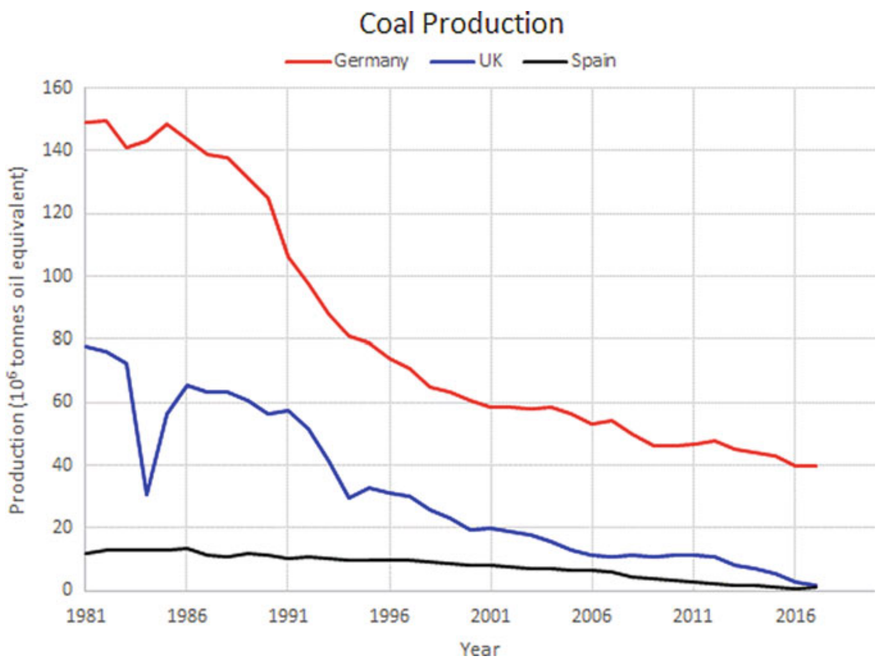

Fig. 12 Coal production from 1981 to 2017 in Germany, UK, and Spain

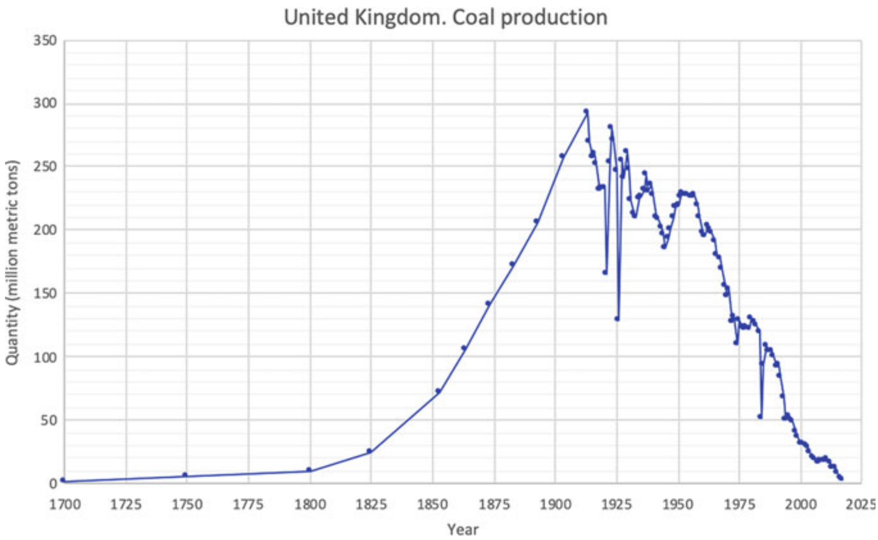

Fig. 13 Coal production in UK from 1700 to 2017

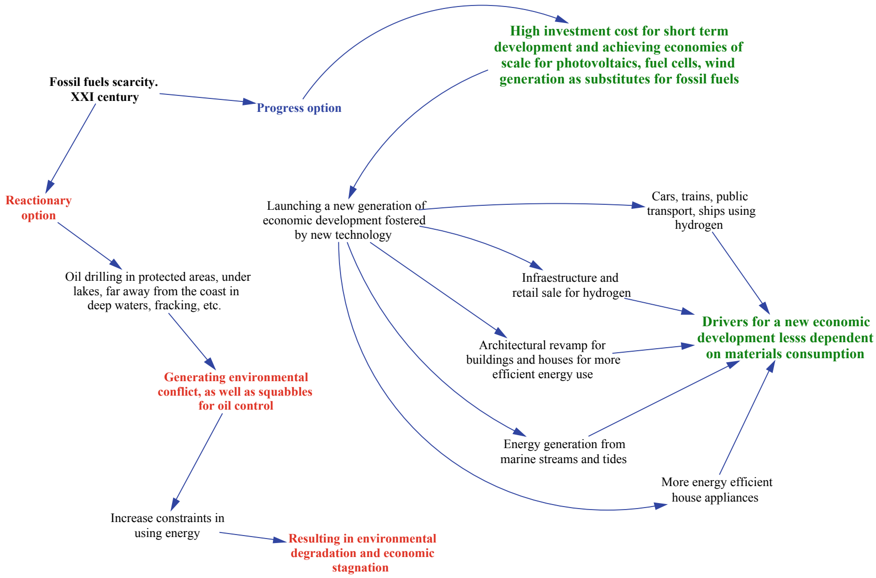

Fig. 14 Milestone crossroads between using fossil fuels and renewable energy sources

energy source or fostering renewable energy sources, the latter can help to promote a sustainable future, as illustrated in Fig. 14.

Besides promoting their evolution, consolidation, and the appearance of new technologies based on renewable resources, through their uptake and consolidation via economies of scale, which will decrease capital and production costs, hence increasing their profitability, and sustainability. Figure 14 helps to understand the areas of sustainability:

4 Main Current Uses in Present day Economy

Use efficiency

Energy production and consumption varies from country to country. The International Energy Agency (IEA) classifies energy consumption in four large categories:

a. Industry
b. Transport
c. Other
d. Non-energy use.

For 2016, consumption mainly consisted of fossil fuels; oil, coal, and natural gas, representing 66.8% of consumption. One aspect to note is that electricity consumed was partially produced by fossil fuels. Taking that into consideration, the overall contribution is 76.3% (IEA 2019c). World consumption data are shown in Fig. 15.

Oil consumption stands out among fossil fuels. For 2017 World production it was 92,649 thousand barrels per day (BP 2018). For 2017 40.9% of consumption corresponded to oil products, see Table 2. For Mexico, USA, and Brazil, it was their main consumption component, while world consumption is evenly distributed between Industry, Transport, and Other (see Table 3. Energy Consumption by destination for World, Mexico, the USA, and Brazil (% of total); for the selected countries in

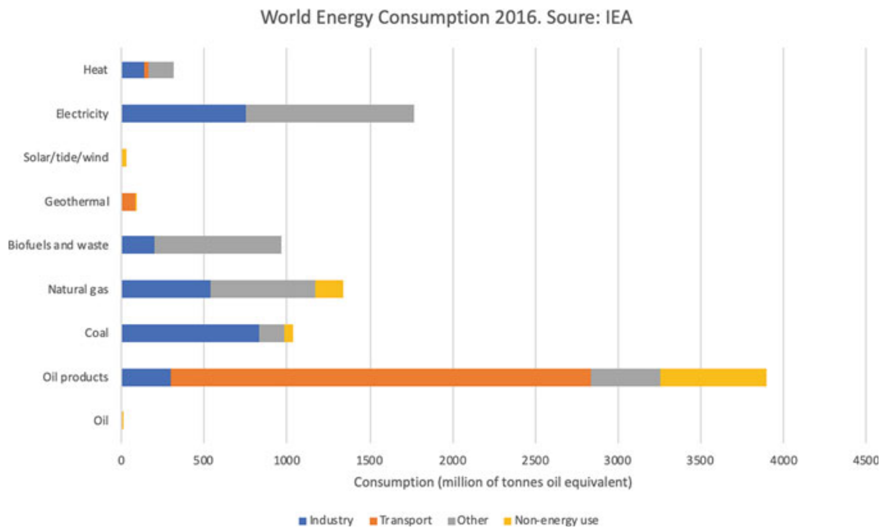

Fig. 15 World energy consumption for 2016. *Source* IEA

Table 2 Energy consumption structure by source for World, Mexico, USA, and Brazil (% of total)

Consumption (% total)				
For 2017	World (%)	Mexico (%)	USA (%)	Brazil (%)
Oil	0.15		0.29	
Oil products	40.86	59.71	48.88	45.00
Coal	10.50	2.79	1.12	3.34
Natural gas	15.46	12.39	22.78	5.39
Biofuels and waste	10.68	5.86	5.27	27.08
Geothermal	0.14		0.02	
Solar/tide/wind	0.33	0.21	0.12	0.37
Electricity	18.91	19.13	21.14	18.82
Heat	2.98		0.38	

IEA (2016a, b, c, d)

Table 3 Energy consumption by destination for World, Mexico, the USA, and Brazil (% of total)

Consumption (% total)				
For 2017	World (%)	Mexico (%)	USA (%)	Brazil (%)
Industry	29.0	30.5	17.2	34.8
Transport	28.9	42.0	41.1	37.2
Other	33.0	23.2	32.1	21.4
Non-energy use	9.0	4.3	9.6	6.5

IEA (2016a, b, c, d)

USA and Mexico, Transport consumes the largest proportion with 41.1% and 42.0% respectively, while Brazil's share is 37.2% of total consumption.

But on a per capita basis the data look differently. USA is the largest consumer with a total of 195.9 GJ/person, Transport and other uses being the main contributors; Mexico and Brazil have 41.0 and 45.9 GJ/person respectively, almost a fifth of USA. For the World, consumption is 54.2 GJ/person, nearly four times less than USA. Emphasising economic development as well as social development, energy intensity use is relevant, and needs to be connected to the first section as discussed by Ayres et al. (2013), Kümmel (2013), White and Smil (2017) (Wikipedia 2019) (Table 4).

Consumption data, as presented, does not reflect the complete picture for fossil fuel usage. Electricity power generation has depended heavily, until now, on fossil fuel use. The data from IEA Energy Balances, taking into account power station energy input and output, are as presented in Table 5, showing that fossil fuels represent the largest contribution for the World, Mexico, and the USA, while Brazil relies on oil

Table 4 Energy consumption per capita basis by destination for World, Mexico, the USA and Brazil

Consumption per capita (GJ/person)				
For 2017	World	Mexico	USA	Brazil
Industry	15.72	12.52	33.68	15.98
Transport	15.66	17.24	80.57	17.09
Other	17.89	9.50	62.91	9.82
Non-energy use	4.90	1.76	18.72	2.99
Total	54.17	41.02	195.88	45.89

Table 5 Total fossil fuels consumption (% of total)

Fossil fuels direct consumption (%total)	
World	66.97%
Mexico	74.89%
USA	73.07%
Brazil	53.74%

IEA (2016a, b, c, d)

and hydro power to generate electricity. Adding up consumption and input to power stations, fossil fuels remain the largest contributors worldwide, and also for the three selected countries being USA the largest consumer with 63% of total, Mexico and Brazil around 58%, and the World 43% (see Tables 6 and 7).

At this point discussing energy efficiency usage is relevant. Since the First Industrial Revolution's dawn up to the present, improvements in energy use have occurred. From Savery's steam engine to Newcomen's engine, and then Watt's engine, the improvements are clear. Let us remember that the Principle of Energy Conservation was fully structured at the end of the nineteenth century, while irreversibility and maximum work attained from heat exchange was understood at the beginning of the nineteenth century with the work of Sadi Carnot. Hence the first improvements were in a sense empirical but laid the foundations for a solid thermodynamic understanding. For steam engines, and internal combustion engines, either Otto or

Table 6. Input energy structure to power stations for World, Mexico, the USA, and Brazil (as % of total input)

	Input to Power stations (% total input)			
	World (%)	Mexico (%)	USA (%)	Brazil (%)
Oil	1.1	0.0	0.0	0.0
Oil products	0.0	13.4	0.8	4.5
Coal	23.2	12.4	36.2	7.5
Natural gas	35.2	57.2	27.3	18.2
Biofuels and waste	5.6	2.8	2.5	13.4
Electricity	0.0	0.0	0.0	0.0
Geothermal	2.0	4.5	1.1	0.0
Other prod (Solar/tide/wind)	3.9	1.5	3.4	5.3
Hydro	9.8	4.0	3.1	45.3
Nuclear	19.2	4.2	25.7	5.8

IEA (2016a, b, c, d)

Table 7. Fossil fuels total use from consumption and power stations for World, Mexico, the USA, and Brazil

Consumption sum (EJ)	World	Mexico	USA	Brazil
Oil, Oil products, Coal, NG	273.71	4.21	46.38	7.76
Consum. + Input Power Stat.	365.36	6.60	69.83	8.68
Total Input in Balance	846.69	11.10	111.07	15.30
Fossil fuels/Total input Bal.	43.2	59.4	62.9	56.7

IEA (2016a, b, c, d)

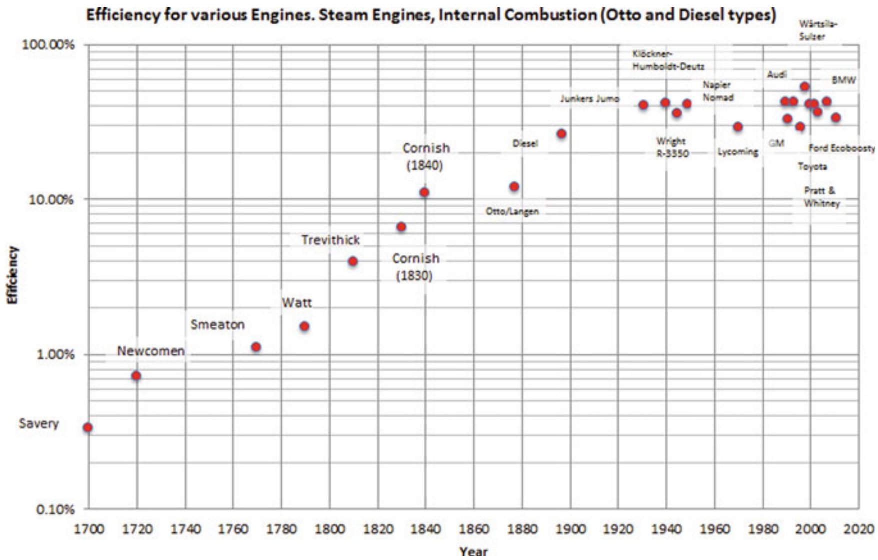

Fig. 16 Efficiency for several steam and internal combustion engines [semilog scale]

Diesel type, see Fig. 16 which presents the time evolution in efficiency from the earliest steam engine designs to present day internal combustion engines. Saver's "Miner's Friendly" engine was a very low efficiency machine, while the Wärtsilla-Sulzer diesel engine, used in large ships, has a 52% efficiency, but a limit is being attained, and that is related to a thermodynamic limit. Also, the increase in power for steam engines over the years is shown in Fig. 17, where the nimble Savery's engine is around 0.75 kW to Corliss engine with 3,500 kW.

Complementing our discussion, for economists a measure of energy use efficiency is given by energy intensity, which relates energy demand or consumption with the Gross Domestic Product (GDP). Providing an insight into wealth generation and the energy used to achieve it. Its change through time gives the evolution of possible efficiency increase or decrease per dollar of generated wealth. In Figs. 18 and 19 energy intensity for Mexico, Sweden and the USA, as well as energy intensity for Brazil, Mexico and Sweden are shown. The USA and Sweden's data decrease over time and Mexico's trend, though decreasing, it is not as strong as the former. In the case of Brazil, the opposite occurs, energy intensity increases through time, implying inefficient energy use. To emphasise the conclusion and for exemplifying, data from only four countries have been chosen, Figs. 20 and 21 show GDP for Brazil, Mexico and Sweden; and for the USA (the order of magnitude difference for the latter is the reason to use two graphs). Thence though GDP increased for all countries, only Brazil had an increase in energy intensity, confirming inefficient use.

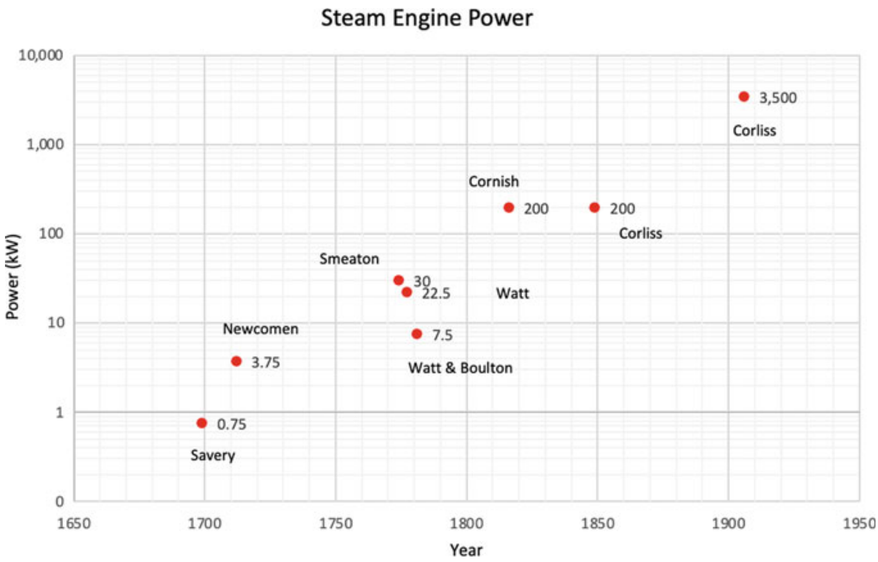

Fig. 17 Power evolution for Steam Engine

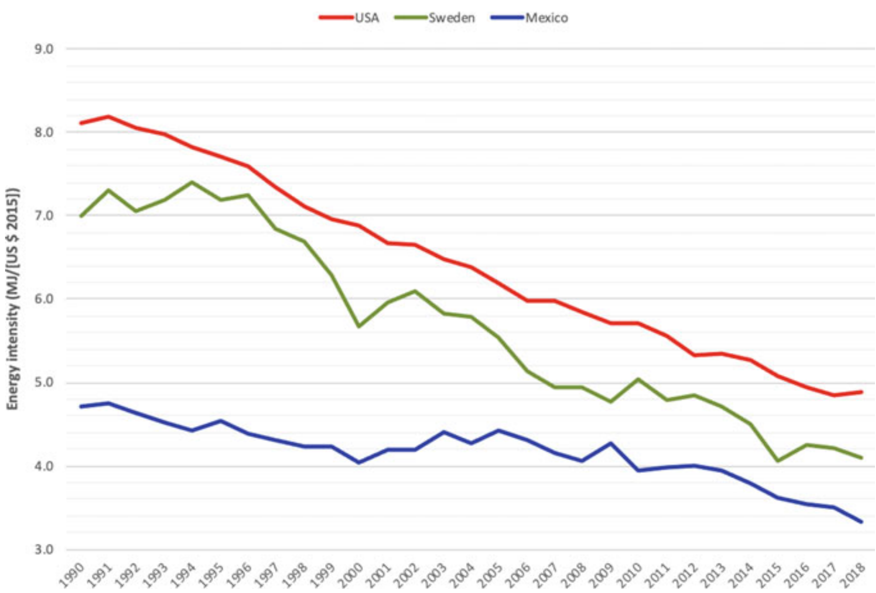

Fig. 18 Energy Intensity for Mexico, Sweden and USA

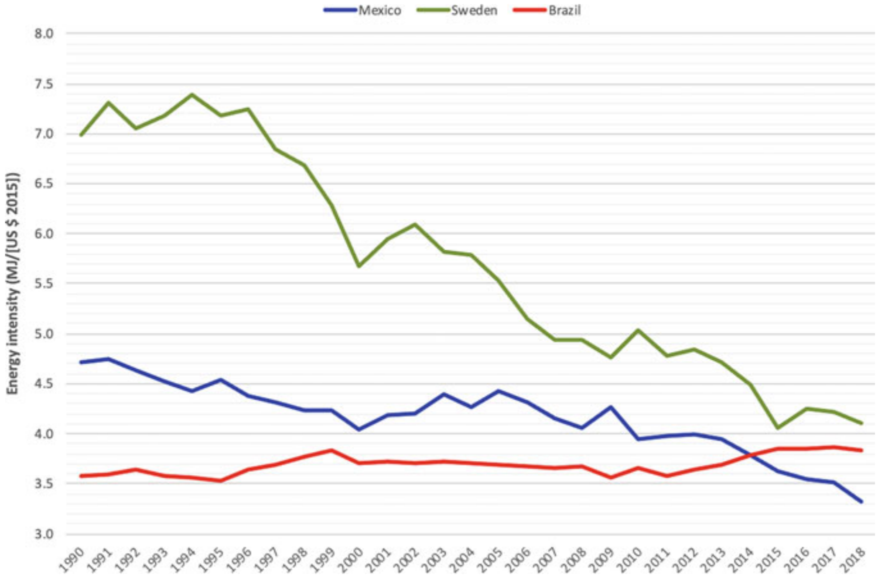

Fig. 19 Energy intensity for Brazil, Mexico and Sweden

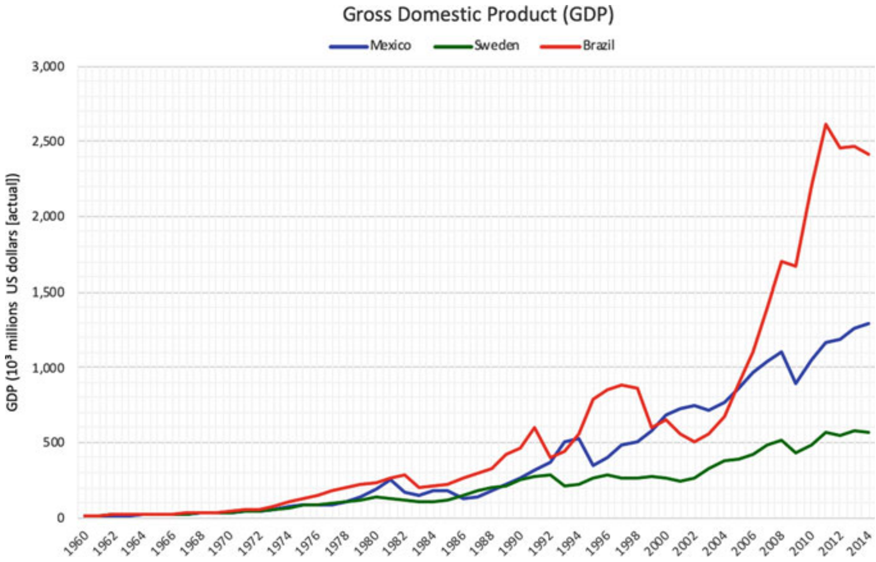

Fig. 20 GDP from 1960 to 2013 for Brazil, Mexico and Sweden

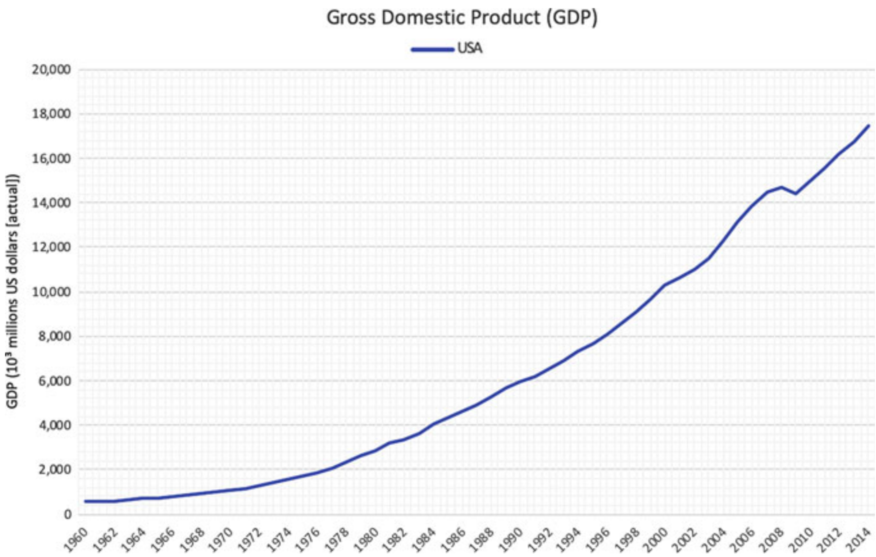

Fig. 21 GDP for USA from 1960 to 2013

5 Source Availability for Different World Regions

Fossil fuel availability is different for each country in the World. Natural resource distribution varies widely on the planet. Societies have used those fuels which are readily available in their territory. Also, transition from a solid fuel (coal) to a liquid (oil) only occurred at the end of the nineteenth century, generating geopolitical pressure to secure oil access. Oil is only found in certain regions of the world; for example, in certain regions of the USA, Mexico, the Middle East. and Russia. This localisation is also the case with coal.

A production distribution map is shown in Fig. 22 [data are from (BP 2018)] where only a few countries have local access to the three main fossil fuels; such is the case for the USA, and the Russian Federation. While in the Middle East the prevalent access is to oil and gas. For China, India, Indonesia, Colombia, Spain, France, Germany, South Africa, and Zimbabwe the prevalent fossil fuel is coal. For Mexico it is oil and natural gas, while for Brazil it is oil.

Due to uneven economic development in different countries, their fossil fuel consumption varies, and some countries need to import certain fossil fuels. Consumption is shown in Fig. 23, where China needs to consume double the amount of oil it produces, half the amount of coal produced, and more gas is consumed than is produced. Generally, each country will have a different fossil fuel balance between production and consumption.

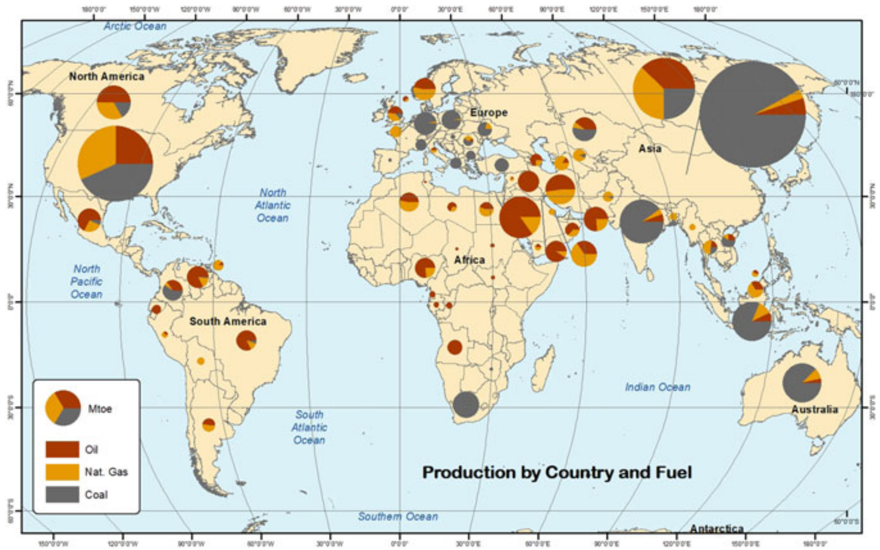

Fig. 22 Fossil fuel production in 2014. Oil, coal and gas (Mtoe)

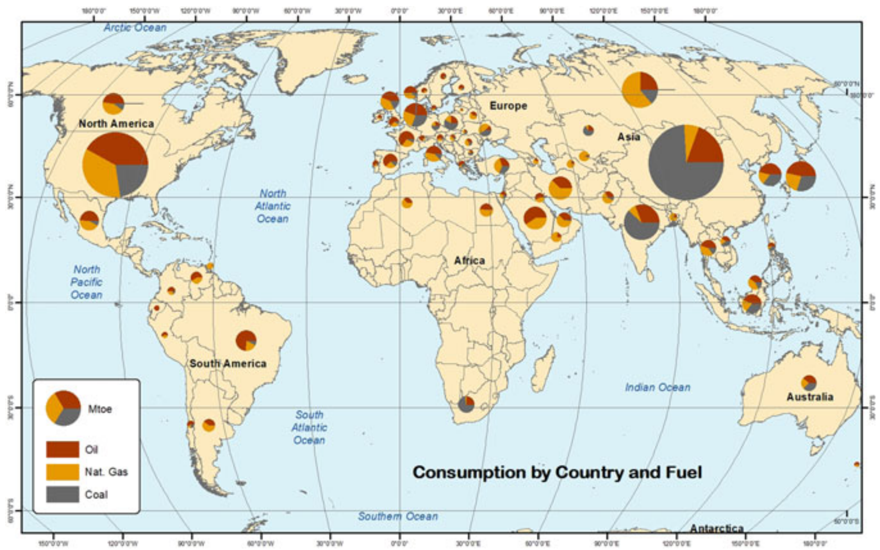

Fig. 23 Fossil fuel Consumption for 2014. Oil, coal and gas (Mtoe)

6 Geopolitical Implications

As stated in Sect. 1, productive activities have depended on large material and energy flows. However, there is evidence that the relationship is bidirectional, such that higher use of energy fosters economic growth (Belke et al. 2011). Thus, economic development has been strictly linked to a powerful energy system and vice versa. For example, according to the World Bank (2020), Mexico is placed 13th in its international export and import capacity, and in place # 70 in its GDP per capita, but way behind in its energy production, trade, and energy efficiency figures.

Energy revolutions have shaped the international map of winners and losers, with those that master energy resources being part of the former group, having clear global economic and political sway. Economically thriving countries during the industrial revolution, for example, were those that were also relatively more able to access coal and integrate it into their productive systems. For that matter, the status and evolution of the energy system is key to their geopolitical strategy for all countries, broadly speaking. Given their main primary resource, countries that found a way to use their main resources more efficiently, fared better than those that let the chance pass away.

The economic growth of the 20th Century can be explained mostly by the dominance of countries over oil and gas. The surge of the United States and the Soviet Union as world superpowers and their endurance in such position can be explained by its ability to domestically produce an—strategically—access energy resources abroad, mainly hydrocarbons.[1] In fact, after the end of World War II (WWII), the energy landscape dramatically changed when the origins of a group of petroleum exporting nations laid the foundations of what would later become the Organisation of Petroleum Exporting Countries (OPEC), to coordinate and unify the policies of its members to ensure benefits for them by controlling prices of the most relevant energy commodity. This event marked the dawn of an era where geopolitics had at its core economic components, of which some were driven by energy commodities (Dolatabadi and Kashkoiyeh 2017).

An imbalance of power might have arisen by the end of the 20th Century because of the increasing energy deficit of the US. However, a major breakthrough (technological and, mostly, business model) occurred when the shale oil industry (*fracking*) boomed at the turn of the century (see Fig. 11), allowing the US not only to reduce its oil and gas imports, mainly from the Middle East, but also to become the largest hydrocarbons and crude oil producer in the world since 2012 and 2013, respectively (U.S. EIA 2018). Such industry proved to be resilient in spite of an aggressive campaign carried out by OPEC member Saudi Arabia in the last quarter of 2014, thus creating the need for Middle East producers to redefine their role on the global

[1] The nuclear race originated to gain military (and ultimately political) advantage after WWII. It also created benefits in the energy mix portfolios for countries such as the US, the USSR, China, India, France, and the United Kingdom.

energy scene and explore alternative markets to place their products, mainly in Asia (Fattouh and Sen 2015).[2]

The next decades will yet surely mark another geopolitical shift related to energy. The digital revolution is entering a new phase, characterized by innovation in materials design, artificial intelligence and automation. The speed at which innovation drives scientific research might result in an era of inverse design, thus reducing scientific discovery times by a factor of ten (Aspuru-Guzik et al. 2018). The challenges posed by Climate Change, as well as society's need for interconnectivity, will require an advanced grid that enables smart and dynamic connectivity accompanied by powerful data processing algorithms, as well as sensible integration and storage management of renewable energy: the so-called smart grid (which is addressed in Chaps. 7 and 8 in more detail). This revolution will certainly affect, once more, the fundamentals upon which national security and geopolitics are defined. All in all, one has to bear in mind that energy shifts, innovation, and focus take many years to produce results, such that social and business benefits accrue and be evidenced in the economic, business, and policy agendas across the world.

7 Market Trends and Sustainable Energy Sourcing

Since fossil fuels are so prevalent in our present-day economies, climate change impacts are inevitable. Anthropogenic CO_2 emissions are generated by burning fossil fuels; thus, the outcome will be high planetary consequence impacts.

Atmospheric carbon dioxide levels have increased since the First Industrial Revolution. Carbon dioxide atmospheric concentration has increased since the beginning of the First Industrial Revolution from 280 ppm (Blasing 2016) to slightly above 400 ppm for 2017. In Fig. 24 the upward trend is clear, while oscillations amplitude for Alert, Canada, correspond to photosynthetic activity, which is higher in summer for the northern hemisphere, decreasing CO_2 concentration slightly, and being higher during winter, as an example. Nevertheless, the South Pole station, shows smaller oscillations amplitude, due to a complete atmospheric mixing, but the upwards trend is clear.

Calculations for CO_2 atmospheric accumulation are shown in Fig. 25 (units Pg of carbon per year [$\text{Pg} = 10^{15}$ g $= 10^9$ metric tons]), emissions from anthropogenic sources have an upward trend; absorption by sea, oceans, agriculture, and biota have increased in response to the higher CO_2 concentration, as a homeostatic response by Earth ecosystems, but atmospheric accumulation has also increased. A snapshot for 2005 CO_2 flows is shown in Fig. 26 where the large amount generated is in the

[2] Even Saudi Arabia has an ambitious plan to restructure its economy; Saudi Vision 2030 proposes a move away from oil and close to a renewable energy economy. But insofar as the global context calls for urgent action, now, against Climate Change damage, Saudi Arabia has not yet taken advantage of its vast potential.

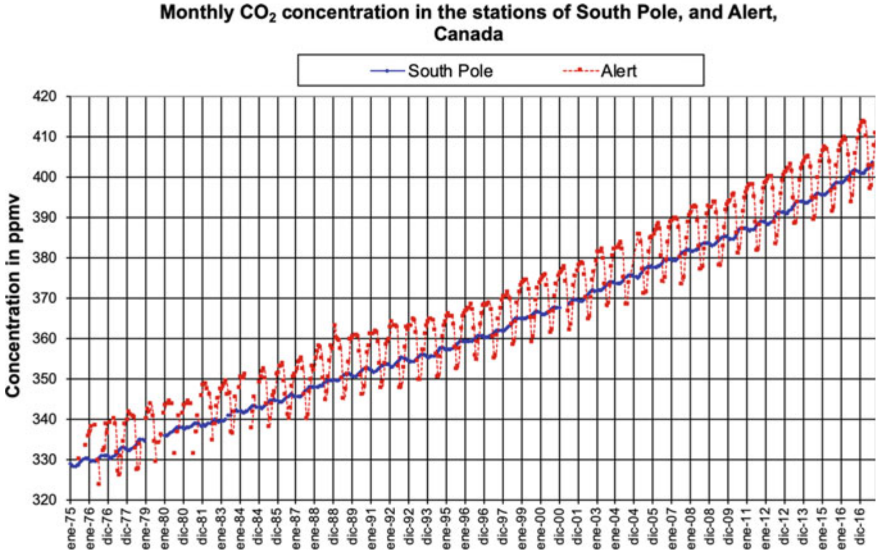

Fig. 24 Atmospheric carbon dioxide concentrations in Alert, Canada and South Pole stations from 1975 to 2017. *Source* Dlugokencky (2017a, b)

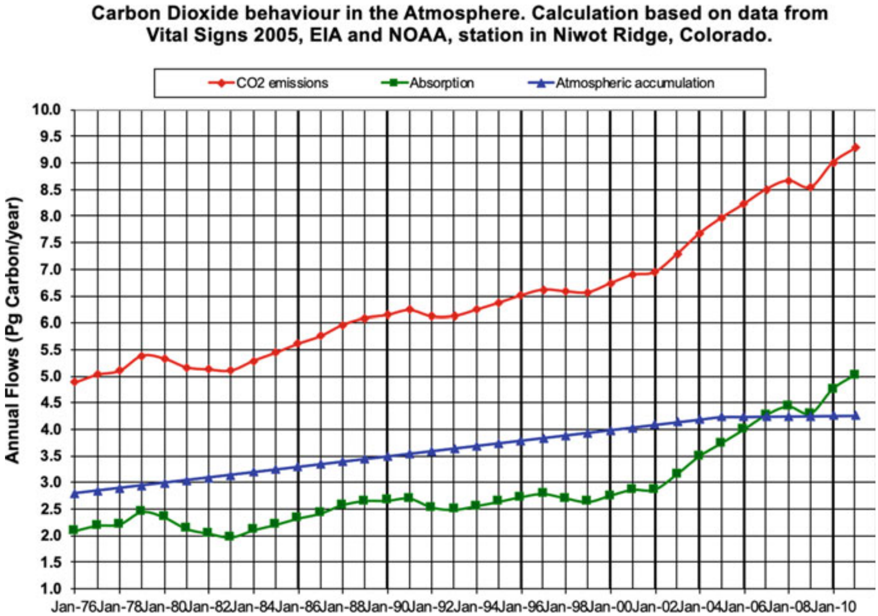

Fig. 25 Carbon dioxide generation and absorption on sea and land. Estimation of atmospheric accumulation from 1976 to 2011

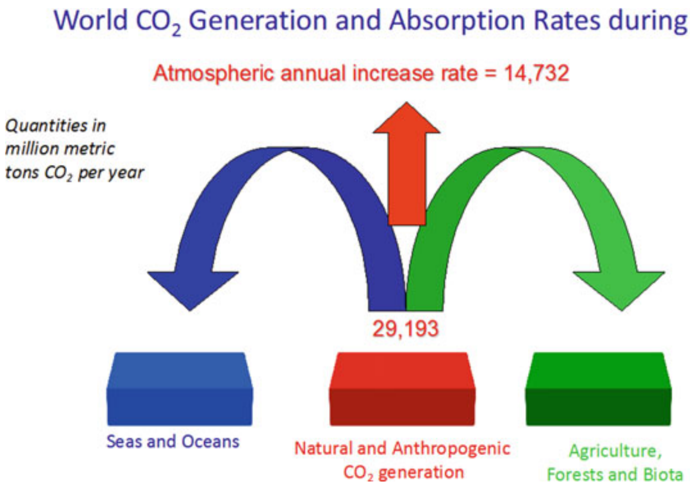

Fig. 26 Carbon dioxide flows due to generation and absorption, showing atmospheric accumulation for 2005

order of 29,200 million metric tons [29.2×10^{15} Pg], and atmospheric accumulation is 14,700 million metric tons [14.7×10^{15} Pg].

According to Wijkman and Rockström (2012) we have reached or are reaching certain irreversible thresholds that can have relevant consequences for earth ecosystems. One of the most important is CO_2 atmospheric concentration that might trigger a set of unwanted consequences, a planetary boundary is climate change where nowadays humanity has crossed the limit proposed by Wijkman and Rockström of 350 ppm CO_2 in the atmosphere, but as is obvious from the previous discussion, this value is above 400 ppm.

A very important quote is "*When tropical forests are depleted or oceans are vacuum-cleaned of fish, the results are posted as a positive item in the GDP statistics. The fact that natural capital in the form of fish stocks and trees has suffered a loss of value – one it may never recover from – is nowhere to be found on any balance shee*t", taken from (Wijkman and Rockström 2012), underlining the biased economy approach to natural resources. Hence also in economic terms, humanity is at a crossroads, and a present-day discussion on the "Circular Economy" is taking place among academic, governmental and business forums on this issue (MacArthur 2013; Tukker 2013; MacArthur et al. 2015; Bocken et al. 2017; Ecofys-WBCSD 2017) to improve and modify the way we use natural resources.

Peter Bakker (WBCSD CEO) addressed accountants in the UK stating the importance of incorporating ecosystem values in financial balance sheets (WBCSD and Bakker 2012).

But the transition to a sustainable future will take time, and certain conditions must be met in order to achieve it. Energy efficiency for goods and services has to be increased, this also entails efficiency in material resource use, according to (Ayres and Ayres 2010), and that is a *sine qua non* condition, but that is not the only condition. A systemic approach is required, where technology, economy, public policy, and societal changes need to resonate together in a concerted manner: renewable energy maturing while participating in energy markets; along with storage technologies to ameliorate renewables' intermittency; and, adequate management of the electricity grids, based on powerful communications technologies, according to Rifkin's Third Industrial Revolution (Rifkin 2011, 2012).

An important stakeholder for a transition to a sustainable future are businesses. In that regard there is a wide spectrum from laggards on one side, to strong sustainability promoters on the other. For the latter an important beacon is the World Business Council for Sustainable Development (WBCSD), where Energy and Circular Economy are relevant topics addressed by them. Their Pathways to 2050 (WBCSD et al. 2005) discuss the changes in consumption and energy sources needed to lessen the climate change impact; also their publication Facts and Trends (WBCSD et al. 2004) present different scenarios to mitigate climate change, presenting a mixture of several technologies to achieve that goal. Additionally, the outlook for a Low Carbon future is another issue to be taken into account, which implies energy, finances, and policy topics (WBCSD 2007; WBCSD and Leban 2008; Lane 2015).

The initiative Sustainable Energy for All (SE4ALL), launched by the United Nations and fostered by businesses (*Sustainable Energy for All | SEforALL*, no date), is an important strategy; as commented by C. Holliday (Holliday 2014), this entails energy services for all, doubling the improvement rate on energy efficiency, and doubling the share of renewable energy in the energy mix.

Presently, renewable energy's contribution to World Energy is marginal, as shown in Fig. 8, where renewables amount to 10.5% for 2017, taking into account Hydro, Solar, Wind, Geothermal, and Biomass (BP 2018). Renewables consumption for 2014 is shown in Fig. 27, where the USA, China and India are the largest consumers. But if a forecast is made, using available data and projected trends, the extrapolated possible growth for oil, wind, and solar, to year 2024, is that solar might reach 9900 Mtoe, wind 1380 Mtoe, and oil 4420 Mtoe, see Fig. 28.

But renewables comprise other options, besides solar (photovoltaic and thermal), wind and geothermal. Those options are: Tidal power; Wave energy; and biomass. For a wider discussion Boyle's reference can be used (Boyle 2004). Another issue is country assessment to obtain data for renewable energy availability. A simpler, but illuminating method, for assessing is presented by (MacKay 2009) where Hydroelectricity, Inland and Offshore Wind, Solar, Wave, Tide and Geothermal sources are evaluated and set properly within society's needs, thereby providing a systemic outlook.

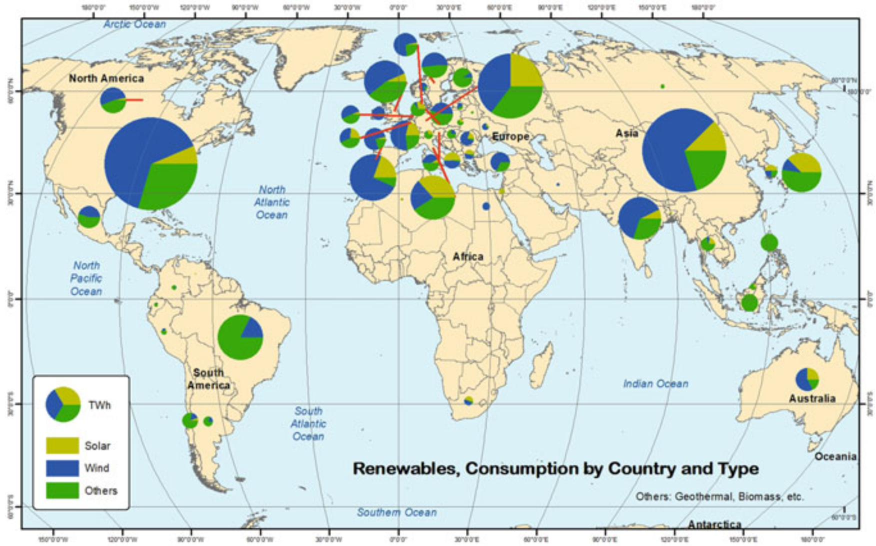

Fig. 27 World renewable energy consumption for 2014

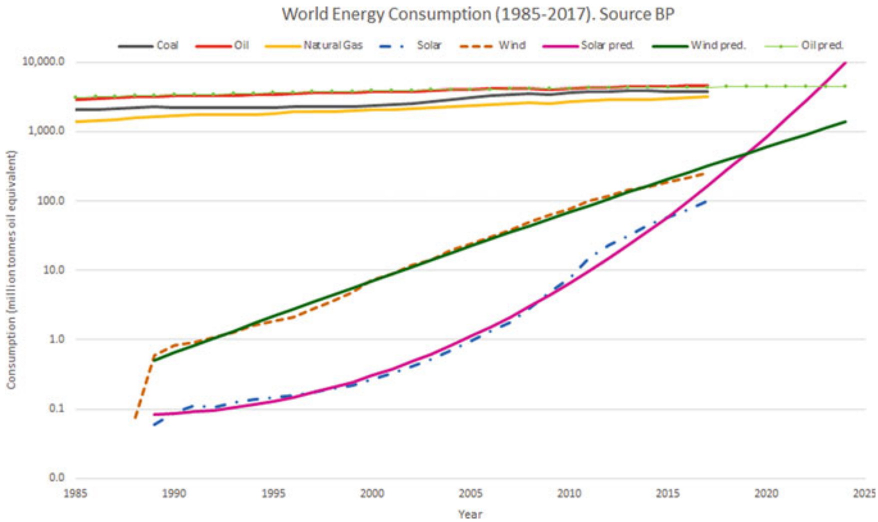

Fig. 28 World energy consumption showing extrapolation for oil, wind and solar up to 2024

8 Conclusions and Recommendations

Other chapters in this book will address different topics regarding policy, energy efficiency regarding transition to a low carbon economy, as well as fossil fuels use, market evolution and restructuring, the role of micro grids, trends and challenges in sustainable electricity generation, assessing residual biomass for energy generation, the relevance of decision-making collaborative centres in sustainable energy in Mexico. Considering as a frame of reference Sustainable Development.

- For Mexico, dependence on fossil fuels, mainly oil and natural gas, will remain for decades to come. But the potential to generate an important energy base with renewables is a Nature's gift.
- Throughout the country Solar and Wind potential exist, as well as Ocean wave electricity generation, in certain regions Geothermal energy is available. The latter to emphasise the possibilities for business participation, as well as to deepen the educational stance towards full consciousness on renewables importance, fostering sustainability.
- Furthermore, based on energy intensity, due to the medium-term reliance on fossils fuels, the recommendation to improve energy efficiency for fossil fuels is paramount, there is a moral and economic mandate to extract maximum usable work from every bit of energy contained in the fossil fuels used.
- This, once again, can generate a myriad of business opportunities, regarding efficiency, and from the educational perspective the training and learning skills to address efficiency for the pertinent professions.
- Participating in this energy efficiency effort the following stakeholders can play their part: Businesses, Municipal, State and Federal Government, Educational institutions, and the general public.

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Chapter 2
Energy and Environmental Policy and Economic Development

Luis Serra-Barragán, Edmundo Molina-Perez, and Zeus Guevara

Abstract The Stockholm Declaration of 1972 first officially recognized the call for worldwide Sustainable Development. Almost fifty years after that, the world has its greatest opportunity to pursue this goal. Environmental policy and energy policy are key tools for achieving sustainable development as there are a fair (and growing) number of worldwide experiences that show that the focus on environmentally-responsible practices can boost growth. Developing countries are those to get the most benefits, as they are the most affected by environmental threats. In light of the latter, this chapter revisits the theoretical perspectives on micro and macro system on economic development and environmental policy. The case of Europe is stressed as an example of successful integration of the latter into overall policy action. The chapter then discusses the role of Sustainable Energy Technologies (SET) and other alternatives as core elements of a sustainable and economic growth driven framework, and analyzes Portugal context within the European Union as a case study. Lastly, this chapter identifies challenges and opportunities for Mexico to build an integrated energy and environmental policy framework that supports development considering the tension this creates with the policy standpoint of the country's current administration.

Abbreviations

ASEA	Agency for the oil and gas sector (Mexico)
CEL	Clean Energy Certificates (Mexico)

L. Serra-Barragán (✉) · E. Molina-Perez · Z. Guevara
Escuela de Gobierno y Transformación Pública, Sede Mixcoac, Tecnológico de Monterrey, Av Revolución 756, Segundo Piso, Nonoalco, Benito Juárez, 03700 Ciudad de México, CDMX, Mexico
e-mail: luisalberto.serra@tec.mx

E. Molina-Perez
e-mail: edmundo.molina@tec.mx

Z. Guevara
e-mail: zeus.guevara@tec.mx

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CFE	Federal Electricity Commission (Mexico)
CIT	Carbon Intensive Technologies
CNH	National Hydrocarbon Commission (Mexico)
CRE	Regulatory Energy Commission (Mexico)
ENE	National Energy Strategy
EU	European Union
GHG	Greenhouse Gases
IMO	International Maritime Organization
MIBEL	Iberian Electricity market
PEMEX	Mexican Oil State Company
PNAC	National Program for Climate Change
PNAE	National Energy Efficiency Action Plan (Portugal)
PNALE	National Plan for the Allocation of Emission Allowances
PV	Photovoltaic
R&D	Research and Development
SCE	National System of Certification of Energy and Air Quality in Buildings
SDG	United Nations' Sustainable Development Goals
SET	Sustainable Energy Technologies
SGCIE	Management System of Intensive Energy Consumption

1 Introduction

In 1987, fifteen years after the Stockholm Declaration of the United Nations that was a pioneer in acknowledging the effects of human activity on the environment, the World Commission on Environment and Development made an urgent call to create a global agenda for change. The response came in the form of the popular Report of the World Commission on Environment and Development; Our Common Future, led by Gro Harlem Brundtland. The so-called "Brundtland Report" aimed to create a long-term agenda for action that could fulfil the goals and aspirations of the world community. But more importantly, this Report also put forward, arguably, the most accepted definition of sustainable development to date: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

This is precisely the departure point of this chapter, since sometimes it is quite clear that there is a tension between fulfilling "present needs" without compromising "future needs", particularly when the quality of life of a society is not high. For those countries that have not reached high levels of development, environmental policy appears as a stark restriction on economic growth. Yet, most often this is false economy, because not aligning their energy requirements with their environmental limits could, in many cases, actually hamper their economic growth.

This chapter thus seeks to throw light on how countries can effectively escape such a trap by considering a systemic approach to sustainable development that makes salient the relevant policy trade-offs that arise when environmental and energy policy are not aligned to foster economic growth.

In the first part, the chapter revisits theoretical perspectives on micro and macro systems on economic development and environmental policy, with emphasis on the literature that has analysed the economic and environmental interactions of developed and developing countries in relation to economic growth. The second part of the chapter is an overview of the historical evolution of the interaction between energy and environmental policy, with stress on the specificity of the latter as key to successfully integrate it into overall policy action, particularly in Europe. The third part of the chapter presents the trade-offs that prevail in fostering economic growth when considering environmental policy in a sustainability framework. The role of Sustainable Energy Technologies (SET) as a core element of such strategy is discussed in depth, as well as different policy alternatives for integration of environmental and energy policy as enablers of economic growth. The fourth part of the chapter introduces best practice for environmental and energy policy integration, within the policy framework of the European Union, with Portugal, particularly, as a relevant case study. Finally, the fifth part of the chapter discusses an emerging economy case: Mexico's dramatic structural rearrangement of 2010s in environmental and energy policy. This part provides insight into how environmental and energy policy are intertwined into facilitating (or obstructing) a sustainable approach towards economic growth.

2 Micro and Macro System Perspectives on Economic Development and Environmental Policy

In the context of contemporary energy and environmental policy, the relationships of interests are those that describe the processes and factors that lead to economic growth. For this reason, in this section, we briefly describe the relevant studies in this field and use them to build a systemic representation of key policy trade-offs.

In this regard, the pioneering work of Austrian economist Joseph Schumpeter (1934) has provided some of the basic systemic concepts that can be used for describing economic growth in an era of accelerated technological change and innovation. Schumpeter places entrepreneurial activities and technological change at the centre of economic evolution. In his view, the economy is changed through innovation waves of "creative destruction" that transform the existing means of production and trade, eliminating the need for some services in the economy, and at the same time creating new ones. These ideas have been very influential in contemporary policy perspectives on economic development and environmental policy and place this field of study at the intersection of economic and natural systems.

Theoretical perspectives on development can be divided into three groups. The first group comprises studies that focus on understanding the role of markets and industries in shaping growth patterns; we defined these as micro-behaviour models. The second group includes studies that focus on understanding growth at the country level; we refer to these as macro-behaviour models. Finally, the third group consists of studies that have specifically focused on studying the economic and environmental interactions of developed and developing countries in relation to economic growth. In reality, these perspectives are closely linked as they use similar concepts and methods, but for the benefit of the present argument it is more suitable to describe them separately.

The micro-behaviour models of growth are primarily focused on dynamic change at industrial levels. For these models, economic development can be understood as the result of the interaction of economic agents through dynamic mechanisms such as research and development (R&D), learning by doing, economics of scale and social learning. For example, Nelson and Winter (1982) focus on understanding the influence of firms' R&D strategies, and of innovation characteristics for shaping industries' long-term structure (i.e. degree of concentration, productivity). Dosi (1988) argues that knowledge needed for developing an innovation which can be ultimately commercialized in the market, is accumulated through several dynamic processes, such as R&D, knowledge spillovers across technologies and companies, and learning by doing in the market. Dasgupta and Stiglitz (1980) incorporate the role of the market structures (i.e. monopoly, oligopoly, perfect product competition, R&D competition), while including the risk profiles of a firm's R&D strategies in their game theory model of industrial development. Their results show that free competition in products only produces suboptimal levels of R&D, while competition on R&D produces research in excess. Finally, Arthur's model (1989) of competing technologies shows that the initial conditions in technology competition can be determinant in shaping growth trajectories. He demonstrates that early random events in technology competition can favour inefficient technologies in the beginning of technological races. This initial advantage can be extremely difficult to overcome, and it can lead to market domination by inefficient technologies in the longer term.

The macro-behaviour models of interest include research studies that specifically concentrate on the dynamics of economic change at a country level. Romer's model (1990) of endogenous technological change is among the pioneering works in this field. His model expands the one-sector neoclassical model by explicitly allowing economic agents to make R&D investment decisions. As a result, economic growth in his model is powered by technological change. His model is one the first models to provide a modelling framework to the empirical findings of Robert Solow (1957), and it is considered to have provided the building blocks of endogenous growth theory.

The models developed by Silverberg and Verspagen (1994) consider a broad system boundary when analysing economic change at a country level. Their model series takes into account several processes of economic change and growth that have been observed empirically, including the co-existence of concurrent technologies and the firm's heterogeneous behaviour. Their analysis shows that firms with higher R&D investment fluctuations tend to fail in the market faster than firms that have a more stable R&D strategy.

Aghion and Howitt (1992) developed an endogenous growth model in which vertical innovations, generated by a competitive research sector, are the engine of economic growth. Their model describes firms as agents that are motivated by the prospect of monopoly gains that can be captured when a successful innovation is patented. However, these gains are lost once a superior innovation is developed. In this model, technological change and growth are closely linked; the rate of growth is positively correlated with the size of innovations, the size of the skilled labour force, and the productivity of research.

In addition to the micro and macro behaviour-oriented models, there are other relevant studies that focus on the dynamics of the economic and environmental interactions of developed and developing countries.

Fernandes and Kumar (2007) use a macroeconomic dynamic model to study the welfare implications of the technological investment choices that poor and rich countries face in light of their trade interactions. Their analysis shows that there are cases in which rich countries have developed economic incentives to improve a poorer country's technology because this can yield positive welfare gains derived from better terms-of-trade with the poorer region, and from greater specialization in sophisticated goods. Lempert et al. (2006) use a system dynamics model to study the economic, demographic and environmental challenges of global sustainability.

In this study, technological change is represented by the rate at which economic development decouples from environmental pollution. They analyse the performance of different static and adaptive policies under a wide range of scenarios (5200) and show that each policy is associated with different trade-offs for the North and South, which is one of the most critical aspects of coordination between these regions. Acemoglu et al. (2009) introduce endogenous technical change in a growth model with environmental constraints and limited resources. Their model considers an economy in which only one good is produced by combining the inputs of two sectors. One of these sectors uses technologies that pollute the environment and deplete resources rapidly, while the other sector uses technologies that are more environmentally efficient. Their analysis shows that it is possible to direct technological change in the direction of clean technologies, while achieving economic growth by implementing a combination of both carbon taxes and research subsidies. They also consider the role of developed and developing countries and show that if clean sectors are substituted for the dirty sectors, policy changes in the North may be enough to avoid global environmental disaster. Silverberg and Verspagen (1995) extend their endogenous growth model to analyse the dynamics of the interaction between multiple countries. In their model, countries can interact through technology transfer and behavioural imitation. Howitt (2000) also has extended his earlier Schumpeterian growth model into a multi-country version. In this model, countries are only connected through technology transfer. Their simulation and analysis show that countries that engage in R&D activities converge to parallel growth trajectories, while countries that do not invest in R&D stagnate.

This review of the relevant models that have been used to study economic growth at an industry level and at an international level is very useful to define and understand pertinent system relationships to be considered in current environmental policy debates. Figure 1 presents a system diagram that captures some of the ideas discussed in the previous paragraphs. Under this conceptualization, competition for R&D

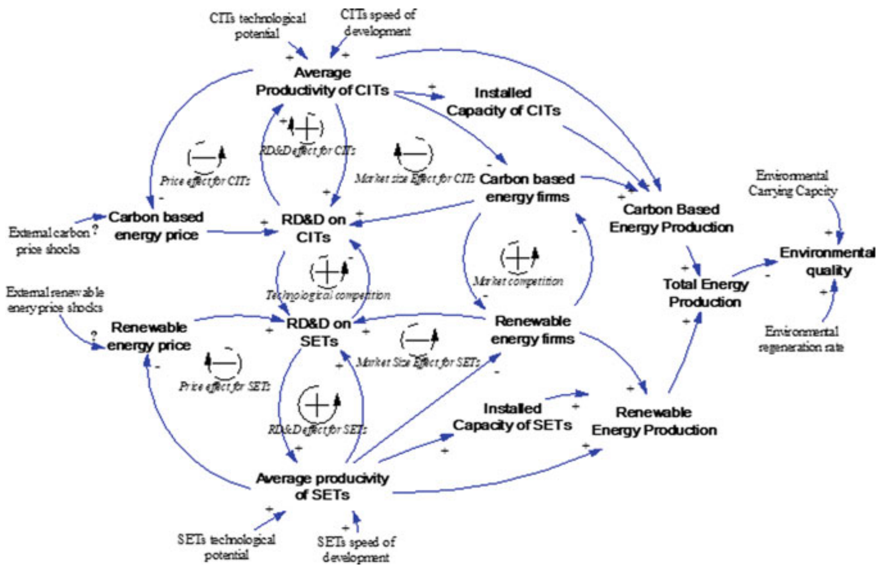

Fig. 1 Regional SETs' diffusion system diagram. *Notes* The links between each variable represent the direction in which a variable influences the other. The cardinality of each link specified is as follows: a positive cardinality indicates that the two variables change in the same direction (e.g. if one variable decreases the other also decreases), a negative cardinality indicates that the two variables change in opposite directions (e.g. if one variable increases the other decreases)

resources and for market power is the central force that directs technological change towards Carbon Intensive Technologies (CITs), or Sustainable Energy Technologies (SETs). We show three feedback loops which are central for supporting the development and penetration of a given technology, these are: The price effect; the R&D effect; and, the market size effect. The evolution of each technology's productivity plays an important role in changing the price of the energy being produced with that technology, and also in creating incentives for investing in its R&D and in the creation of new firms that use this technology for energy production. The productivity of each technology is a function of its technological potential and of its rate of development. The technological potential refers to the marginal increase in productivity per incremental innovation, and the speed of development refers to the frequency at which these innovations occur. The energy mix produced using CITs and SETs impacts directly the environmental quality of the region, for example, quantity of greenhouse gases emitted per unit of energy produced. Finally, the initial state of this system is such that SETs are behind CITs in terms of productivity and market share. Therefore, the diffusion of SETs in this system occurs only when SETs are able to capture sufficient R&D resources and market power to make the price, R&D, and market feedback loops work for their benefit.

3 A Short History of Energy and Environmental Policy

Environmental policy encompasses a wide variety of rules, laws, and regulations regarding the use of environmental assets (including energy flows) by humans and externalities on the environment caused by human activities. We structured the history of environmental policy in five phases: Pre-industrialized; industrialization; growing environmental awareness; sustainability focus; and, integration.

The pre-industrial phase describes the set of mechanisms, rules and norms to protect and control the environment, set before the industrial revolution. Environmental policy during those times entirely focused on avoiding direct consequences of the scarcity of environmental assets on the continuation of societies, but also on reducing environmental damage that lead to human welfare decline within the immediate environmental limits (Kraft 2017; Yoffee and Cowgill 1991). For instance, there is evidence of waste disposal rules in the Roman Empire (Gray 1940), forest-harvesting quotas in the Greek empire (Hughes and Thirgood 1982), sanitation norms in the Aztec city of Tenochtitlan (León 1992), hunting restrictions in colonial America (Andrews 2006) and natural protected areas in South Asia and the Americas (mainly related to the areas' sacred designation). Energy use and consumption relied mainly on muscle power by humans and animals, and on traditional biomass (as discussed in Chap. 1, Sect. 1.1); therefore, there was not a specific energy policy. Instead, energy flows were discussed under the norms for agriculture and forestry (Harris 2013).

The industrialization phase characterizes the efforts made by early industrialized societies in the nineteenth and early twentieth centuries. The focus on environmental policy did not change drastically from the previous phase, i.e., it still focused on direct consequences and damage within the immediate environmental limits,[1] the scale of those limits grew as urban societies and its technological base became more complex and connected to each other (Kraft 2017). Moreover, industrialisation led to a radical change in manufacturing processes, which in turn put more pressure on environmental assets (Andrews 2006). Also, during this phase, the first two official natural protected areas worldwide were legally recognized: one, in the island of Tobago and the other, in the United States (WHC 2019; Kraft 2017). Particularly, energy policy consisted mostly of allocating the ownership of natural energy resources among the industries that extracted, transformed, and marketed them for securing supply and meeting domestic demand (Colmenares 2008; Stiftung 2014).

The growing environmental awareness phase describes the arising consciousness about environmental threats from within and outside the immediate environmental limits by modern societies. This occurred from around the mid-twentieth century until the early 1970s, and the rising activism by society and governmental actors as a response to these perceived threats (Kraft 2017). Formal economy-wide policies were set, which were self-contained and included several policy instruments for its implementation and enforcement. For example, the Clean Air Act in 1956 in the UK

[1] The immediate environment refers to an area of natural environment within which a certain society lives and performs most of its activities. Particularly, the immediate environment provides **direct** environmental services to the particular society (e.g., sanitation, air cleansing, and water provision).

and the Air Pollution Control Act in 1955 in the U.S. were the first legislation to approach the increasing pollution problem in big cities (Muskie 1968; Sanderson 1961) Also, the first Environment Action Program of the European Council was crafted in 1973 and included product and environmental quality norms (Hey 2005). Moreover, during this phase, some of the most important environmental protection organizations were funded, e.g. the World Wide Fund for Nature in 1961, and Greenpeace in 1971 (Greenpeace 2019). Therefore, this phase marks the beginning of modern environmental policy and governance (Andrews 2006). On the flip side, the Arab Oil Embargo of 1973 put emphasis on the fundamental role of energy use in economic growth (Hoffman and Jorgenson 1977; Manne et al 1979) [1] and on the need for reducing oil dependence for energy security concerns (Stiftung 2014), but also on mechanisms to foster energy efficiency in industry, particularly in the chemical industry as presented in Chap. 3. Due to the latter, energy policy expanded its focus to setting market rules for the energy sector, specifically on trade tariffs, taxation, and oil commodity prices (Hartnett 1991; Bamberger 2003). It also extended to research and the development of alternative energy sources and energy-saving strategies (Solorio and Jörgens 2017; Stiftung 2014).

During the sustainability focus phase (1980s and early 1990s), there was a change of focus for environmental policy due to a worldwide awareness of the natural limits of growth related to the scarcity of non-renewable natural resources (Hey 2005) [the example for copper is presented in Chap. 1], and also on the related economic, social and intergenerational issues. Environmental policy represented one of the most important tools to fulfil the recommendations for sustainable development of the 1987 Brundtland report (Keeble 1988). Moreover, climate change concerns, arising in the early 1990s, required further specialisation of environmental policy and became one of its central considerations. Thus, the evolution of environmental policy became more complex as it needed to balance counteracting forces, such as, economic progress, growth of material consumption, energy security, emissions reduction, international cooperation, and political control (Kraft 2017). During this phase, the first United Nations Climate Change Conference took place in 1995, where the foundations of the Kyoto Protocol were established (Stiftung 2014; Oberthür and Ott 1999). Energy policy kept a market-based orientation, mainly focusing on enhancing market efficiency through liberalisation, competition, and privatisation (Helm 2005; Pearson and Watson 2012; Tenenbaum et al. 1992). Policy for the promotion of renewable energy technology attracted more attention, but had little success (Hey 2005). In addition, despite the main focus on energy, policy at that time was not on concerns about climate change and energy-related environmental impact (Fells and Lucas 1992; Jackson 1992), this market-oriented approach induced better quality of policy instruments for reducing GHG emissions (Pollitt 2012).

Finally, the integration phase refers to the trend of complete integration of environmental and sustainable development objectives into all areas of policymaking, including non-environmental sectoral policy, during the last two decades (Lafferty and Hovden 2003). This integration also includes a better coordination between individual environmental policies (EU 2019a) and the full realignment of energy policy to other environmental policies (Pearson and Watson 2012)—see Sect. 5. Despite this, the fact that such integration has only occurred partially, especially in Europe, it has therefore made slow progress so far (Nilsson 2005). Environmental policies have become less ambitious than their predecessors, but more specific in terms of implementation and enforcement to increase their chances of success (Hey 2005; EU 2019a). During this phase, energy policy has deepened its focus on climate change, even fossil-related policy (Murray and King 2012; Van de Graaf and Verbruggen 2015). In this regard, policies for the development and promotion of renewable energy, and for the regulation of residential and industrial energy consumption and efficiency have been issued in most countries that signed the Paris Agreement (Braun and Glidden 2014; Meckling et al. 2017; Solorio and Jörgens 2017).

[1] The Arab Oil Embargo also boosted the field of energy-economic modelling (Miller and Blair 2009; Manne et al 1979).

4 Trade-Offs in Inducing Growth Through Environmental Policy and Sustainability

In response to several multi-lateral agreements, a large set of counties have defined national energy and environmental policies to face common challenges, such as Climate Change. The objectives of these strategies are to prepare nations for future Climate Change, and to reduce the Greenhouse Gas emissions (GHG) of their economies in order to induce economic growth (CICC 2007).

The diffusion of Sustainable Energy Technologies (SETs) is a core element of these strategies. The assumption is that SETs have the potential for protecting a nation's natural resources, reducing GHG emissions, and fostering the creation of new environmentally sustainable market niches. However, although the intent of these policies seems to balance correctly the economic, environmental, and social concerns, in reality, it is still a contentious issue of how to achieve the right balance between protecting the environment, and enhancing equitable economic growth and social development. This has raised concerns about an individual nation's capacity for successfully achieving these multiplicities of goals.

Future prospects are also challenging. The rate of economic and demographic growth of developing economies is expected to continue rising over the following decades, and this will increase the pressure on their natural resources and the vulnerability of their populations to Climate Change.

Social factors are especially important when considering the developmental trajectories of developing countries in the context of environmental policy. In contrast to developed nations, developing countries are undergoing a process of transformation in which their public institutions, as well as their citizens' economic values, are being established as a direct consequence of the maturation progress of their democracies. The outcome of these transformations is highly uncertain, and history provides various examples where unexpected transformations can take place in developing countries (e.g. the Arab spring, China's vigorous economic growth).

There are three dimensions to these social factors that seem to be the most relevant for environmental policy and for stabilising these countries' greenhouse gas emissions: (a) population growth, (b) economic growth, and (c) consumers' preferences. In particular, these dimensions are more relevant in emerging markets, such as China, India, and Brazil.

The population growth of developing countries is an important consideration in this context. Population growth increases these countries' energy demands, which may result in higher greenhouse gas emissions. However, it also increases the potential economic value of their energy markets which increases the attractiveness of these markets for developers of SETs and CITs. Nevertheless, it is not clear if the populations of these countries will continue growing in the coming decades. Experience in some developing countries suggests that deviations can occur. For example, the growth path of Mexico's population drastically changed during the 80s because of the implementation of family planning policies which contributed to stabilising Mexico's growing population. However, recently Mexico's birth rate has steadily grown, making it uncertain whether the population of Mexico will remain at stable levels, or will continue growing in the coming decades. China offers another interesting example. In this case, the one child policy successfully stabilised China's population, but current concerns about the fiscal burden of China's aging population may incentivise Chinese policy makers to encourage population growth in the coming decades.

The economic growth path of developing countries is perhaps more relevant than their population growth. Especially when considering the future economic growth of emerging economies such as China, Brazil and India. Over the last decade there has been ample speculation regarding the economic prospects of these countries. However, recent economic events show that the economic dynamisms of these economies may be diminishing. For instance, the sustained rapid economic growth of emerging economies may allow them to adopt SETs more rapidly because their consumers and firms will have more resources to invest on cleaner energy sources. Economic growth may also help these countries develop their local human capital, which can also support the adoption of more advanced SETs. In contrast, economic growth is also strongly correlated with growth in energy demand which can rapidly increase the usage of CITs and result in higher greenhouse gas emissions for these countries. As has been presented in Chap. 1, as discussed by Smil (2017) and White (2007).

The evolution of consumers, firms, and policy makers' preferences in developing nations is another important factor for determining the success of environmental policy. In particular, it is unknown to what extent these actors will become environmentally conscious, which can have a significant impact in their technology adoption decisions.

Although each country faces its particular conditions for the successful diffusion of SETs, generally, policy alternatives to foster its diffusion face two major challenges for their large-scale success. First, many of these technologies need to be diffused in mature industries in which dominant technologies already exist. Such is the case of the automobile and fuel industries, in which the internal combustion engine is the dominant technology. The internal combustion engine has been improved to such an extent that it has become a cost-effective mobility solution for a vast number of consumers. Therefore, the use of vehicles with internal combustion engines is deeply rooted in the preferences and practices of car manufacturers, fuel suppliers, and consumers. Similar complexities can be found in other fields in which SETs are intended to be diffused, such as electricity production. Secondly, SETs are highly sophisticated technologies that need advanced human capital, and advanced institutional and innovation systems to foster their development. Even in the case of wind energy, which is one of the most mature SETs, the technical complexities of the technology have influenced the creation of new firms and institutional arrangement to steer its diffusion. For example, Shell tried over several decades to become a wind energy developer, but it failed to do so while other newly created firms, such as Iberdrola, have become global leaders in the field. In addition, not all countries have been successful in developing the adequate institutional and innovation arrangements for wind energy. Germany and Denmark are well known success stories, while The Netherlands has fallen behind these countries, in spite of having started the first diffusion of wind energy (Jacobsson 2000, pp. 635–639).

Thus, competition with incumbent technologies and the sophistication of SETs are two important factors to consider when seeking to use environmental policy as a lever of economic development.

Many countries are implementing a mixture of policies aimed at strengthening the development and diffusion of SETs and inducing growth (IEA 2011). In general terms, these strategies can be grouped in two main categories; these are: hybridization strategies and market niche management strategies. Hybridization strategies consist in achieving first the diffusion of an intermediate technology between the incumbent carbon intensive technology and the radical sustainable energy technology. The diffusion of the hybrid technology can create sufficient institutional and economic inertia, and technological learning to foster a more cost-effective second phase transition towards the radical technology. Market niche management strategies are aimed at creating controlled competition environments for SETs, through the implementation of targeted policy incentives aimed at strengthening the competitive position of SETs, while maintaining economic growth inertia. It can also be carried out through the deployment of regional policy experiments that can enhance the adoption of SETs in specific regions, and to scale diffusion afterwards to larger regions. In general, market niche management strategies aim at creating an environment in which policy makers can learn more about the economic challenges of SETs, without being negatively affected by competing against mature incumbent technologies, or causing unintended economic consequences (Raven 2007).

In addition, for many countries, technology transfer is another important strategy, needed for the successful diffusion of SETs in their territories. Technology transfer can provide developing countries with the means to catch up on advanced economies in the diffusion of SETs. The dilemma is to find an approach to technology transfer that is cost effective for both technology developers and technology adopters (OECD 2009, pp 19–20). This is particularly important because if SETs' technology transfer is enhanced vis-à-vis CITs, emerging economies could potentially leapfrog advanced economies' SETs diffusion rates.

Table 1 provides a qualitative assessment of these policy alternatives. It is clear that the analysis remains at a very abstract and general level. Nevertheless, it shows that these alternatives could be complementary to each other, and that their importance to enhance economic growth will vary across regions.

The types of carbon regulation policies and the timing of their implementation represent an important strategic issue for developed and developing countries in the context of environmental policy, growth and the stabilisation of greenhouse gases. In principle, it is expected that countries will carefully consider the national and international economic stakes of implementing these types of policies. However, political and economic stakes, as well as the democratic and governance differences among developed and developing countries make it extremely difficult to realistically estimate the course of action that developed and developing countries will follow regarding the implementation of carbon regulations in their economies. Differences in regulation systems among developed and developing countries are important factors that can determine the economic and political feasibility of cooperation in environmental policy (Mattoo and Subramanian 2013).

For the case of developed nations three aspects are the most relevant: the national regulation of their economies' carbon intensity; the regulation of their trade flows' carbon intensity; and, the timing of their regulatory changes. For instance, if developed nations decide to continue supporting carbon regulation in their economies, and developing countries decide not to do so, it might be possible that this regulatory difference creates pollution havens for firms, rather than to continue pursuing a low-cost carbon intensive production strategy.

Table 1 Environmental policies and growth

Alternatives	SETs diffusion rate	Economic cost	Long term orientation
Hybridization	**Low**-Two phases required, supported by lengthy market process	**Low**-Cost of implementation is shared mainly by consumers and firms, some incentives from government	**High-**Requires commitment for several decades
Market niche management	**Medium**-Successful experiments have the potential of rapidly scaling up	**High**-Need to invest heavily on market incentives to protect SETs	**Medium**-Successful implementation in small scale environment, does not guarantee success in large scale
Technology transfer	**High**-Diffusion depends on successful adaptation of existing technologies	**Unknown**-Economic cost may vary depending on the investment needed in R&D and property rights	**Low**-It creates no endogenous capacity in developing countries to support SETs

This can have serious negative consequences for developed nations in terms of their economic competitiveness against developing countries, but also an unknown environmental impact (Mattoo and Subramanian 2013). As a result, it is likely that developed countries will also attempt to implement a border carbon tax to regulate flows from more carbon intensive economies. It is also unknown if this will be possible because the implementation of such trade regulations is extremely controversial considering current World Trade Organization's standards and regulations. Finally, developed nations can choose to implement these policies in the near term or to act later in the future when more information regarding climate change and the economic progress of developing countries becomes available.

For the case of developing nations, the set of options available is more constrained. For most developing countries (especially for emerging nations) their exports to developed countries play an important role in their economic development models (Mattoo and Subramanian 2013). Therefore, developing countries have higher stakes in choosing to implement local carbon regulation systems. For instance, if developed nations implement both border and local carbon regulations, there might also be an economic incentive for developing countries to implement local carbon regulations to continue trading with developed nations. However, the economic cost of implementing these policies for developing countries may also surpass the potential trade gains.

Developed and developing countries, through their finance and science ministries, will define over the coming years the type of support that they will grant to environmental policies. Individual countries are more concerned with technology creation policies, such as direct R&D investments, technology subsidies, or advancement market commitments that can incentivize firms to use SETs for energy production. Since there are technology spill-overs across countries and trade among their energy and technology firms, it is expected that the technology policy actions of one region will also have a technological impact on other regions.

Although, their decisions seem to be the same, the decision context differs. Governments and firms in developed countries have already invested greatly in the R&D of critical SETs, such as solar panels, wind turbines, and other critical CITs. As a result, most of the firms that are leading these technology sectors are native to these types of countries (Susman 2008). Success for developed countries implies the ability to transform their R&D and fiscal investments into new firms and markets for these technologies, while also reducing their economies' greenhouse gas emissions.

Developing countries have not invested in these technologies at the same level, and, as a result, critical SETs are external to them. Therefore, these countries will likely need to import these technologies from developed countries, which can be expensive for some of them or which can result in a failure to diffuse these technologies in their economies due to lack of native technical capacities (Ramanathan, 2002). More importantly, developing countries' first priority seems to be to achieve economic development in the most cost-effective way, which implies using mature and cheap CITs for satisfying their economic development energy needs (Mattoo and Subramanian 2013). Therefore, for developing countries it is important to decide which type of technologies their environmental policies will support (i.e. SETs or

CITs). These individual country decisions will be made in a complex trade and technological environment. The interconnection of these countries will likely bring surprises to their individually cantered objectives.

5 Best Practices: The European Union Policy Framework

The European Union has developed some of the most sophisticated energy, and environmental policies worldwide since the 1990s (Andersen and Liefferink 1999). Nowadays, EU environmental policy framework represents the standard of quality, completeness, integration and overall alignment to sustainable development objectives (Haigh 2015). The construction of this framework has required innovative governance to achieve convergence of countries, with previously narrow national environmental policies, towards the most advanced member states; as well as, to reach acceptance of supranational policy directives by individual governments (Bondarouk and Mastenbroek 2018). Moreover, the successful negotiations of the former Kyoto Protocol and the recent Paris Agreement have confirmed the global EU leadership in international climate policy (Hey 2005; Oberthür and Groen 2017).

Nevertheless, the EU environmental policy framework is not without drawbacks and challenges. For example, incomplete compliance by member states has caused a halt to EU policy-making and, instead, led to multiple amendments to existing policies (Börzela and Buzogány 2019, Scanlan et al. 2013).Renewable energy and energy efficiency policy, instead of promoting green growth, has affected competitiveness mainly because of rising costs of climate measures, economic distortions brought about by environmental taxes and exemptions, and high energy prices driven by ambitious short-term renewable goals (Ekins and Speck 1999; Helm 2014; Slominski 2016). Furthermore, the over-focus on climate change objectives has caused a passive policy dismantling in other policy areas such as clean air and water protection policies, which have been relegated in the environmental policy agenda since 2010 (Steinebach and Knill 2017). The internal energy market (i.e. a unified cross-border energy market system) has not materialised mainly due to energy security concerns, such as ownership of natural resources, protection of national energy companies and mistrust between member states, and due to incompatibility issues of physical infrastructure (Eikeland 2011; Helm 2014). In addition, emission reduction trends were mainly caused by de-industrialization and slow growth rather than by the direct effect of environmental policy (Helm 2014).

EU environmental policy framework

The EU environmental policy's legal basis rests in four articles in the Treaty of Functioning of European Union, which establish EU's competency in all areas of environment policy (Fig. 2) within five policy levels (Hey 2005, EU 2019a).

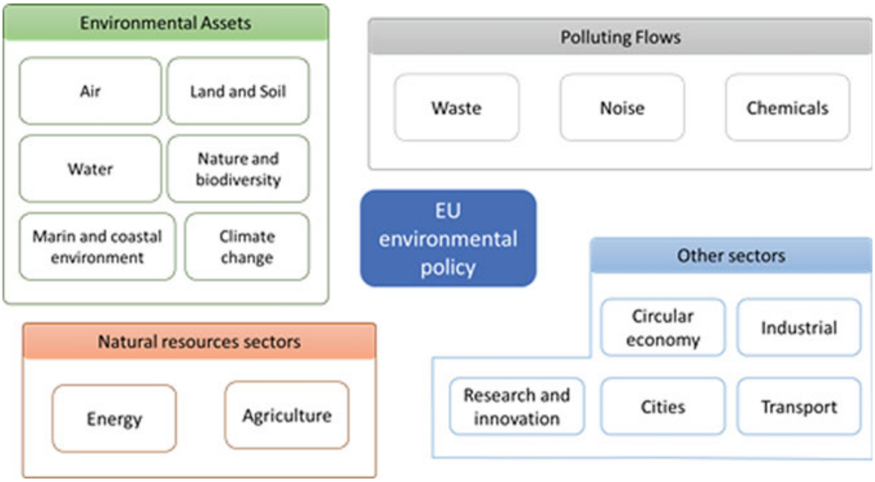

Fig. 2 Areas of EU Environmental Policy. *Source* EU (2019b). *Note* Figure of our own making and own classification

(1) The Environment Action Programme, the highest order policy, establishes nine priority objectives, such as ecological resilience and low carbon growth, and defines strategic initiatives and implementation considerations.
(2) Horizontal Strategies define detailed sustainable development pathways to reach all priority objectives. For example, the Europe 2020 strategy.
(3) International environmental cooperation aligns EU policy under international agreements and aims to maintain EU global leadership in environmental policy.
(4) Environmental impact assessment and public participation establishes the obligations on environmental responsibility for economic sectors and public rights in environmental decision-making.
(5) Implementation, enforcement and monitoring consists of specific policy instruments, contained in hundreds of directives, regulations and official decisions. At this last level, supranational policy is transposed into national policy for implementation.

As shown in Fig. 2, EU environmental policy framework covers most, if not all, environmentally relevant areas for sustainable development. Notably, it still requires further evolution to address current and future challenges regarding, for example, compliance, policy integration, state-level governance, emission transfers through trade and over-regulation (IEA 2014). Nevertheless, it remains the most advanced and flexible framework worldwide to approach global and regional environmental threats.

EU energy policy

EU energy policy is key for fulfilling climate change objectives and international commitments, as well as for guaranteeing economic security, geopolitical stability and sustainable growth in the EU bloc for the long run (Goldthau and Sitter 2015; Szulecki et al. 2016). It is centrally planned by the EU, though it is flexible in respect of member state sensitivities about decision-making on national energy mix, and energy resources ownership (Herweg 2017; IEA 2014).

This policy has the following objectives (EU 2019c).

1. A functioning internal energy market and interconnected energy networks;
2. Security of energy supply;
3. Improvements in energy efficiency and savings;
4. De-carbonization and transition towards a low-carbon economy;
5. Development of alternative energy technologies within the internal energy market; and
6. Research, innovation, and competitiveness.

Furthermore, it defines targets, support schemes, safety standards, monitoring procedures, market rules and financing mechanisms in the field of Energy efficiency, Renewable energy, Fossil energy, Nuclear energy, Energy security, Markets and consumers and Energy infrastructure (IEA 2014; Kanellakis et al. 2013). In addition, the implementation of such a complex policy framework leads to lower compliance than for other environmental policies (Herweg 2017). Nevertheless, there have been successful cases among member states; specifically, the case of Portugal is described below, as it can provide insights on how to successfully integrate advanced energy policy into underdeveloped energy governance settings.

Example of successful compliance to EU energy policy :Portugal 1995–2010

Portugal is an energy success story of the EU as it transitioned from a mostly fossil to a mostly renewable power sector, and significantly diversified its primary energy mix in less than 15 years (Guevara and Rodriguez 2016). To do so, it gradually transformed its energy policy for complete compliance with the EU and proposed other policy instruments that helped EU's energy policy to better adapt for the domestic settings (Guevara and Domingos 2017).

By 1995, two main energy policies were in force: The Regulation on Energy Management, and the Energy Program. These policies lacked a roadmap for their implementation and did not set specific targets on energy efficiency and renewable primary energy share. Notably, in 1998, the country received for the first-time natural gas from a recently opened distribution network in Northern Africa.

Aligned with rising climate concerns, the national Climate Change Commission was created in 1998 and the National Strategy of Climate Change, issued in 2001 (ENAC), included general measures on energy supply and consumption without specific targets. Portugal ratified the Kyoto protocol in 2002, in which the country, as part of the EU, was allowed to increase its GHG emissions by 27% compared to 1990 due to its lower economic development than other member states.

The 2003 energy regulation resolution established a target of 39% share for renewable electricity generation by 2010, with a non-conventional renewable generation capacity of 4.68 GW (more than 10 times the 2001 capacity) due to an estimated investment of 5 billion euros (10^9 euros). Moreover, this resolution outlined the liberalisation of the energy market (aligned to EU Directives 2003/54/EC and 2003/55/EC), the concretization of the Iberian Energy Market, and support schemes for rational energy use. In addition, this resolution led to the total liberalisation of fuel prices to final consumers as of January 2004 (ENMC 2016).

Furthermore, after two years of public discussion, the National Program for Climate Change (PNAC) was launched. The PNAC set the following energy objectives: 8.6% less losses in the transformation and distribution of energy, an increase to 18% cogeneration for power generation, 1,300 GWh energy savings in direct demand, deployment of 3.75 GW renewable generation capacity, and the introduction of natural gas to Madeira Island. Furthermore, the government between, 2003 and 2005, increased the targets for renewable generation capacity (Maranhão de Abreu 2006). It also put pressure on quality and cost improvements in energy utilities and services, on implementation of the Iberian Electricity Market, and on liberalisation of natural gas and electricity markets.

A National Energy strategy was issued in 2005 (ENE, aligned to EU Directive 2001/77/EC). This strategy was extensive: it considered a regulatory framework for competition in the electricity sector; an energy efficiency action program; carbon and energy taxation schemes; licensing simplification for renewable projects; support for research and development on energy diversification, energy efficiency and carbon capture and sequestration; and programs for public awareness and evaluation of the ENE. Moreover, the National Plan for the Allocation of Emission Allowances was issued in 2005 (PNALE), which set measures for emission license trading, aligned to the EU Directive 2003/87/EC, and proposed the creation of the Portuguese Carbon Fund to support projects in energy efficiency and renewable sources (Carvalho et al. 2014).

In 2006, policies for a National Electric System, and a National Natural Gas System structure and operation were launched, in accordance with EU directives 2003/54/EC and 2003/55/EC, respectively. As of September 2006, the energy market established that all consumers can purchase electricity from the supplier of their choice, with independent distribution system operators, thereby meeting the requirement of EU directive 2003/54/EC (ERSE 2009a). However, the natural gas market was not able to meet the requirements of the EU directive 2003/54/EC; instead, the Ministers' Council determined the schedule for later compliance (ERSE 2009b).

In that year, the Portuguese Carbon Fund was created; a new version of the PNAC was launched; the EU Directive 2003/30/EC on the promotion of renewable fuels for transport was implemented; and the National System of Certification of Energy and Air Quality in Buildings (SCE) was created (in line with EU Directive 2002/91/EC).

The Iberian Electricity market (MIBEL) started operating in 2007 (Carvalho et al. 2014). The MIBEL structures the operation of the joint market, establishes a single price, enhances transparency and free competition, removes entry barriers, and promotes economic efficiency (Domínguez and Bernat 2007). A similar joint market for natural gas was discussed (IEA 2016).

The National Energy Efficiency Action Plan 2008–2015 (PNAE, aligned to EU Directive 2006/32/EC) defined measures to achieve the EU target of 10% savings in direct energy use by 2015. The PNAE included measures and programs for the promotion of rational energy use in the residential and service sectors and complements the PNAC and ENE measures for the industrial and public sectors. In the same year, the Management System of Intensive Energy Consumption (SGCIE) was launched (aligned to EU Directive 2006/32/EC), which required from energy intensive industries a strategic plan for rational energy use and imposed on them compulsory energy auditing. Moreover, EU Directive 2006/32/EC on energy end-use efficiency and energy services was transposed, which established an energy saving target of at least 9% by 2016 and was related to other policies such as the PNAE, the SCE and the SGCIE.

Finally, in 2010, the ENE was updated (EU Directive 2009/28/EC), which extended the planning period to 2020. The 2010 ENE highlighted the contribution of other renewable sources besides wind generation, and increased support for research and development activities. Also, the first version for public discussion of the National Renewable Energy Action Plan (PNAER), and the Energy Efficiency Fund were released in that year.

6 Mexico's Position

Mexico's current environmental and energy institutional frameworks have been largely shaped over the course of the 2010s decade.[2] Driven by market liberalisation reforms and by an ambitious agenda of international investment attraction, in just a six year-span Mexico allowed for private participation in its energy sector and adhered to both the Paris Agreement and United Nations' Sustainable Development Goals (SDGs).[3] It was precisely during this period that article 25 of Mexico's Constitution was amended to include the concept of promotion of "sustainable development" as one of the State's roles in the economy.

Such grand task entailed a complete institutional rearrangement of the environmental and energy sector that included, but was not limited to: a new law of climate change, a sectorised institute for the environment and climate change, the creation of independent regulatory energy agencies and independent system operators for natural

[2] Environmental concerns were first included in the National Plan of Development in 1983 (CITA), and some advances were established during the next couple of decades. However, such efforts were isolated and did not constitute a strategic central element of Mexican policy. One of the first long run measures that tried to incorporate environmental concerns with energy planning was attained during Felipe Calderon's presidential term under the National Strategy of Energy. It was a yearly publication that spanned actions to be carried out for the next 15 years in order to foster the energy trilemma: energy security, energy transition and energy efficiency. However, the document was eradicated in Enrique Peña Nieto's second year at office never to return again.

[3] This period comprehends the six years from the promulgation of the General Law of Climate Change to the last year of Peña Nieto's presidential term, which de facto was the last year of full implementation of energy reform advances.

gas and electricity networks, a brand new environmental and industrial safety regulatory agency for the oil & gas sector (ASEA), and the legal definition of "clean energy".

The environmental objectives of the country are best summarised by the General Law of Climate Change, which establishes a commitment towards cutting Greenhouse Gas (GHG) emissions 30% by 2030 and 50% by 2050 with respect to its baseline. This implied a major challenge, insofar as Mexico, despite representing only 1% of total global GHG emissions, has an energy portfolio that relies heavily on hydrocarbons.

For that matter, several instruments had been developed to attain this goal. Some of the instruments have been complementary, like the instauration of a Cap and Trade system operated by Mexico2 and the Clean Energy Certificates program (CEL, by its acronym in Spanish) operated by the Regulatory Energy Commission (CRE). However, the underlying objectives of Mexico's 2013 energy reform and environmental commitments seem to be misaligned shall they both aim towards a sustainable model. On the one hand, there is an ambitious goal of to reduce GHG emissions, but on the other there is also the vision (and fiscal revenue requirement) to revamp oil & gas production back to 2.5 million barrels per day by 2024.

Mexico's new administration's energy policy has also complicated matters of alignment with respect to the previous environmental commitments on several trenches.[4] Firstly, GHG emissions reduction would come in part from the increasing use of renewable energy in electricity generation. But this in turn depended on the continuation of key infrastructure for electricity transmission projects that would allow more remote renewable sources to be incorporated into the grid, as well as on the follow up of tender processes that generated incentives for new investments.[5] President Lopez Obrador's administration cancelled both.

In second place, the independence of regulatory agencies is cornerstone to preserve the framework for incentive mechanisms to shift the energy use portfolio from fossil fuels to non-fossil sources. As it turns out, on 28 October 2019, the Ministry of Energy presented an agreement through which the rules that established the criteria to assign and acquire CEL were modified. The accepted modification, of which CRE has been supportive despite international astonishment, basically eroded the additionality criterion that laid out the basis for CEL to promote new investments

[4] The starkest of them comes from the fact that in the Nation's Project 2018–2024, President López Obrador's political platform as a candidate, the energy vision is called "Oil Program", with a strong stance in favor of increasing oil and gas and fuels production. But others include the increase in coal purchases for CFE's generation plants and the constant public declarations of high officials from CFE and CENACE (grid's ISO) that renewable sources are both expensive and inefficient.

[5] Peña Nieto's administration created three tender processes with more than 40 firms participating with a total 9 thousand million USD investment for generation capacity, of which more than 90% was renewable. The average price of the last tender reached a worldwide record-breaking level of \$20.57 USD/MWh.

on (cheaper) renewable energy projects.[6] Without such instruments, it would prove really hard for Mexico to fulfil the mark of 35% renewable generation by 2024.

Third, one of the flagship projects of the current administration is the construction of a new refinery in Paraíso, Dos Bocas, Tabasco. While it is true that Mexico has, in the last decade, lost its status of energy net exporter to become a net importer, the project presents at least two major flaws relevant to our discussion. On the one hand, the mere existence of a new refinery would represent a net increase in GHG emissions by 2030.[7] On the other hand, the technical assessment with respect to the environmental impact of the refinery, although approved by ASEA, it is incomplete because it does not reveal the full extent of the territory the project comprises nor the exact coordinates where it would be located.[8]

Last but not least, because of lack of a long run energy policy, Mexico faces a scenario where perverse incentives might be triggered to go back to fossil fuel (and more costly) electricity generation. In January 2020, the new regulation of the International Maritime Organization comes to place, by which a limitation of 0.5% sulfur specification for bunker fuel needs to be met (IMO 2020). Mexico is an exporter of fuel oil, but its current refineries configuration would certainly not allow the country to meet IMO 2020 in time. In order to not waste the product, it might be tempting for Mexico's public electricity utility, Federal Electricity Commission (CFE), to use such product for its own plants.

While not flawless, the institutional framework created over this decade in Mexico for a more encompassed energy and environmental policy seemed to be on a right path. Nevertheless, only one year after the most radical shift in economic policy in the past four decades, the joint fulfillment of energy and environmental goals in order to establish a sustainable paradigm is jeopardized.

As other countries, Mexico faces the challenge to balance its short run needs with its long run aspirations. There are technological game changers that lie ahead to speed up fossil-fuels phasing out, like the evolution of the electricity storage industry (i.e. batteries), electromobility, smart grids, and distributed generation. Yet, the major

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[6] Basically, the incentive-based mechanisms were designed to promote new investments in clean energy (mainly from solar PV and wind generation plants) by giving them market advantage with respect to older more expensive and dirtier generation plants. The mechanism aimed to create an environment where firms with the latter central plants (mainly CFE) would have to buy certificates from the former (mainly new investments), thus giving recent clean energy projects a competitive advantage that would allow the addition of new (clean) energy sources that might have not occurred otherwise.

[7] According to the Mexican Center of Environmental Law (CEMDA), if the new refinery initiates its operation by 2022, the annual CO_2 equivalent output would rise to 2.16 million metric tons which would imply a total output of 17.3 $MtCO_2$ equivalent by 2030, thus jeopardizing the Nationally Determined Contributions under the United Nations Framework Convention on Climate Change (CEMDA Bulletin No. 33/19).

[8] While ASEA's argument about not providing full information about the refinery project is based on grounds of industrial protection for PEMEX in an open market setting, there is genuine concern about the independence of ASEA's environmental impact assessment given that the new Executive Director lacks professional experience in both environmental and industrial security fields, but is a close former collaborator of Mexico's President.

threat for a country like Mexico, given its current status of electricity coverage, cost and grid reliability is to focus on such opportunities without exploring first the low-hanging fruit: the strategic expansion of its transmission network. Even if the technological adoption of batteries comes earlier than expected, Mexico's energy transition largely depends on the capacity to connect generation hubs with consumers, a matter that batteries on its own will not resolve.

The sector in Mexico with the highest contribution to GHG emissions is transport. In this respect too, Mexico faces a wide array of challenges should it create opportunities for massive electromobility. Yet, once a more robust transmission network is addressed, infrastructure of distribution and of electric service stations, as well as new business ventures for public transport must be the at the top of priorities for public policy.

Another element that must be revisited in aligning energy and environmental policy and goals is the role of private investment in the energy sector. According to the Ministry of Energy, Mexico's installed capacity of solar PV reported an increase by a factor of 11 during the 2012–2018 period, due to private participation and cumulative investments of 9 billion USD stimulated by the energy reform. The financial health of CFE does not seem to allow the company for big new renewable energy projects from public investment.[9]

Finally, one of the major characteristics of President López Obrador's administration is the lackluster place environmental concerns occupy in his agenda. While several efforts, as claimed in this section, were pushed by the Mexican government throughout the 2010s decade, the main challenge for a comprehensive environmental policy in the country is still related to the weak recognition that negative environmental impacts in Mexico represent economic costs (Serra 2017).

7 Mexico's Future

As stated in the previous section, Mexico's energy policy implemented by the current administration moves in the opposite direction of global trends in general and of its institutional framework in particular, as envisioned by 2013's energy reform.

SARS-CoV-2 pandemic is still unfolding at the time of writing this book, so there are no reliable forecasts to characterise the extent of lower than expected demand for oil and gas. Even so, and despite no change in fundamentals have been observed in the hydrocarbon's markets, it seems that the safe bet is to pursue a decisive agenda of energy transition in a country with premier renewable resources and highly vulnerable to climate change like Mexico. Furthermore, while President López Obrador has made it clear that no further private investments in the energy sector will be allowed

[9] CFE's financial statements report a deterioration on the Operational Balance that closed 2015 from $2.1 billion USD to 2019–$820 million USD. Net total debt in 2019 accounts for $1 billion USD. And, while total investment increased from an average of $1.67 billion USD during the period of 2015–2018 to $2.5 billion USD in 2019, most of resources were devoted to maintenance of coal, combined cycle and thermal generation plants.

in his administration, it seems not plausible he will amend any piece of the legal architecture of the energy reform, specially not after July 1st, 2020, when USMCA came into effect.

These elements provide quite a good recipe for a brighter and greener future for Mexico. What potential directions would lead to it? The very first step is to reinstate the mechanisms of market development for crude oil, natural gas, fuels, and wholesale electricity. It might seem contradictory to advocate the rehabilitation of bidding rounds for oil and gas while also pushing a sustainable paradigm. Yet, a competitive market for oil and gas might provide greater social gains than a state-monopoly model driven by a financially fragile and unregulated PEMEX. It could also set free fiscal resources to devote towards very needed infrastructure in the electricity sector, namely transmission and distribution. In the electricity sector, renewed tenders for long term energy purchase will not only represent investment flows produced by energy transition projects aligned with Mexico's overall environmental policy, but also might translate into lower prices for end use consumers, namely industry, commerce, agriculture and residential users of electricity.

The second step in the process is to allow regulators to proceed their mandate with autonomy and technical capabilities, as described in the law. Otherwise, anti-competitive behavior of PEMEX and CFE in their respective realms will accrue in deadweight loss. With the energy reform, market development required sharp and precise regulatory instruments to provide certainty for investors and ensure more efficient results in favor of consumers. Before being captured by López Obrador's energy policy and political objectives, both Regulatory Energy Commission (CRE) and National Hydrocarbons Commission (CNH) were on track to become tip of the spear amongst regional regulatory bodies in the energy industry; sustainable energy policy requires to recover such institutions as they were envisioned by law.

Another major element to reactivate are energy infrastructure plans, particularly regarding natural gas and electricity networks. The world is leaning towards both industries as the steering wheel of the economy. Mexico has enormous potential to generate clean energy from both renewable sources and natural gas, yet it faces road-blocks to implement new infrastructure projects, especially in vulnerable and indigenous communities. An adequate consultation mechanism with strong enforcement must be placed to ensure the coexistence of millennial cultures with a market-driven energy industry, and Canada's experience with First Nations' population could serve as a guide for best practices. Furthermore, infrastructure plans should characterize long-term uncertainties so as to establish resilient networks to foster energy security for the country by responding to global trends and unexpected shocks.

An additional element that must be resolved within the energy policy sphere that creates externalities on Mexico's environmental policy is the use of fossil-fuel subsidies. If compared to Middle East countries, Mexico's proportion of energy subsidies with respect to its Gross Domestic Group is quite small (circa 0.5%, IEA 2016). However, they convey misguidance for both producers and consumers and result not only in detriment of energy transition by producing an artificial advantage of fossil over renewable sources, but also in higher GHG emissions due to higher consumption. Moreover, even with the market liberalisation of fuels, the Ministry of Finance (SHCP by its acronym in Spanish) has placed price controls on gasoline and diesel through fiscal stimulus. This hinders adequate signals in a market with a consumption that produces the largest share of Mexico's GHG emissions.

Finally, Mexico has placed a heavy burden on its national energy companies, PEMEX and CFE. Not only it is expected of them to satisfy domestic demand and develop grand infrastructure projects, some of which are not profitable, but also to produce revenue and stand as the stronghold of economic development. This might have partially worked in the distant past, but it is certainly not attainable in the current energy landscape.

8 Conclusions

This chapter describes the complexity of building an environmental and energy policy framework that works for achieving economic growth and sustainable development by any nation. It highlights the main theoretical and empirical findings regarding the binomial environmental policy - growth and, based on them, suggests a sustainable path for a relevant emerging economy, i.e., Mexico.

The design of a successful environmental policy in encouraging economic growth must consider:

- The degree of substitution between carbon-intensive and sustainable energy technologies;
- A balanced environmental tax/subsidies basket;
- The configuration of the physical infrastructure for managing energy and other natural resources;
- Investment in R&D with management of competition for resources and market power;
- The socio-political context set by the incumbent government and other directly involved actors;
- An adequate timing for policy design and implementation;
- The growth, preferences and environmental consciousness of the population;
- A long-term implementation strategy for changing conditions;
- The level of development and growth path of the economy;
- The current structure of non-environmental policy; and
- Other social priorities such as health, security and well-being.

Particularly, the diffusion of sustainable energy technologies, which entails technology development and penetration to existing markets, is an indispensable condition for greener growth. To achieve so, energy policy must understand and balance the necessary price, R&D and market size conditions for such diffusion. An adequate path consists of directing an initial penetration in mature industries, in which dominant technologies already exists; while advancing human capital and institutional/innovation systems that foster the development of new firms and markets for these technologies.

Moreover, beyond growth, the integration of environmental policy is the only path that can bring a sustainable future. Therefore, the desired environmental policy framework should be flexible to allow coordination between individual environmental policies and realignment of other policy areas to environmental objectives.

Mexico's case, as exemplified by the mismatch between environmental and energy policy rearrangements of 2010s decade, represents a potential failure in the adoption of a hybrid model of SET. The most cost-effective way to introduce renewable energy and cleaner technologies to foster economic growth in Mexico was through market-based incentives, i.e. through lengthy market development processes. Yet, political disruption and a different agenda of economic development in Mexico upon the arrival of a new administration misaligned environmental and energy agendas, thus placing high risk on attaining a sustainable paradigm for the country.

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Chapter 3
Fossil Fuels Use and Efficiency During the Transition to a Low-Carbon Economy

Francisco J. Lozano, Miguel Ángel Gijón-Rivera, and María E. Huertas-Bolaños

Abstract During the transition to a Low-Carbon Economy, the need to continue using fossil fuels has to be linked with an increase in energy efficiency use. Phasing out or diminishing fossil fuel use is a medium-term challenge. This chapter will address the present-day efficiencies and potential improvement for various fossil fuels, as well as the various technologies that function based on these fuels, for electricity use, the building environment, and transport sector.

Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BASF	German Chemical Company
CEMEX	Mexican Cement Company
DOE	Department of Energy (USA)
EU	European Union
EWS	Energy World Scenario
FIDE	Trust Fund for Electric Energy Saving in Mexico
FTP	Federal Test Procedure
GRI	Global Reporting Initiative

F. J. Lozano (✉)
Tecnologico de Monterrey, Campus Toluca Avenida Eduardo Monroy Cárdenas 2000 San Antonio Buenavista, 50110 Toluca de Lerdo, Mexico
e-mail: fjlozano@tec.mx

M. Á. Gijón-Rivera
Tecnologico de Monterrey, Campus Puebla, Atlixcáyotl 5718, Reserva Territorial Atlixcáyotl, 72453 Puebla, Mexico
e-mail: miguel.gijon@tec.mx

M. E. Huertas-Bolaños
Tecnologico de Montesrrey, Campus Monterrey, Av. Eugenio Garza Sada Sur No. 2501, Colonia Tecnológico en Monterrey, C.P. 64849 Nuevo León, Mexico
e-mail: maria.huertas@tec.mx

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IEA	International Energy Agency
IECC	International Energy Conservation Code
INEGI	National Institute of Statistics and Geography in Mexico
LDV	Light Duty Vehicles
LED	Light Emitting Diode
LEED	Leadership in Energy and Environmental Design
LPG	Liquefied Petroleum Gas
NEDC	New European Driving Cycle
NOM	Norma Oficial Mexicana (Offical Mexican Standards)
OECD	Organisation for Economic Co-operation and Development
SDS	Sustainable Development Scenario
SUV	Sport Utility Vehicles
WBCSD	World Business Council for Sustainable Development

1 Introduction

An ample discussion about the transition to a "Low Carbon Economy" has occurred in recent years (WBCSD 2007; WBCSD and Leban 2008; China Council for International Cooperation 2009; McKinsey 2009). A personal commitment to a low-carbon life is presented and discussed by Goodall (2007).

But the transition will not be straightforward, it will take time. Widespread use of fossil fuels (coal, oil and natural gas) in 2017 has reached the amount of 11,510 millions of tonnes oil equivalent (BP 2018).

In Chap. 1 of present book, consumption trends for several energy sources were presented (Fig. 8). Although fossil fuel usage seems to flatten out, the total amount is still the highest. Renewable sources such as photovoltaics, wind, and solar production are increasing worldwide. Ayres and Ayres (2010) review, in depth, this transition towards a clean energy future, underlining that the time scale is in decades.

Hence, upon using energy resources the purpose is to extract as much usable energy from fossil fuels to ameliorate the transition and increase use efficiency. The term used for the latter is *exergy*; that is, the maximum amount of work that can be extracted from a system (Ayres et al. 2003; Warr and Ayres 2006). Inherent to using fossil fuels with different transforming technologies are the limits set by the laws of thermodynamics that need to be taken into account, forming part of the exergy concept.

United Nations declared 2014–2024 the "Decade of Sustainable Energy for All", related to the Millennium Development Goals, specifically item number 7 (United Nations 2012, 2019; UNDESA 2019). One relevant action for the initiative is energy efficiency.

Furthermore, Energy Intensity provides a link between economic performance and energy performance. As defined, it represents the energy use for a country, divided by the Gross Domestic Product (GDP). Values for selected countries across several years are shown in Fig. 1 (Sustainable Energy for All 2018). The lowest values are for countries with efficient use of energy, while the largest, such as South Africa, have poor energy use performance. Normally countries with adequate public policies, regarding energy use, tend to lower energy intensity through time (Fig. 1).

The latter information is on a country basis. But, considering Eco-efficiency (OECD 1998), which is a concept originated by the World Business Council for Sustainable Development (WBCSD), that states: "*Eco-efficiency is reached by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impact and resource intensity throughout the life cycle, to a level at least in line with the earth's estimated carrying capacity*" (Keffer et al. 1999). And one of the actions is to "***reduce the energy intensity of goods and services***". To measure eco-efficiency indexes the WBCSD proposes dividing the product or service value (sales) by the environmental influence (Verfaillie and Bidwell 2000). The importance of this calculation rests in the fact that if the environmental influence diminishes through time, the index increases.

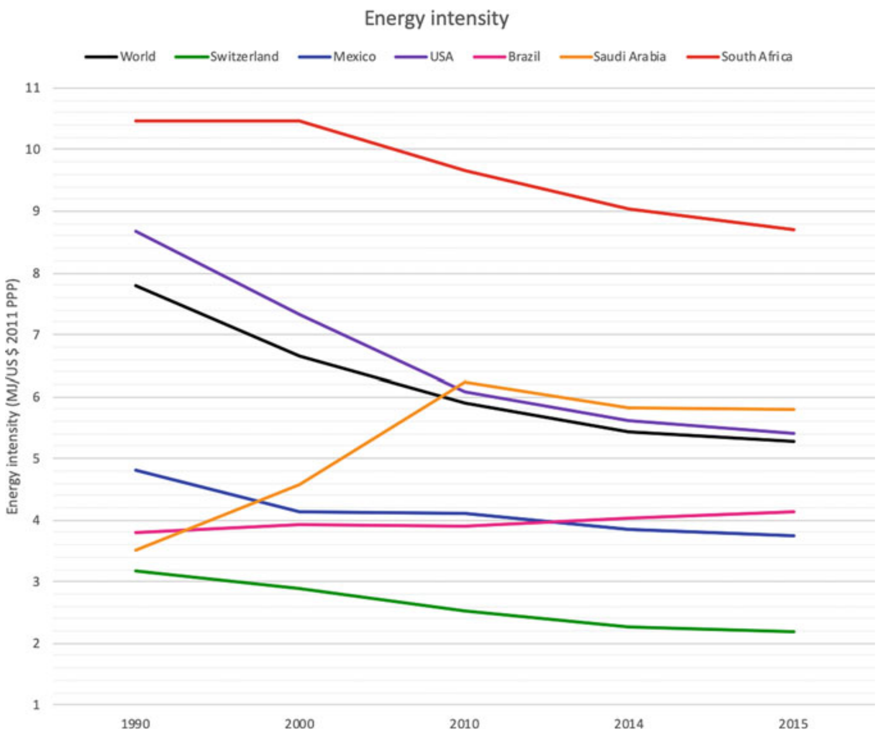

Fig. 1 Energy intensity for world and several countries

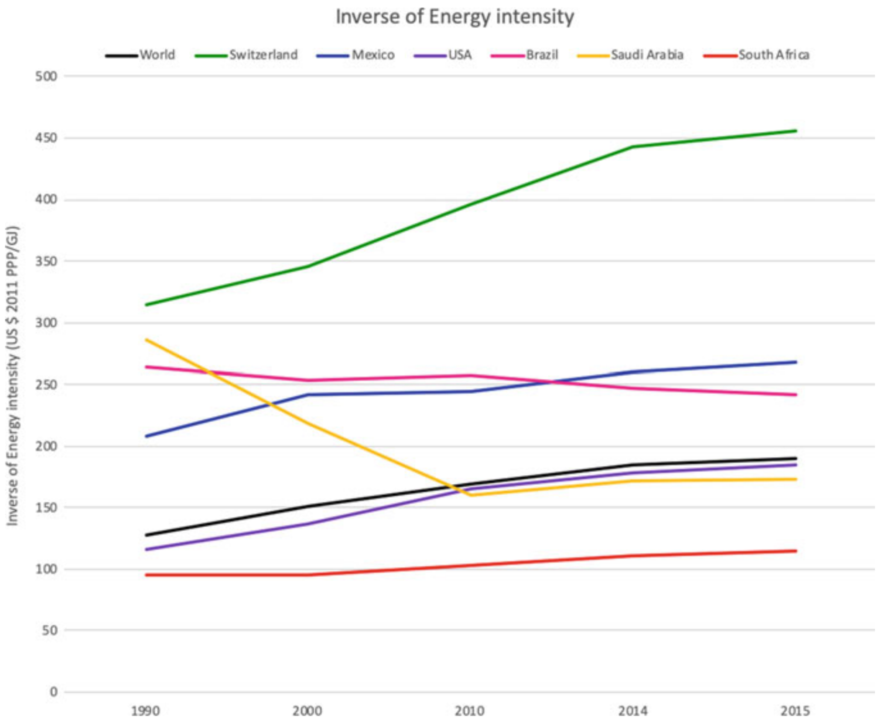

Fig. 2 Inverse of energy intensity. World and several countries. Equivalent to an Eco-efficiency index for energy

Hence, obtaining the inverse of the energy intensity is equivalent to calculating the energy eco-efficient index on a country basis. Figure 2 shows this calculation for the World, and countries as presented in Fig. 1.

The best performer is Switzerland with an increase of 45% from 1990 to 2015.

The previous paragraphs present recent performance for energy intensity. The European Union (EU) presents a forecast for the energy intensity to 2050, in Fig. 3; and Fig. 4 presents the forecast detailed according to fuel type.

A short analysis for energy efficiency in three main sectors will be discussed. Uses in Industry, Transport, and Buildings. Figure 5 presents a simple concept map relating relevant themes for the discussion.

According to International Energy Agency (IEA), energy efficiency in transport, industry, and buildings has the most relevant impact on energy use (IEA 2018a), as presented with more detail in Chap. 1.

From a worldwide perspective energy consumption is as follows; 28.8% by industry, 28.8% transport, and 32.9 Other uses for 2016 (IEA 2019c).

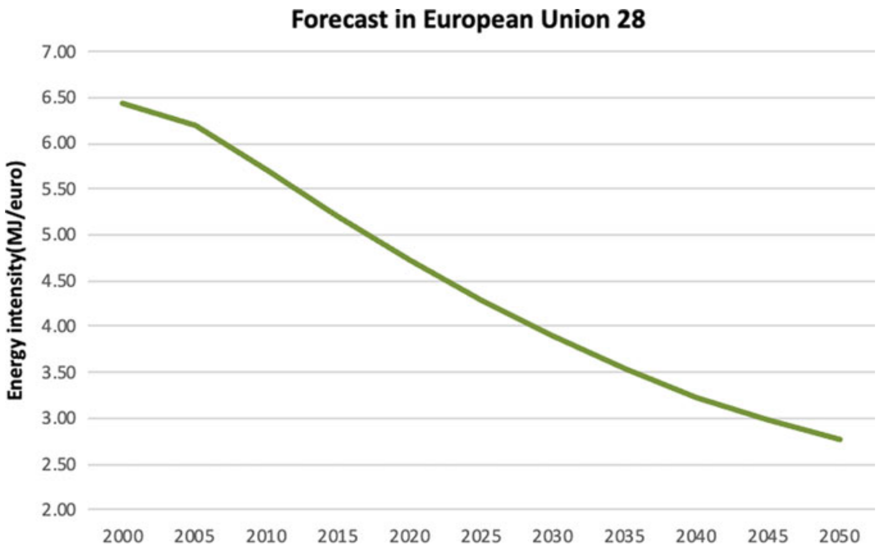

Fig. 3 Energy intensity forecast for the European Union (28)

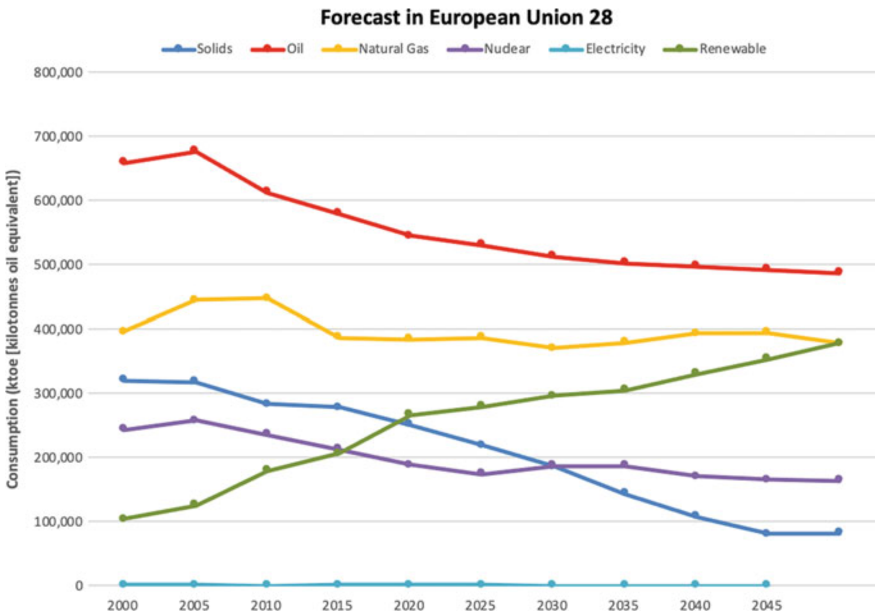

Fig. 4 Forecast for type of fuel used in the European Union (28)

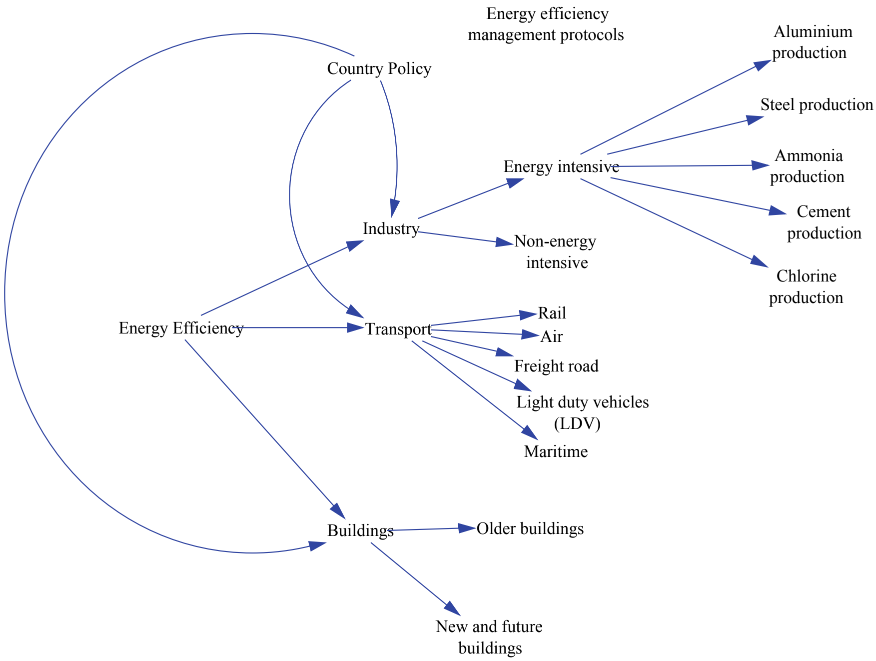

Fig. 5 Simplified concept maps connecting categories and issues for energy efficiency

2 Industry

Section 1 presents the energy intensity for some countries, together with the EU forecast. Eco-efficiency relates, on a business basis, the environmental influence caused by energy use with a related index.

Table 1 presents Eco-efficiency energy indexes and Environmental impact indexes (which are the former's inverse) for various companies. This illustrates: First, the variability of values among businesses, but that is something to be expected due to the different forms in which each company generates their products or services; secondly, the comparison needs to be internal for the company over time. Similarly, energy intensity is presented across several years. Since Interceramic intense use of energy for production has the smallest eco-efficiency index, nonetheless the company is embarked on improving its energy use; while Bombardier, in a similar fashion is fostering sustainability, has the highest eco-efficiency index. But one has to underline that comparing businesses in different production categories is misleading. One has to compare businesses producing similar goods or services.

Illustrating change through time, Fig. 6 presents Energy Eco-efficiency index data for BASF (a chemical company) for several years. From 2002 (base year) to 2012 the eco-efficiency improved, but in 2016–2017 there was a decrease. This trend signals that companies ought to act for improvement.

Table 1 Energy Eco-efficiency index and environmental footprint for various companies

						Eco-efficiency *		Environmental impact or environmental footprint **
Company	Sales	Unit	Sales in	Energy consumption	Unit	Energy index	Year	Energy index
			10^6 US $			10^3 US $/GJ		GJ/(10^3 US $)
Henkel	16,510	million €	21,575	2,197,000	MWh	2.728	2012	0.367
Interceramic	5,726	million $ Mx	486	7,503,917	GJ	**0.065**	2011	**15.451**
Givaudan	3,925	million CHF	4,709	2,692,906	GJ	1.749	2011	0.572
Pemex	1,558,429	million $ Mx	132,170	663,373,610	GJ	0.199	2011	5.019
Bombardier	16,768	million US $	16,768	4,552,012	GJ	**3.684**	2012	**0.271**
Alfa	14,728	million US $	14,728	31,000,000	GJ	0.475	2011	2.105
ICA	47,543	million $ Mx	3,534	3,447,525	GJ	1.025	2012	0.975
Mexichem	63,398	million $ Mx	4,713	15,143,975	GJ	0.311	2012	3.213
BASF	78,729	million €	102,880	61,535,000	MWh	0.464	2012	2.153
P&G	83,680	million US $	83,680	72,306,000	GJ	1.157	2012	0.864
Kimberly Clark	21,100	million US $	21,100	64	10^{12} BTU	0.311	2012	3.213
Philips	24,788	million €	32,392	14,421,000	GJ	2.246	2012	0.445

*In **blue** the largest ecoefficiency; in **red** the smallest
In **blue the smallest footprint; in **red** the largest
Sources From Global Reporting Initiative data reports, except for Kimberly Clark

The above information provides a focal insight into energy performance, but the strategic stance for companies should be a systemic approach considering, as Global Reporting Initiative (GRI) requires, the economic, environmental, and social issues through time. Energy use does not occur in a vacuum within businesses.

Showing energy efficiency in cement production, Fig. 7 presents the improvement in the energy eco-efficiency index world-wide, and the increase from 1990 to 2017 is significant, but there is also some asymptotic behaviour.

Also, in Table 2 cement production in four countries is presented, with the highest eco-efficiency index at the top; Mexican companies use dry-basis technologies, where raw material are not water-wetted, hence there is no need to spend energy evaporating water before input to kiln. At the table bottom some indexes are presented showing the best available performance, including one for an almost half century old plant with the highest energy use.

For lime production in a vertical kiln, Table 3 shows an energy summary, as well as the energy eco-efficiency index, where the output gas temperature is lowered. The highest eco-efficiency index is for the case of ambient temperature output. This

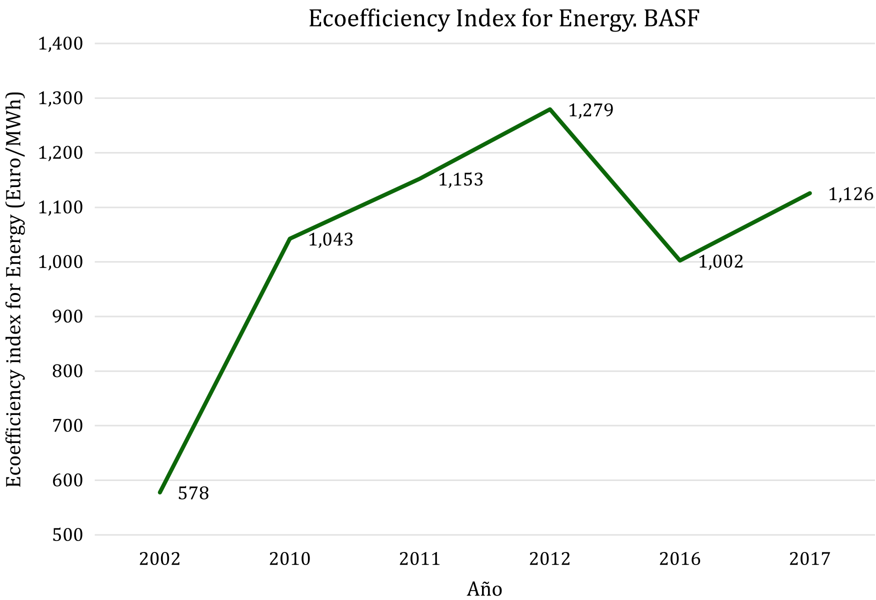

Fig. 6 BASF energy eco-efficiency index. (BASF 2012, 2017)

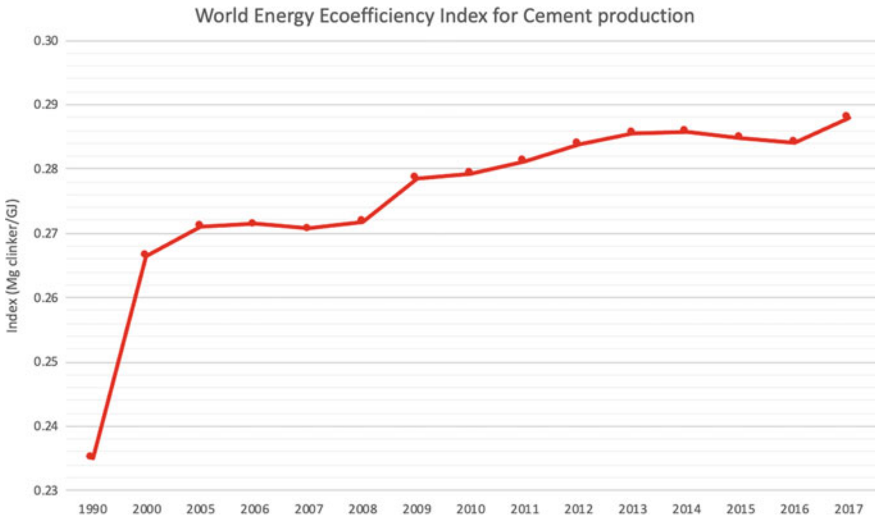

Fig. 7 World cement energy eco-efficiency index

Table 2 Energy eco-efficiency index for cement production in several countries using different technologies

	Cement produced	Energy used	Eco-efficiency index for energy
	x10^3 Mg	Petajoules	kg/MJ
México	23,971	90.463	**0.265**
EUA	79,353	344.778	**0.230**
Canada	10,722	56.400	**0.190**
Brazil	25,500	134.387	**0.190**

New furnaces, dry process	**0.288**
CEMEX furnace, Tepeaca, Puebla	**0.319**
Old furnaces	**0.245**
Old Technology (Shreve & Brink)	**0.144**

Table 3 Energy balance summary and Energy Eco-efficiency index for lime production in a vertical kiln

T_2 Gases	Fuel	Energy ecoefficiency index
°C	kg/kg lime	kg lime/MJ
400	0.1218	0.203
350	0.1163	0.212
250	0.1064	0.232
200	0.1020	0.242
150	0.0978	0.253
25	0.0726	0.340

represent a thermodynamic limit in lime production, where, no matter what is done, nature prevents energy use improvement beyond a certain limit.

Some data for specific industries has been shown. As presented in Table 1, there are some energy intensive industries, where energy efficiency can have a larger impact. According to research from the Copernicus Institute of Sustainable Development (Kermeli et al. 2014) for the decade 1990–2009 the annual decrease in energy use for Aluminium smelting, Alumina refining, Cement, Iron and Steel, and Pulp and paper have been 0.4%, 0.4%, 1.3% 0.5% and 0.5% respectively; their forecast for energy demand, based on the IEA reference scenario of 2011 from 2009 to 2050, is from 100 to 185 EJ. But, if a Low energy scenario were implemented, the demand for 2050 would be 140 EJ.

In the case of steel production a typical energy use is between 17–18 GJ/Mg, the current best practice is 14.5 GJ/Mg, and the theoretical minimum is 6.6 GJ/Mg for primary steel production, depending on the process technology in use (Fruehan et al. 2000).

Estimated savings in 2050, for a reference with low energy demand scenarios, have been estimated for some of the energy intensive industries, including chemicals

Table 4 Industry Energy Intensity improvements

Industry sector	2000–2017 (%)	2018–2040 (EWS) (%)
Aluminium	−16	−28
Cement	−38	−12
Chemicals and Petrochemicals	−16	−14
Iron & Steel	−5	−25
Paper, pulp and print	−29	−25
Other industries	−17	−41

Historical data from 2000–2017 and EWS for 2018–2040 forecast
Source (International Energy Agency 2018)

and petrochemicals (Kermeli et al. 2014). Iron and steel might have savings of 32%, with 11% for fuels and electricity; Chemicals and Petrochemicals 11%, and 15% for fuels and electricity.

While many countries have adopted fuel efficiency standards, the growth in demand in non-OECD countries more than offsets the effect of these improvements. (Bhavanam and Sastry 2011).

According to IEA, intensive energy industries, as well as other industries, are susceptible of improvements in energy efficiency. In Table 4, energy intensity decrease by industry sector is presented from 2000 to 2017 (historical data) and based on the Energy World Scenario (EWS) from 2018 to 2040 (International Energy Agency 2018), implying significant energy savings. It is relevant to underline the energy intensity improvement in the cement industry from 2000 to 2017, corresponding to the graph presented in Fig. 7.

3 Transport

As already indicated in Chap. 1, Transport is the sector with the second largest oil consumption worldwide and for Mexico and US, transport consumes the largest fraction. Therefore, this is a key sector with high challenges to make a transition to a low carbon economy. It is estimated that if actions are not considered, energy consumption and transport CO_2 emissions would increase around 50% by 2030 and 80% by 2050 (CEPAL 2018).

Gasoline and diesel are the main fuels used in the transport sector, both fuels count for 77% of the total energy consumption in this sector (as shown in Fig. 8). Gasoline is mainly used in light road vehicles while diesel in heavy road vehicles. The lowest energy consumption is related to rail (2%), water (10%) and air transportation (11%) and the passenger transport energy consumption is slightly higher than the freight transport energy consumption.

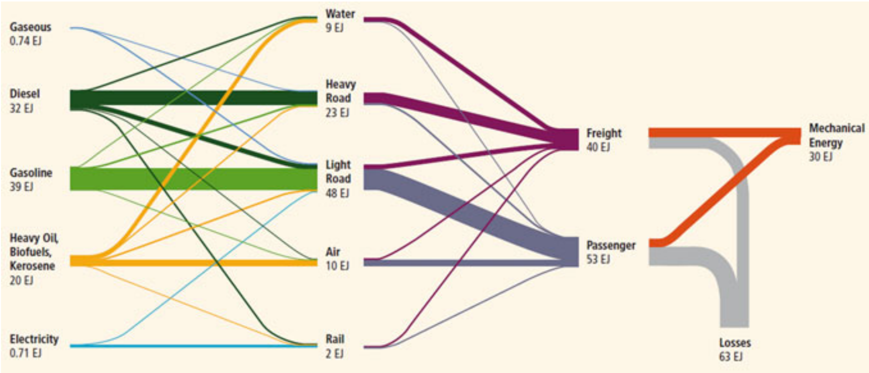

Fig. 8 Final energy consumption of fuels by transport sub-sectors in 2009 for freight and passengers, with heat losses at around two thirds of total fuel energy giving an average conversion efficiency of fuel to kinetic energy of around 32%. Note: Width of lines depicts total energy flows. *Source* (Sims et al. 2014)

The energy efficiency in land vehicles depends on their driving cycle, vehicle type (weight, size and power) and technology incorporated on them. The energy assessment is expressed in terms of kilometre per litres (km/L) (or in the USA in miles/gallon) or litres per hundred kilometres (L/100 km). The increase in energy efficiency has direct impacts in the reduction of air pollution (greenhouses gases and criteria pollutants) because less fossil fuel is consumed per kilometre travelled.

Driving cycle is a pattern represented by a time series of speed, which describes the workloads imposed on the vehicles (Huertas et al. 2018). Hence, driving cycles are used to estimate fuel consumption and mass emission of air pollutants. In order to commercialise a new vehicle, manufactures must report fuel consumption when the vehicle follows a specific driving cycle, which is defined by each country, and the new vehicle have to fulfil the fuel consumption or emission standard. As an example, the New European Driving Cycle (NEDC) and Federal Test Procedure (FTP) are well-known approved driving cycles.

Ten countries or regions: Japan, China, United States, Brazil, Canada, Mexico, South Korea, the European Union, Saudi Arabia and India, which represents 80% of the global light duty vehicles (LDV) sales (ICCT 2017), have established fuel economy or greenhouse standards which have a direct influence in the energy efficiency in new vehicles. The International Council on Clear Transportation have compiled the passenger vehicle fuel efficiency standards worldwide since 2000 and project the standards according to the policy plans in different countries or regions. Figures 9 and 10 depict the historical reduction of fuel consumption and CO_2 emission values considering the New European Driving Cycle (NEDC) for passenger cars and light trucks, respectively. On one hand, since 2000, it is observed that fuel consumption in passenger cars has decreased from 9 L/100 km, in countries like China and South Korea, to 5–6 L/100 km for 2017. In terms of CO_2 equivalent per kilometre, it implies a reduction up to 40 g/km depending on the country. On the other

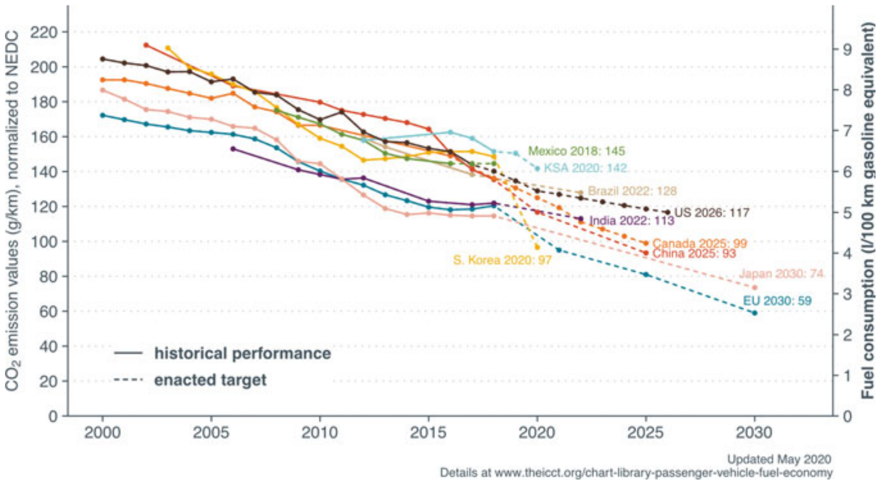

Fig. 9 Fuel consumption and CO_2 emission values for passenger car considering the New European Driving Cycle (NEDC). *Source* (ICCT 2017)

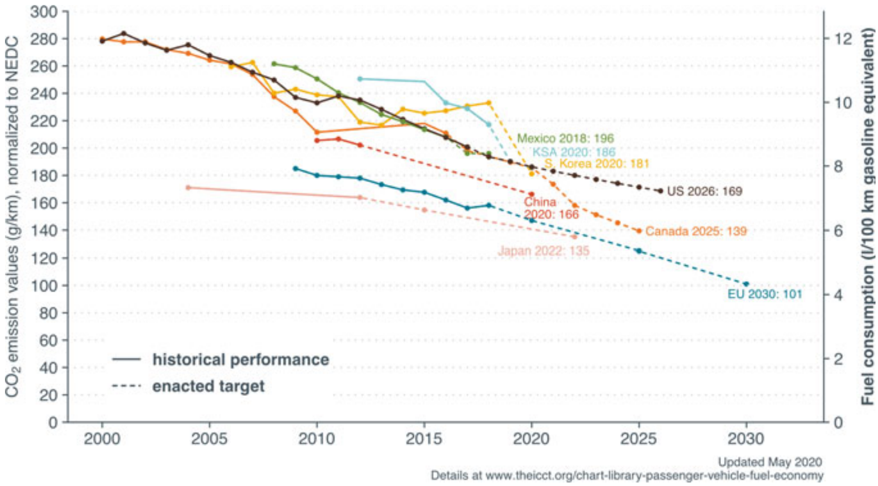

Fig. 10 Fuel consumption and CO_2 emission values for light truck considering the New European Driving Cycle (NEDC). *Source* (ICCT 2017)

hand, a higher fuel consumption is showed for light trucks, close to 12 L/100 km in 2000, while for 2017 it ranged between 6 and 10 L/100 km. This improvement in the energy efficiency has represented a reduction up to 80 g/km of CO_2 emissions. The European Union has the lowest fleet average goal of 95 gCO_2/km by 2021, however, if Japan pursues the reduction of CO_2 emissions at the same rate as from 2010 to 2014, Japan's passenger vehicle fleet would achieve 82 g/km in the current year

(2020) (ICCT 2017). In general, since 2014, non-OECD economies have improved their light-duty vehicle fuel consumption faster that OECD economies (OECD and IEA, 2017).

Although fuel consumption standard is a good parameter to identify the tendency of the energy efficiency on vehicles, diverse studies have indicated that there is a gap between the vehicle certification and the real-world fuel consumption (Fontaras et al. 2017). This is because standard driving cycles do not describe properly the real pattern of any particular area (Huertas et al. 2018). The gap is estimated to be between 30 and 40%, which means an increase of fuel consumption of about 1.5 to 2 L/100 km (petrol equivalent) (Fontaras et al. 2017).

The energy efficiency has improved for all modes of transportation. Table 5 shows the historical percentage of improvement between 2000 and 2016, where aviation and international shipping has showed the highest improvements. In the near future (2017–2040), it is expected an increment in the energy efficiency for all modes of transportation, as it is shown in the table.

The energy efficiency in the transport sector is also measured by the energy intensity indicator, which is the energy used per transport unit. In other words, is the energy required to move one passenger or tonne over one kilometre. Tiwari and Gulati (2013) made a comparison among seven countries with different stages of economic development, respect to the share of passenger and freight transport energy consumption. Transport trend indicated that passenger transport is the dominant consumer of energy in all of the countries except China and US, for 2007. Similar results are reported by Sims et al. (2014), for data of 2009, as is shown in Fig. 11.

Figure 11 depicts the passenger energy intensity within countries that are part of the International Energy Agency (IEA). It is observed that rail transport is the most energy efficiency mode of passenger transport and large cars transport (e.g. SUV—Sport Utility Vehicles) is the least efficiency. The intensity levels vary across countries depending on the vehicle type, share modes and average occupancy (passenger per vehicle). This last characteristic has declined over time in many countries (IEA 2020).

According to the IEA (2020), United States has a particular high passenger transport intensity due to large use of domestic flights and large use of passenger vehicles. Whereas, countries like United Kingdom has decreased their passenger transport

Table 5 Energy efficiency improvements for transport. Historical data and EWS forecast

Transport type	2000–2016 (%)	2017–2040 (EWS) (%)
Aviation[a]	3.6	3.1
International shipping	2.1	2.8
Passenger light duty vehicles	0.5	2.8
Road freight	0.1	1.5

[a]Energy use per revenue passenger kilometre
Source (International Energy Agency 2018)

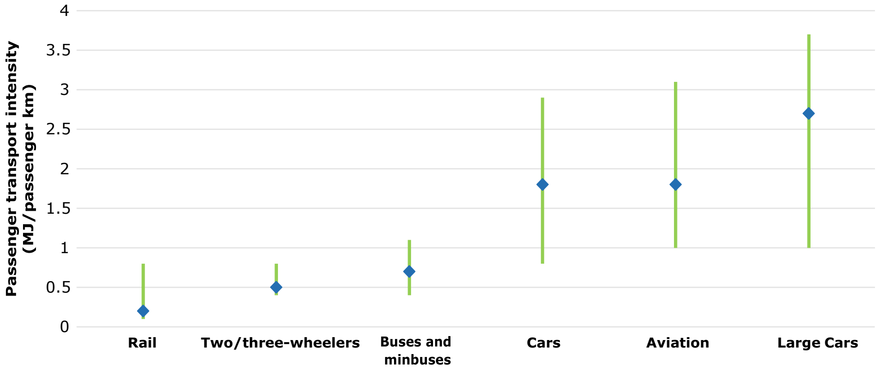

Fig. 11 Passenger energy intensity in the IEA countries. Bars are the variability at country level. *Source* IEA (2018)

intensity (16% decreasing from 2000 to 2017) due to the improvements in fuel efficiency and the modal shift in transport.

Overall, the energy efficiency in the transport sector requires the implementation of technologies that reduce fuel consumption, an efficient vehicle utilization (increasing in the average occupancy, modal shift in transport) and, in turn, policies that promote these changes. This means that in the transition to a low carbon economy, transport sector needs to incorporate diverse strategies within the framework of sustainable mobility. In this sense, Fig. 12 shows diverse alternatives that can be applied according to the particular conditions for each country.

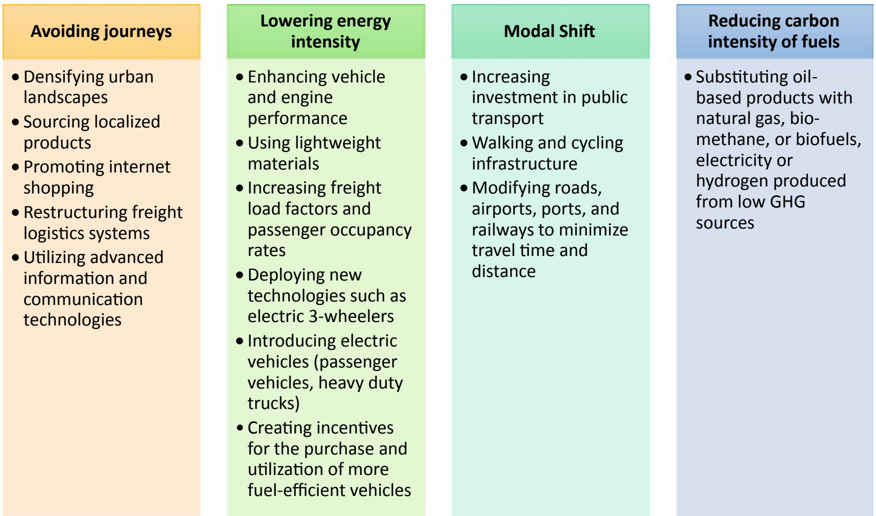

Fig. 12 Strategies to promote a sustainable mobility. *Source* (Sims et al. 2014)

4 Buildings

4.1 Energy Consumption Analysis

Because of industrial development and economic growth, the building construction sector has become one of the biggest industries in the world. The energy consumption in buildings represents a significant part of world energy consumption, and it involves a high occupational activity. For instance, Americans and Europeans spend approximately 90% of their time indoors: two-third of this time in their homes, workplaces, schools, and public spaces (USEPA 1989; Sarigiannis 2013). The main factors that have contributed to the growth of energy use in buildings are the increase in population, household growth, a higher number of miscellaneous energy-based devices, and more concern about health and comfortable indoor environments. From the population factor, we expect an increase of 26% (World), 25% (U.S.), and 18% (Latin America and the Caribbean) from now to 2050 (ONUDESA 2019). The number of households has also increased for the last two decades by nearly 10% and 24% in the U.S (USCB 2019) and Mexico (INEGI 2015), respectively. Similar forecasts are expected over the next several decades for both countries. The challenge of quantifying the evolution and forecasting of comfort levels and energy-based devices in any region can get quite complicated.

According to international energy statistics, it is estimated that the building sector (commercial, residential, and public) represented more than 35% of global final use and roughly 40% of energy-related CO_2 emissions (UNE-IEA 2017). It is also expected that buildings in non-OECD nations will consume about twice the amount of electricity in comparison to buildings in OECD nations to 2050 (USEIA 2019). The U.S. total energy consumption by buildings (commercial and residential) accounts for about 39% of total end-use sectors, and it contributes 9% of the carbon dioxide emissions worldwide (USEIA 2020) (Fig. 13).

From U.S. total energy consumption in the commercial and residential sectors (40 EJ), electricity is the most-consumed energy source with 72.6%, followed by natural gas with 20.67%, and oil with 4.5% (USEERE 2019). The residential and commercial segments accounted for 28% U.S. total end-use energy consumption in 2019 (22 EJ) (USEIA 2020). U.S. energy consumption in the building sector have barely increased by an average of 0.12% per year until 2019. The energy consumption is projected to fall by 14.1% for the residential sector and rise by 7.4% for the commercial one under the reference case conditions to 2050 (Fig. 14).

The energy-related CO_2 emissions followed a qualitatively similar behavior than those observed for the energy consumption throughout the years, except for the emissions produced by the industrial sector that were always below the transportation sector levels. CO_2 emissions from 2019 to 2050 will decrease by 12.9% for the residential segment and increase by 6.9% for the commercial sector considering the AEO2020 Reference case conditions (Fig. 15).

For the last energy use survey available (2012), there existed about 5.6 million commercial buildings in the U.S. (retail, education, service, lodging, and office),

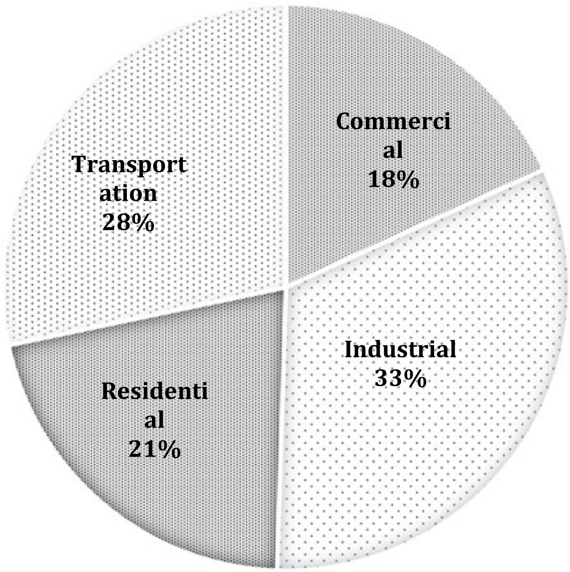

Fig. 13 Total energy consumption statistics by different end-use sectors in the U.S. by 2018. Author's elaboration with (USEIA 2020). *Note* Total energy consumption includes primary energy use, purchased electricity and energy losses by production, conversion, transmission, and distribution

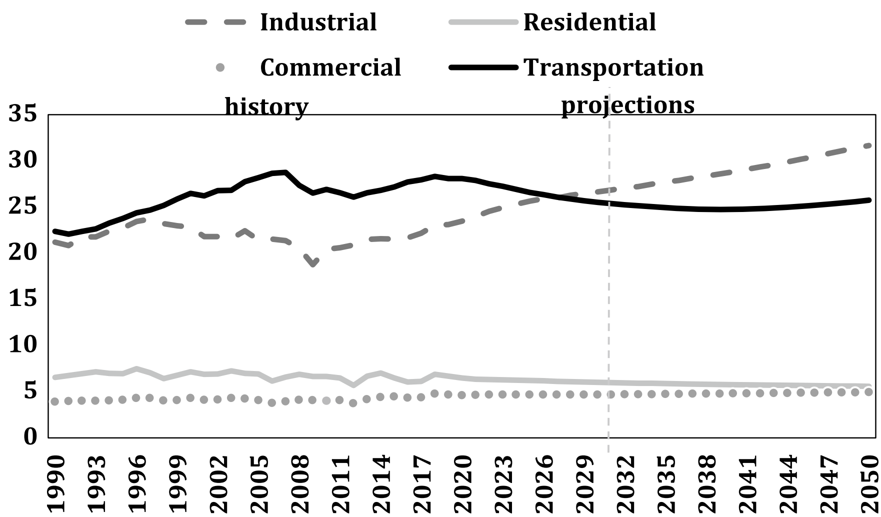

Fig. 14 Energy consumption by sector (regarding the AEO2020 Baseline Case), in quadrillion Btu. Author's elaboration with (USEIA 2020)

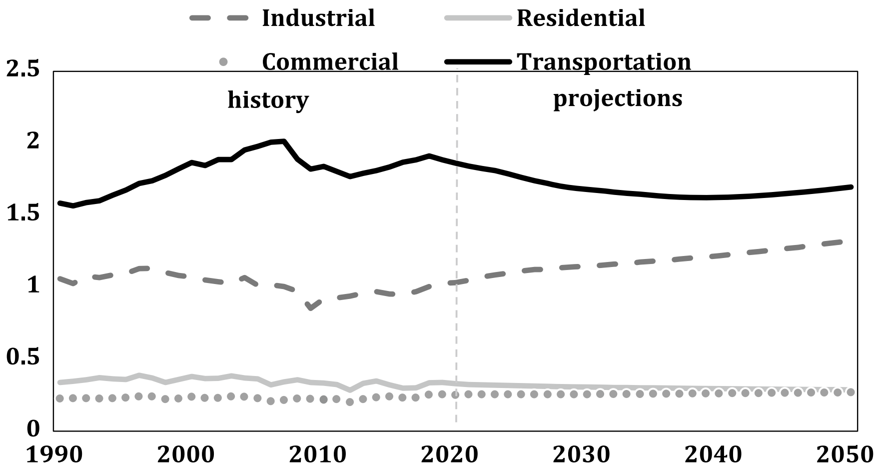

Fig. 15 Energy-related CO_2 emissions by the energy sector (regarding the AEO2020 Reference Case), in billions of metric tons. Author's elaboration with (USIEA 2020)

which had about 8,092 million square meter of floor space (USEIA 2016). The commercial building floor space will grow by an average of 1% per year through 2050. From the variety of commercial building types, warehouses, health care and lodging will grow at a higher rate of 1% over the forecast period (USEIA 2020). The two main energy sources in commercial buildings were electricity and natural gas, with about 93% of the total energy consumed. Natural gas represented 32% of total energy end-use consumption in commercial buildings in 2012, and it was mainly used for water heating and space heating. On the other hand, electricity represented 61% of total energy end-use consumption in commercial buildings in 2012, with an increase of 23% during the last three decades (USEIA 2016). Electricity was mostly used for lighting (17%), refrigeration (16%), ventilation (16%), cooling (15%), and computers (10%) in commercial buildings in 2012. The increase in electricity consumption in recent years can be attained to both the growing use of electrical and electronic devices and higher electricity consumption for cooling and ventilation systems. From the total energy use of the commercial sector, the office, mercantile, education, and health care buildings were the most energy consumers with 17.8, 14.5, 12.1, 10.3%, respectively (USEIA 2016).

Regarding the residential sector, the number of households in 2015 in the U.S. was 118 million; it includes single-family detached, single-family attached, apartments, and mobile homes (USEIA 2015). The total number of households will increase by an average of 0.6% per year through 2050. Multifamily homes will grow at a rate of 0.6% per year, whereas mobile homes will decrease by 1.2% to 2050 (USEIA 2015). In general, a single-family detached home consumed nearly three times more energy than a five-unit apartment because space flor differences and insulation levels proportioned by neighbors. In 2015, electricity and natural gas were the foremost energy sources in residential buildings with 44 and 43%, respectively. The annual energy consumption by the residential sector in 2015 was distributed by equipment and devices as follows: space heating and air conditioning (51%), water heating, lighting and refrigeration (27%), and electronic devices, cooking appliances, and clothes washers and dryers (21%) (USEIA 2015). We can see that the main factors affecting the energy consumption in residential buildings are climate conditions (location), building characteristics, the number of occupants, operation time, and type of energy- consuming devices. Nevertheless, the annual energy use per home in the U.S. has declined due to improvements in the building envelope (passive strategies), migration changes, and efficiency of lighting technologies, HVAC systems, and appliances (USEIA 2015). The migration effect can be seen in terms of the decreasing of space heating (fewer heating degree-days) and the increase of space cooling demand (higher cooling degree-days) through 2050 (USEIA 2020).

It is well-known that building energy consumption in non-OECD nations might increase about five times faster than in OECD nations. However, there are several developing countries such as Mexico that are OECD members. This fact makes peculiar the analysis of building energy consumption in those countries. The U.S. per capita use of electricity in buildings was about 30 GJ/capita in 2018 with a projected decrease of 3.7% by 2050, while the Mexican per capita use of electricity was 3.2 GJ/capita in the same year, with a projected growth of about 40% to 2050 (USEIA 2019). The Department of Energy in Mexico showed that residential/public/commercial sectors represented a 17.6% of the total energy consumption in the country (0.9 EJ) and electricity was the largest power source used with a 34.3% of the subsector, followed by the LPG with 32.9% and firewood with 26.5% in 2017 (SENER 2018) (Fig. 16). Furthermore, the Mexican building sector represented about 12% of total emissions (De Buen 2009).

Figure 17 shows the evolution of energy consumption in the building sector in Mexico from 2007 to 2017. It was noted that energy consumption has remained nearly constant for the period under analysis. The energy consumption in the Mexican residential sector has decreased by 1.3%, while the commercial and public services sector has increased by 28.1% from 2007 to 2017. From the comparative analysis between both countries, it was observed that the energy consumption in the residential U.S. sector is almost 10 times higher than that observed in the same Mexican building sector. Also, the energy consumption in the U.S. commercial building sector is approximately 40 times higher than the reported in the Mexican commercial and public services building sector.

The historical CO_2 emissions produced by the residential and commercial/public services sectors in Mexico showed a qualitatively similar behavior than those observed for the energy consumption throughout the period from 2007 to 2017 (Fig. 18). The CO_2 emissions are four times higher for the residential sector in comparison with those observed by commercial and public services sectors. The higher levels of emissions showed by the industry sector are explained because it includes the contribution of three industry sub-sectors: the energy industry, manufacturing, construction, and industrial processes.

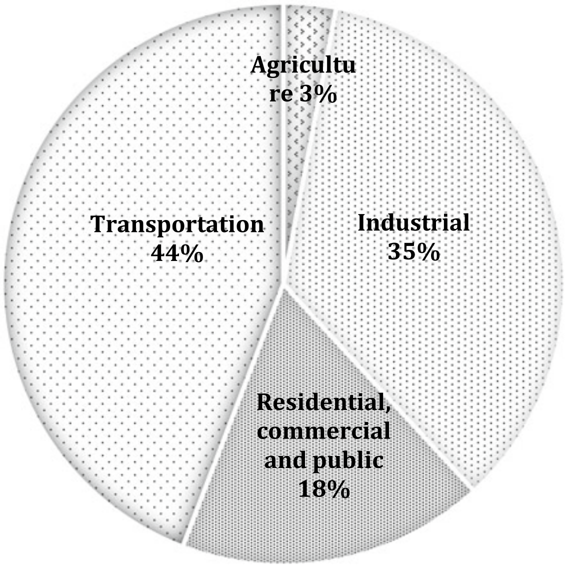

Fig. 16 Total energy consumption statistics by different end-use sectors in Mexico in 2016. Author's elaboration with (SENER 2018). *Note* Total energy consumption includes primary energy use, purchased electricity, and energy losses by production, conversion, transmission, and distribution

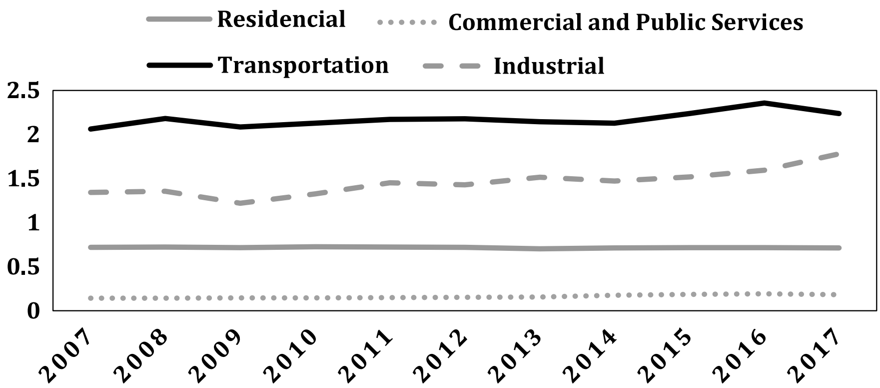

Fig. 17 Historic data of buildings energy consumption in residential and commercial/publics services sectors in Mexico—Quadrillion Btu—Author's elaboration with (SENER 2018)

There were found some differences between historical data reported by IEA (IEAS 2019) and SENER (SENER 2018) from 2007 to 2017. For the whole period of analysis, the IEA information underestimates the building energy consumption reported by the local Mexican government. Those maximum differences were about 2.7% for the residential sector and 18.2% for the commercial and public services sector. Similarly, the CO_2 emissions reported by IEA (IEADD 2019) underestimate those

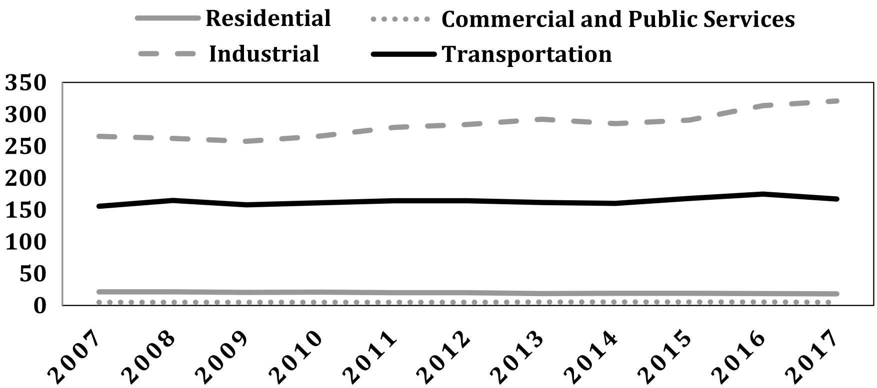

Fig. 18 Historical CO_2 emissions released by residential and commercial/public services sectors in Mexico—MT CO_2—Author's elaboration with (INECC 2018)

reported by the Mexican official indicators (INECC 2018). Now, maximum differences were about 9.3% for the residential sector and 20.7% for the commercial and public services sector. It worth to say that historical data available by IEA covers a broad period from 1990 to 2017. But the comparison was performed for the last reported decade in both information sources (2007–2017).

Detailed and reliable information about energy use and space floor on non-residential buildings in Mexico (commercial and public sector) is very scarce. A summary of a variety of surveys performed by industrial chambers and associations revealed some conservative estimations about the energy use and built space in commercial and public services in Mexico until 2009 (De Buen 2009). Based on those estimations, it was observed that warehouse accounts for about 5.0 million m^2, hotels and large restaurants about 17 million m^2, offices about 4.6 million m^2, wholesale and retail about 15.2 million m^2, theaters and recreational facilities approximately 30.7 million m^2, hospitals around 6.0 million m^2, schools around 121 million m^2, and small business nearly 0.1 million m^2. The energy use estimations were based on Canadian commercial buildings, information reported by the Trust Fund for Electric Energy Saving in Mexico (FIDE), and additional assumptions and calibrations to obtain an average electricity use in commercial buildings in Mexico by end-use and by building type (De Buen 2009). The average electricity use estimations are observed in Table 6.

According to FIDE, there are four general end-uses for commercial buildings in Mexico: space cooling, lighting, auxiliary motors (pumps, elevators, electrical stairs), and auxiliary equipment (computing, miscellaneous and others). Electricity, LPG, and natural gas are the main energy sources in commercial buildings in Mexico. Electricity represented approximately 70% of the total energy consumed, while LPG accounts for about 25% of total energy end-use consumption in commercial buildings from 2005 to 2009 (De Buen 2009). Electricity use in commercial buildings in Mexico is uniformly distributed among the end-use sector for almost all types of commercial buildings. Two exceptions occurred for the warehouse buildings where the electricity

Table 6 Electricity use by type of commercial building in Mexico—Author's elaboration with (De Buen 2009)

Type of commercial building	Electricity use (kWh/m^2 year)
Schools	90
Warehouses	150
Office buildings	160
Small businesses	180
Wholesale and retail	190
Theaters and recreational facilities	245
Hotels and restaurants	90
Hospitals	340

use by auxiliary equipment was negligible, and for school buildings that had the lower electricity requirements for space cooling in Mexico; 8% for space cooling and 25% for each of the other end-use sectors (De Buen 2009). Moreover, the commercial and public services emissions are projected to grow more than three times to 2050 (105 Tg CO_2 eqv).

The information included in a United Nations report (De Buen 2009) is compared with a more recent work (Kerdan 2011) that considers in-situ measurements of building energy consumption in commercial buildings for a limited number of cases throughout Mexico. From that comparison, it was noted maximum differences between 8 and 14% for office buildings, wholesale/retail, schools, and hospitals. More and better information about the energy use in non-residential buildings in Mexico should be considered as mandatory by the Mexican government, research community, and industrial associations.

Figure 19 shows the evolution of electric energy consumption per square meter at Tecnologico de Monterrey (the university flagship campus in Monterrey) from 1998 to 2012. Total electricity rates include office buildings, classrooms, auditoriums, labs, dormitories, gymnasiums, other sports facilities, libraries, and cafeterias. Those measurements are part of strategical actions taken by the "Tec Sustainable Development Programme", which is focused on operating and building physical facilities based upon sustainability criteria. It has been found a reduction in electricity consumption per area in campus buildings of about 22.5% from 2000 to 2012.

From the last survey in 2010, there are an estimated 35.6 million households in Mexico with 2.6% annual growth rate and an average of 3.9 family members (INEGIS 2010). In 2050 the housing stock might increase to more than 50 million units. On the whole, the rate of growth in the residential sector is the result of having a faster-growing in households than population, an important family size reduction, a urban population rapid growth in Mexico, and decentralization and migration of people to locations with extreme climate conditions. In 2010, the National Institute of Statistics and Geography in Mexico (INEGI) reported that 97.8% of the households surveyed had electricity, 91.5% had an adequate supply of clean water, 90.3% had effective drainage systems. The distribution type of households in Mexico can be

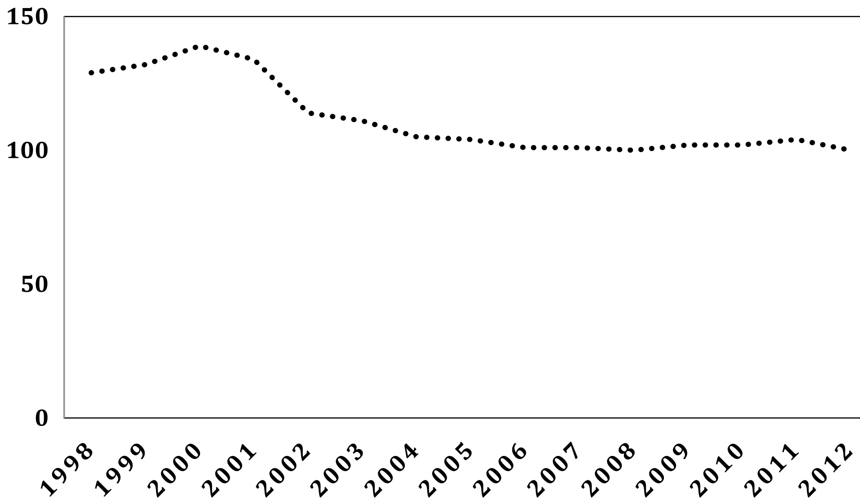

Fig. 19 Electric energy consumption per area (kWh/m^2) at Tecnologico de Monterrey (Monterrey campus) under the Sustainable Development Programme (1998–2012). Author's elaboration with Information provided from the physical plant direction of ITESM

classified as independent houses (92%), apartment buildings (6.5%), and others such as rooftop room, mobile home, shelters, and collective housing (1.5%) (INEGIV 2017). According to the housing finance industry and the single national housing registry (RUV 2020), 72.4% of households in Mexico are horizontal and 27.6% are vertical residential buildings. In particular, the finance industry distributes households in Mexico as shown in Table 7. The distribution indicates that 16.8% of those homes have a built area between 38 and 45 m^2, 44.35% an area between 45 and 60 m^2, 18.7% an area between 60 and 80 m^2, and 20.1% an area larger than 80 m^2.

In 2017, firewood was the main energy source in the residential sector (33.1%), followed by LPG (32.7%), and electricity (28.3%) (SENER 2018). Residential energy use in Mexico is distributed by services like air-conditioning, water heating, refrigeration, lighting, other electricity-based devices. From the total residential

Table 7 Residential building distribution according to the construction and finance industry in Mexico—Author's elaboration with (RUV 2020)

Type of commercial building	Percentage of total (%)
Affordable	3
Popular 128	5.2
Popular 158	25.5
Popular 200	23.5
Traditional	24.8
Media	15.3
Residential	2.2
Residential plus	0.5

energy consumption, 52% was for cooking, 29% for water heating, 10% for appliances (refrigeration, tv, clothes washer, ironing, other), 6% for lighting, and 3% for space cooling (Rosas-Flores et al. 2011). Residential emissions are estimated to raise about nine times by 2050 (400 Gg CO_2 eqv), where the electricity used for space cooling and other electrical appliances (tv, washing machines, computing, ironing, others) will represent more than 85% of total emissions (De Buen 2009).

From the residential building energy use analysis presented above, it can be concluded that public policies in Mexico should be aligned to encourage the next actions: (a) promote energy efficient building designs in early stages (bioclimatic design) and energy efficiency building retrofit programmes, (b) foster the use of energy-efficient building technologies for air conditioning, refrigeration, appliances, and lighting, (c) making efforts in more ambitious energy efficiency programs, (d) development and regulation of energy efficiency standards and codes for appliances, lighting, building envelope, use of solar thermal systems, and generation of energy by renewable sources, (e) implement more subsidies and incentives for green building technologies, (f) development of integrated urban planning at district/city levels.

4.2 Energy Efficiency

Energy efficiency improvements in the building sector can contribute to saving energy (electricity bills), reduce environmental emissions, and enhance indoor built environments (health, comfort, and productivity). Energy intensity can be used as an indicator of energy efficiency in buildings, chosen as energy per floor area for residential and energy per value-added for services (commercial sector). Newer technologies for different appliances or equipment, wherein a lower energy use can be achieved. Proper building design considering efficient energy use is another complementary method. And public policy addressing the efficient use of energy in the building environment further will enhance the latter two issues. Energy intensity is a measure of the energy inefficiency of an economy, but its variation is also influenced by economic structure (energy intensity levels), climate conditions, and monetary policies. As an example, countries with higher cooling requirements such as Mexico will have lower space heating intensities than colder countries such as the U.S. because of its lower energy demand, but not necessarily resulting from the adoption of better energy efficiency policies.

The rate of decrease of global energy intensity in buildings has suffered a deceleration from 1.5% in 2015 to 0.4% in 2019 (Fig. 20)**.** This building energy behaviour can be attributed to a slow-growing in energy efficiency policies, lower energy efficiency investments, a lack of implementation of building codes in developing countries, a tendency of a constant increase of the energy intensity in China, and any sudden change in vision of other large economies. Under the Sustainable Development Scenario (SDS) developed by IEA, the rate of decrease of the energy intensity for North America (including Mexico U.S. and Canada) for the next ten years is

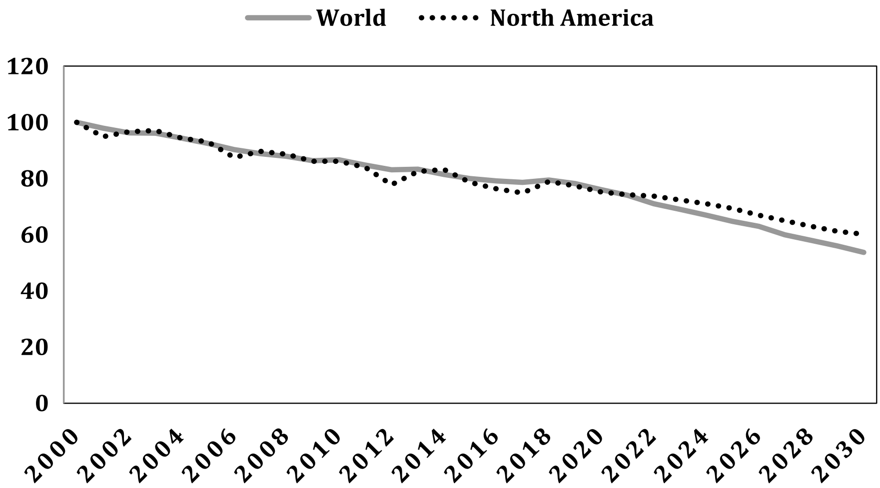

Fig. 20 World and North America evolution of energy Intensity Index for buildings (2000 = 100)—Author's elaboration with (IEAEE 2019). Data under the Sustainable Development Scenario, which is a global strategy that tries to address climate change, improve air quality, and achieve universal energy and water access)

projected to be slower in about 30% than that forecasted worldwide. The transformation of the energy system proposed by the SDS requires larger annual energy intensity reductions by approximately 2.5% (IEAEE 2019). Indeed, the annual rate of reduction of energy intensity should be quite higher in developing countries such as Mexico.

From the global analysis of residential and non-residential buildings, it was noted that the energy intensity per floor area in both sectors have slightly decreased in quite similar rates by 1.6–1.7% a year on average since 2000 (IEAEE 2019). Figure 21 depicts the evolution of residential energy intensity per floor area in U.S. and Mexico from 2000 to 2017. The residential sector includes private households that use energy for space heating and cooling, water heating, lighting, cooking, refrigeration, and appliances. The Mexican residential energy intensity per floor area showed a continuously improving pattern over the specified period, while the U.S. energy intensity behaviour was increasing and decreasing at an irregular pace throughout the years. In the end, the indicator in U.S. residential buildings has remained without changing in 0.51 GJ/m^2 since 2000, while the Mexican residential sector has improved by 38% passing from 0.48 GJ/m^2 in 2000 to 0.3 GJ/m^2 in 2017.

The evolution of energy intensity per value added (MJ/USD PPP 2010) in the service sector in U.S. and Mexico from 2000 to 2017 is graphically presented in Fig. 22. The services sector includes public and commercial spaces and activities such as space heating and cooling, indoor and outdoor lighting, ventilation, commercial appliances, and medical and office equipment. The indicator in Mexico remained relatively flat with time for an average value of 0.15 MJ/USD PPP from 2000 to 2015, then it slightly improved by approximately 15% in 2017. The U.S. indicator

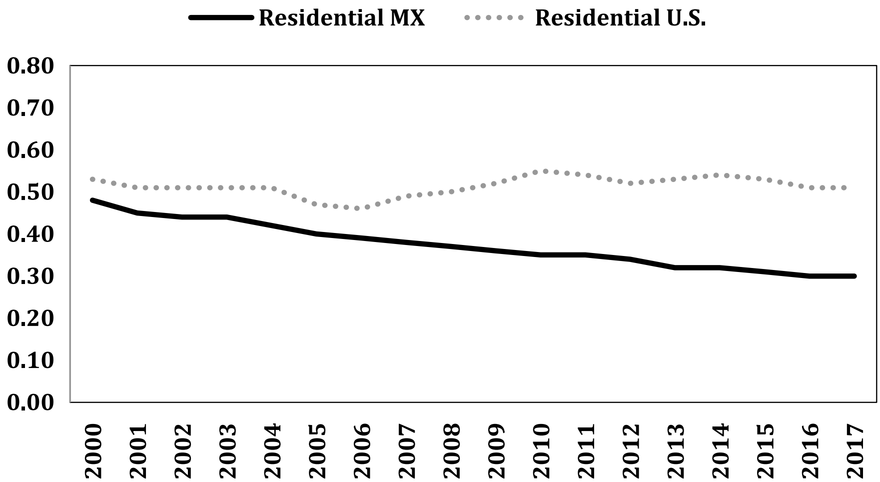

Fig. 21 Evolution of residential energy intensity per floor area (GJ/m^2): Mexico and U.S.—Author's elaboration with (IEAEEI 2019). Energy intensity per floor area was calculated as energy consumption divided by flor area with a temperature correction using the degree-days

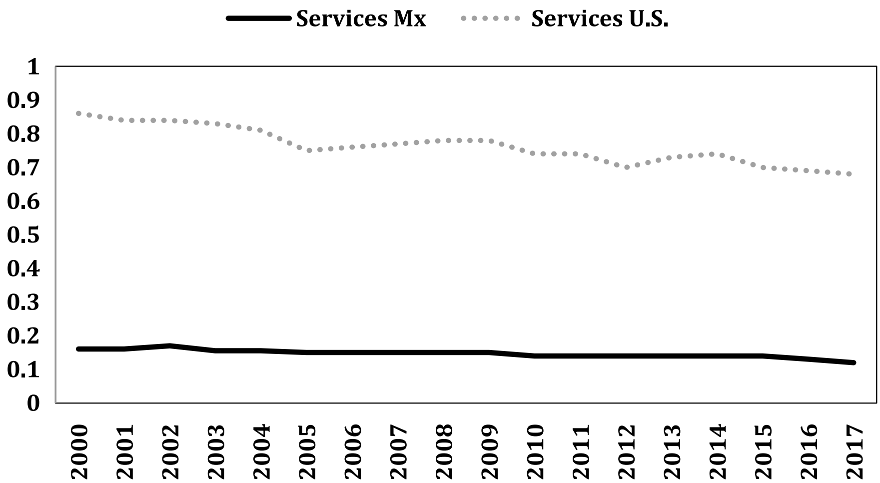

Fig. 22 Evolution of energy intensity per value added in the services sector: Mexico and U.S. (MJ/USD PPP 2010)—Author's elaboration with (IEAEEI 2019). Energy intensity per value added was calculated as the ratio between energy consumption and value added. PPP 2010 (purchasing power parities at 2010)

showed a variation of about 21% over the entire time period, which represented improvements of 0.18 MJ/USD PPP from 2000 up to 2017. The services sector has the lowest data availability among energy efficiency end-use segments, and those estimations usually come from energy balances in many countries. Therefore, more

Table 8 Status of key global building sector end-uses—Author's elaboration with (IEAEE 2020)

Technology	Status in relation to SDS
Lighting	On track
Cooling	Off track (with improvements)
Appliances and equipment	Off track (with improvements)
Heating	Off track
Building envelope	Off track
Data centres	On track

and better data collection and estimations through surveys and models are needed to develop more reliable energy efficiency indicators (IEAWB 2015).

A summary of the worldwide status of the building sector end-use under the Sustainable Development Scenario (SDS) is presented in Table 8. Lighting and data centers track well the SDS mainly due to: (a) a larger LED share of the global market, (b) an increasing adoption/substitution of LED by incandescence/fluorescent lamps in developing countries, (c) expansion of LED technologies in commercial buildings an public spaces, (d) the declining cost of LED lighting, and (e) improving energy efficiency policies by telecommunication industry and governments on data centres and transmission networks. The SDS projects that efficacy of LED lamps will be enhanced by 58% (from 103 lm/W to 163 lm/W) by 2030, followed by the linear fluorescent technology by about 6%, and negligible improvements are expected for compact fluorescent, halogen and incandescent technologies (IEATERL 2020). The lighting market in the U.S. is dominated by less-consuming technologies such as halogen, CFLs, and LEDs that meet energy standards and consume up to 80% less energy than traditional incandescent. In Mexico, the lighting end-use has been enhanced using more energy-efficient technologies and replacement older and less efficient lamps through green credits and tax incentives.

Unlike previous end-uses, the building envelope, heating, cooling, and appliances have a lot of opportunities to improve. First, building envelope can be improved by establishing mandatory building energy codes, high-performance designs, and energy-efficient retrofits for all countries to reach goals by 2030. According to IEA (IEAEGBC 2019), only one-third of countries had mandatory building energy codes in 2018. On this subject, U.S. has mandatory local building energy codes aligned to the national model energy codes for residential and non-residential buildings (DOE/ASHRAE/IECC[1]), and Mexico has some envelope energy efficiency standards (NOM) but not mandatory up to 2019. Second, space and water heating can reach the SDS goals in 2030 by increasing one-quarter of the total new sales by renewables or high-efficient heat pumps. As discussed above, energy consumption for space heating in Mexico is negligible in comparison with the national building energy matrix and even more regarding the U.S. building sector.

[1] **DOE: U.S. Department of Energy/ASHRAE: American Society of Heating, Refrigeration and Air Conditioning Engineers/IECC: International Energy Conservation Code.*

Space cooling grows faster than other technologies, and it shows improvements in the development of energy-efficient cooling technologies. However, the SDS demands implementing regulations that enable people to access high-efficiency systems, designing energy efficient buildings, increasing renewables integration, smart controls, and improving air-conditioning energy performance more than 50% by 2030 (IEATB 2020). It can be said that similar barriers should be overcome in U.S. and Mexico. However, more strategic plans on cooling standards and research on innovative cooling technologies can be observed in U.S; for instance, ultra-efficient cooling, evaporative cooling, solar cooling, magnetic or solid-state cooling, etc.

Finally, mandatory energy performance standards by appliances need to be extended in most countries to keep on track with SDS expectations (IEAEGBC 2019). The national U.S. standards set by de Department of Energy (DOE) are applied to appliances manufactured or imported into U.S. and additional local standards are enforced to appliances sold on each state. Thus, U.S. is a world leader in standardization for appliance technologies and the appliance standards program has been one of the most successful energy efficiency strategies to reduce national energy consumption. In Mexico, there are several mandatory standards for appliances regulated by the federal laws and aligned to U.S performance standards. Those standards (NOM's) are used for both residential and non-residential buildings. Indeed, those standards have strongly contributed to reducing electricity consumption in Mexican buildings. Table 9 presents a comparison of the appliances per dwelling from 2000 to 2017 in U.S and Mexico (IEAEEI 2019). It can be noted that consumer electronics and dishwashers (major appliances) showed a higher percentage of change in U.S. (15–24%). Otherwise, some major and basic home appliances such as refrigerators, clothes washers, and entertainment appliances (TVs) presented higher increases in Mexico (15–27%). Those differences in the use of energy and trends by home and electronic appliances in buildings in U.S. and Mexico can be explained due to several socio-economic factors, policies, regulations, and electricity prices between countries. Finally, the energy use of minor appliances (portable) and small electronics and their environmental impact should be further investigated in both residential and non-residential sectors.

The International Energy Agency (IEA) developed the "Efficient World Scenario" (EWS), which is focused on highlighting potential benefits to the global energy

Table 9 Appliances per dwelling in U.S. and Mexico 2000–2017—Author's elaboration with (IEAEEI 2019)

Appliance	U.S (% of change) (%)	Mexico (% of change)
Refrigerators	1	15%
Clothes washers	1	27%
TVs	15	23%
PCs	24	–
Dish washers	15	–
Clothes dryers	6	–

Table 10 Historical data (2000–2017) and forecast (2018–2040 EWS) of energy intensity per floor area in buildings for the end-use category worldwide—Author's elaboration with (IEAEE 2019)

Type of end-use in buildings	2000–2017 (%)	2018–2040 (%)
Space heating	36	43
Cooking	25	50
Lighting	22	32
Water heating	25	42
[a]Space cooling	−26	4
[a]Appliances	−5	4

[a]*Note* Positive values mean improvements and negative ones indicate diminishments

system (industry, transport, and buildings) from the adoption of energy efficiency measures and policies. The efficiency statements are essentially aligned to those followed by the Sustainable Development Scenario (SDS). Table 10 presents the evolution from 2000 to 2017 and a forecast from 2018 to 2040 (EWS) of the energy intensities per floor area by end-use in buildings (IEAEE 2019). It was observed that space heating, cooking, lighting, and water heating showed a historical energy intensity improvement (shown as % of decrease or positive values) between 20 to 36%, while space cooling and appliances presented a negative energy intensity tendency (shown as % of increase or negative values) between −5 and −26%. The negative behaviour for space cooling and appliances can be explained due to an increased usage of space cooling systems and appliances, and their international expansion in emerging markets.

Important improvements are forecasted for space heating, water heating, and cooking, representing a total of 74% of 24 EJ saved to 2040. On the other hand, space cooling and appliances could reach similar energy intensity benefits of 4% under the EWS, representing a total of 21% of 24 EJ saved in 2040 (IEAEE 2019). According to IEA, space cooling requires special attention because it is the fastest-growing energy end-use in buildings caused by two main issues: (1) higher demands for comfort (warmer temperatures), and (2) population and economic growth. Mexico and other emerging economies with higher cooling demand play an important role in improving global cooling energy intensity by 2040.

The electricity intensity evolution in the U.S. residential and commercial sectors is presented in Table 11. In residential buildings, space heating and lighting exhibit the highest electricity intensity improvements between 37 and 50% from 2018 to 205O in the AEO2019 Scenario, while the indicator gets worse by 15–39% (an increase of electricity intensity) for space cooling, laundry/dishwashing, and other uses (USIEA 2020).

Positive and negative tendencies for residential heating and cooling spaces are mainly driven by people migration to warmer locations as globally occurs. Also, the replacement of incandescent and fluorescent technologies for LED lighting has highly contributed to a decrease in the electricity intensity in U.S. The efficiency progress of home appliances is directly related to successful incentive programs and energy efficiency standardization. In commercial buildings, space heating, water heating,

Table 11 Residential (MWh per household) and commercial (kWh/ft^2) building energy intensity by end-use in U.S. (2000–2050 AEO2019 Reference Case)—Author's elaboration with (USEIA 2020)

Residential end-use	2019	2050	Commercial end-use	2019	2050
Space heating	1.70	1.10	Space heating	0.39	0.21
Water heating	1.40	1.20	Water heating	0.08	0.04
Lighting	0.60	0.30	Lighting	1.50	0.80
Refrigeration	0.90	0.80	Refrigeration	2.10	1.80
TV and PCs	0.70	0.60	Ventilation	1.60	1.00
Cooking	0.13	0.11	Cooking	0.30	0.20
Laundry and dishwashing	0.70	0.80	Computer and office equipment	2.30	2.90
Space cooling	1.80	2.50	Space cooling	1.70	1.50
Other uses	3.80	4.40	Other uses	4.70	5.40

ventilation, and lighting show the highest efficiency improvements ranging from 37–47% for the projected period. Now, computer/office equipment and other uses indicates a negative efficiency tendency (increase of electricity intensity) with intensities of about 15–26% (USIEA 2020). The intensities of HVAC systems decline over time because the use of high-efficient technologies in commercial buildings. Finally, the accelerated adoption of office equipment and electronic devices in commercial sector still surpasses the increased equipment efficiencies.

There is only scarce information concerning the energy intensity evolution in residential and commercial buildings in Mexico. A general estimation of energy intensity by end-use in both sectors was made by (De Buen 2009). Table 12 illustrates the energy intensity evolution in residential and commercial sectors in Mexico under the Scenario 2006–2050. The scenario considers a constant level of GHG emissions from 2006 to 2050, which can be achieved through several assumptions for each end-use technology. In the residential sector, all end-uses show quite important energy improvements, except for space cooling. As in the U.S., the negative efficiency tendency of space cooling and other electrical intensities is a growing concern in Mexico. On the other hand, efficiency gains in lighting, refrigeration

Table 12 Residential (MWh per year) and commercial (MJ/m^2) building energy intensity by end-use in Mexico—Author's elaboration with (De Buen 2009)

Residential end-use	Scenario 2006–2050 (%)	Commercial end-use	Scenario 2006–2050 (%)
Space cooling	480	Space cooling	75
Water heating	74	Auxiliary equipment	75
Lighting	91	Lighting	75
Refrigeration	80	Auxiliary motors	60
Other electrical	150	Water heating	60

and water heating reflect the increased use of high-efficient and solar thermal technologies. In the commercial sector, all the end-use services/technologies observe efficiency gains of about 60–70% under the projected scenario (2006–2050).

4.3 Final Remarks

In response to global climate challenges that we are facing, ambitious energy-efficient strategies have been focused on both energy infrastructure innovations and consumer behaviour changes. In the building sector, achieving these higher sustainability targets implies optimization of energy production/consumption in buildings without sacrificing comfortable indoor environments. In this regard, developed and emerging nations have contributed to specific activities reducing greenhouse emissions in the building sector. For instance, building integration of low carbon technologies (passive and/or active), implementation of low-energy public policies for new and existing buildings, energy-efficiency audits, standards development and adoption, public information campaigns, economic incentives for final users and developers, etc. The comparative energy performance analysis presented above can help to observe the present and future role of the building sector in both countries, and particularly to identify challenges found on the Mexican side. It also can be helpful to bring the information closer to decision makers and to develop sustainable policies and programs. Finally, a set of global and local challenges and opportunities for the building sector are listed below (IEAEE 2019; USEERE 2008, De Buen 2009).

Firstly, the international challenges with a particular focus on emerging countries are pointed out next: (a) increase the expansion of energy codes and labelling for new and existing buildings, and for equipment and appliances, (b) promote financial incentives and market-based instruments to encourage consumers to invest in energy efficiency technologies, adopt high-efficiency appliances, and increase more innovative business models. (c) work on quality and availability of energy performance information for buildings and components, (d) increase human resources capacity in building sector though training, accreditations and certifications, (e) the efficiency in space and water heating must be focused on more efficient heating equipment (building insulation, advance window technologies, and heat pumps), and (f) the efficiency in space cooling must consider high-efficiency AC and controls, building insulation, and advance window technologies.

Secondly, the U.S. energy use has been mainly driven by population (number of households), economic growth (commercial floorspace), building size, service demands, and energy prices. Improvements in building technologies, design, and construction have contributed to increased energy efficiency in the residential and commercial sectors. We can see the next opportunities for the case of U.S:

(a) Continuing the trend of energy efficiency improvements of end-uses with a special focus on space cooling intensity caused by migration changes from heating-intensive to cooling-intensive locations in U.S.,

(b) Extend the application and regulation of ambitious and cutting-edge state building codes; for instance, the 2019 California Building Code, which impulses moving to net-zero residential homes should be extensively promoted and adopted by more U.S. states and overseas,
(c) Extend the market share of high-performance homes through standards, incentives and efficiency programs,
(d) Increase the efficiency of home appliances, electronic equipment and other uses in residential buildings through the application and regulation of voluntary energy efficiency programs such as Building America, Energy Star, LEED homes, etc.,
(e) Keep the attention of incentives and efficiency programs in offices and retail, which are the two largest energy-consuming in the commercial sector,
(f) Incentivise the participation on building performance programs and labelling (Energy Star, LEED, and ASHRAE) to improve the energy intensity in the commercial sector,
(g) Increase policies and incentives such as tax credits, utility rebates, pricing structures, and government-backed research to develop energy-efficient technologies, and
(h) Increase the amount of information collected by surveys of the energy use of minor appliances and small electronics residential and non-residential buildings.

Finally, to attain the next level of energy efficiency in the Mexican building sector, some challenges and opportunities are described as following:

(a) Develop more and high-quality information for the energy use in the commercial sector including, building type, building stock, floor area, energy by end-use, and energy intensity,
(b) Improve and complement information obtained by INEGI census for the energy use in the residential sector through detailed surveys and periodical campaigns throughout the country,
(c) Mexico has mandatory building envelope (residential and commercial) and lighting standards (commercial). However, those building energy standards for residential and commercial sectors must be integrated into local building codes. It is the only way to assess the contribution and effectiveness of those mandatory building standards in Mexico. The adoption of a Roadmap for building energy codes and standard in 2007 seems to be promising,
(d) Change the participation of energy subsidies to enhanced energy efficiency programs,
(e) Implement mandatory labelling for new commercial buildings; the third-party green building labelling in not enough for energy efficiency goals,
(f) Take the successful mandatory labelling program for appliances, lighting, and equipment to engage other technology sectors,
(g) Space cooling should be strategic in energy efficiency planning because it is the fastest-growing use of energy in building and approximately half of Mexicans lives in warm climates,

(h) Increase the investments of national surveys on household behaviour, energy use patterns and change in lifestyles, and
(i) Aim for net-zero energy consumption in buildings in the medium term.

5 Public Policy

Complementing the improvements in technology, design methods, and management procedures, Public Policy shall foster energy efficiency in the years to come, until limits are reached where further improvements will not be feasible. In the previous section an overall analysis was done regarding the economy's three main sectors that presently are the largest users of energy, based, as discussed in this chapter and also in Chap. 1, on the use of fossil fuels.

Hence, the transition to a low carbon economy needs an efficient use of fossil fuels in the following decades.

Discussing the public policy support for this transition has been done in Chap. 2. Here a more focused analysis on the economy sectors mentioned in the previous paragraph will be carried out.

6 Conclusions and Recommendations

Worldwide there has been a trend to improve energy efficiency and the sectors in the economy with largest consumption: industry, transport and buildings have contributed throughout the years. Energy intensity, eco-efficiency indexes, fuel consumption per distance travelled, are some of the ways to assess this efficiency.

For Mexico, based on this chapter, the following recommendations are proposed:

- Adopting energy audits linked to some type of energy eco-efficiency index or sustainability metric, either through the WBCSD or GRI proposals, will improve energy intensity and decrease impact on climate change.
- Regarding transport, newer vehicles have been designed with better fuel economy, replacing older vehicles with newer ones requires capital investment, which some business sectors lack. Public policy providing some type of incentive can foster this change. Also, urban planning taking into consideration the need to improve fuel economy is needed.
- Introduction of electric vehicles or vehicles with hydrogen fuel cells presently being tested, can lower climate change impact but a reinforced power grid will be needed to supply electricity. For hydrogen fuel cells a network of hydrogen selling stations will be needed.
- Shifting the transport modes in Mexico can help to reduce the energy intensity, which implies to invest in public transport (increasing the average occupancy), and cycling and walking infrastructure.

- In the Mexican building sector, establishing proper building codes, via public policy, that take into account energy efficiency is an adequate action. Besides educating and training those professionals and clerical personnel regarding energy efficiency is a long-term needed action.
- Mexico is a member of the IEA, as well as of OECD, where they are embarked in important energy efficiency programs. Hence strengthening the links and implementing the policies and programs from these insitutions can foster energy efficiency efforts in Mexico, as well as set the foundations for businesses as well.

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Chapter 4
Energy Market Evolution in Lieu of Fossil Fuels Use and Renewables Penetration Due to Regulatory Changes

Alejandro Ibarra-Yunez

Abstract The present chapter concentrates on a comparative analysis of the path of regulatory change, and the drive and incentive perception of increasing number of participants in deregulated energy systems in Mexico and some adjacent markets in the United States: CAISO and ERCOT. The chapter also makes an emphasis of the long term (10 or more) years for a market to mature, as is demonstrated in the analysis applied to US cases and FERC decisions and legal acts, as lessons for Mexico. Incentives are separated between fiscal, financial, and regulatory promotion of markets. Finally, the chapter makes a case that the environmental agenda and the energy mix changes towards renewables should set clear policy bridges between the two energy system policies. Conclusions and then derived from the economic analysis.

Abbreviations

CAPEX	Capital Expenditure
CAISO	California Independent System Operator
CC	Combined Cycle
CENACE	National Centre for Energy Control or Centro Nacional para Control de Energía
CFE	Comisión Federal de Electricidad or National Utility Company
CPUC	California Public Utility Commission
CRE	Energy Regulatory Commission or Comisión Reguladora de Energía
CREZ	Competitive Renewable Energy Zones
DACG	General Administrative Decisions
EIA	Energy Information Administration
EPE	State Productive Enterprises or Empresas Productoras de Energía
EPES	Empresa Productiva del Estado

A. Ibarra-Yunez (✉)
EGADE Business School Monterrey, Tecnológico de Monterrey, Rufino Tamayo y Eugenio, Av. Eugenio Garza Lagüera, Valle Oriente, 66269 San Pedro Garza García, NL, Mexico
e-mail: aibarra@tec.mx

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ERCOT	Electric Reliability Council of Texas
FTR	Financial transmission rights
FERC	Federal Energy Regulatory Commission
IOU	Investor Owned Utility
ISO	Independent System Operator
LCOE	Levelized Cost of Energy
LIE	Ley de la Industria Eléctrica
LSE	Load Service Entity
LSPEE	Law for the Public Service of Electricity Use
NERC	National Energy Reliability Council
OPEX	Operating Expense
PCG	Power Generation Company
PIE	Mexico Independent Power Producers or Productores Independiente de Energía
PPA	Purchasing Power Agreement
PRODESEN	National Development Program of the Energy Sector or Programa de Desarrollo del Sistema Eléctrico Nacional
PTP	Point to Point
PUC	Public Utilities Commission
PV	Photovoltaic
QF	Qualified Facility
REC	Renewable Energy Certificates
REP	Retail Energy Producers in ERCOT, different from Mexico's Renewable Energy Projects (refer specifically to ERCOT)
RTO	Regional Transmission Organization
SENER	Secretary of Energy
SHCP	Secretary of the Treasury
TDSP	Transmission and Distribution Provider
TPUC	Texas Public Utility Commission
WECC	Western Electricity Coordinating Council

1 Introduction and Framework for Analysis

The contrast between a mature market in the United States, and an emerging market in Mexico, poses big challenges, and opportunities to integrate energy mix adjustments on both sides of the border. The penetration of renewables into mature markets, such as California's CAISO, the Texas ERCOT market (that covers most of the state), and Mexico as a unified, yet comparative market, and its evolution, is rather asymmetric. The three regional markets are of similar size but different in maturity regarding incentives, products being traded, and each regulatory compact.

This chapter addresses the asymmetries in market development, renewable penetration, infrastructure maintenance and expansion to integrate new renewable sources of energy, and compares the state of regulations and incentives at the fiscal, financial, and promotion dimensions. Hence this chapter is justified if the reader is to gain understanding, not only about the institutional framework in each market, but also to become aware of the long historical dynamics towards maturity in the US regional markets *vis-à-vis* Mexico, where the latter's regulatory and institutional compact is much more recent, and where the promotion of business participants seems more difficult, and with less long-term and clear investment incentives (reform was begun with the Constitutional changes in 2013, see OECD 2005 as a global framework).

Additionally, the present chapter concentrates on deregulation and vertical disaggregation (somewhat horizontal, initially), of the former Mexican parastatals "Comisión Federal de Electricidad" CFE, and the oil company PEMEX, that have faced, as a first step, disaggregation of the non-monopoly segments of their markets, to then recently experience a turning back towards centralisation since the new Mexican administration of 2018–2024. Mexico has not faced a return to centralisation as an outlier in worldly electricity markets, but has rather been present in other economies, from developed ones such as Norway, or Spain, but also developing ones such as Argentina, or interconnection hurdles (see Lund 2014 for Norway's restructuring since the nineties; Arocena and Price 2002 for Spanish market restructuring; EU Commission for Electricity Interconnection Targets 2019 for interconnection). Some markets make deregulatory moves to then go back to re-regulation and centralisation. Some have seen a smoother dynamic in some Scandinavian examples, and in Entso-E markets in Europe (Entso-E 2020).

As is shown in next Chap. 5 in present book, market arrangements are rather varied in electricity market restructuring, where rather than the proprietorship of market segments between public or private participation, the key elements include promoting competition and investment participation, with strong, market-driven regulators. Also, the instruments of policy are important to foster the development of technology and emerging market segments, such as demand response and efficiency experiences, use of new technologies and grid development, fast uptake of renewables, transport, and smart grid technologies, as discussed in Chaps. 5 and 8 in present book, on distributed energy and infrastructure, or in Chap. 7 in present book on micro-grids.

The present chapter is organised as follows: In the next section, a comparative review of regulatory schemes and long-term planning commitment efforts are developed. In a comparative manner, it is shown how different deregulation and market-driven efforts have fared in Mexico, compared to some key European experiences, and mostly in the neighbouring California and Texas regional markets and their regulations. Then in section three, critical aspects of regulation, including international convergence, and connections are approached. Then in section four, energy, capacity markets, long term and short-term auctions and submarkets for energy, and capacity of fossil fuels, but mainly clean and renewable energies, are analysed. Then ancillary services markets, financial transmission rights (FTRs), clean energy certificates, and aggregation in supply, including demand-side efforts and commitments, are analysed and compared. Section five concludes.

2 Regulatory Institutions, Laws, and Instruments: A Comparison with CAISO and ERCOT

Regulation is framed as a locus of market and submarket promotion, despite incumbents with market power (the well-known utilities). For that matter, regional markets have seen a timeline of regulatory instruments and dockets that extend over more than 20 years, and have handed down, not only asymmetric regulation towards utilities with market power, but different and more stringent rules than for new investment and technological efforts. The locus of regulations have to guarantee coverage and basic service to all users, irrespective of their buying power, meaning that universal service provisions are part of the regulatory compact. The generally accepted deregulation historically meant that successful market rearrangement has had a welfare enhancing effect from such government measures, as in more competition, prices aligned to nodal (local) costs, more economic "effort", a characteristic of competitive segments, increased quality of service, with more innovation and technological investment.

Evaluation of deregulation could proceed on two well established fronts: (a) on the strength, professionalism, and economic justification for the regulatory agencies' administrative, jurisdictional, decision assets, or the institutional settings and endowments; and (b) the quality of instruments, and what beneficial (economic and market growth mainly) effects they provoke by issuing well designed incentives (Laffont and Tirole 1993; Laffont and Martimort 2002), and the economic and agency theories of regulation and antitrust relied on (Viscusi et al. 1995). Regulation is considered here within the definition of institutions and institutional pressures, outlined by North, as "humanly devised constraints needed to structure political, economic, and social interaction. Their purpose is to create order and reduce uncertainty" (North 1991).

International convergence of regulations has been addressed by Jordana and Levi-Faur (2005), where the question has been whether *ex ante* (sectoral) regulators show resemblances across countries of the same sector to be regulated, or whether there is a stronger tendency to find regulation similarities inside a country, across the subjects of regulation; typically monopoly sectors such as telecommunications, banking, central banking, and energy. The referenced study as applied to Latin America between the late seventies and the nineties, shows a stronger trend across countries in a defined sector, such as the one we are interested in here; energy, and all its submarkets.

Take as a first explicit quantity analysis, the comparison of population coverage, capacity, and transmission lines in the Mexican, CAISO in California, and Texas ERCOT regional markets (Mexico can be considered another regional market in North America). The results are as shown in Table 1.

As one can see from Table 1, the regional market sizes are roughly similar in population numbers, yet Mexico leads in population served, although having approximately similar transmission lines. This is due to the fact that Mexico's grid is much less meshed. Also, electricity prices are rather dissimilar, since basic power is much more subsidised in Mexico than is the case with its northern neighbours.

Table 1 Energy market comparison: 2011 versus 2016/17

	CAISO	ERCOT	CFE
Installed generation (peak demand) MW 2011 versus 2017	57,124–63,500	63,025–69,600	60,440–68,000
Transmission lines (miles 2016)	26,100	46,500	36,343 (76,815 if sub-transmission included) + planned 17,655 2016–2030
Population served (customers 2016)	31 million	24 million	40.2 million customers, with population of 110 million
Planned reserve margin 2011 versus 2017 (operational %)	15% (2017)	13.75–18% in 2017	13% (2017)
Average annual load weighted price US $/MWh	$39.91	$26–$170 (7 pm)	$12–$21
Renewable % of total MWh (2011, 2016)	11–23 (9.8 hydro)	15.1–17.4 (wind and solar)	14.2 (wind and hydro) to 21%

Source Updated from own generation, with data from Ibarra-Yunez et al. (2017)

On the other hand, if one considers basic mid-size industrial energy tariffs, Mexico's prices are around 50–65% higher, given equilibrium purchasing parity exchange rates, as shown in Fig. 2. Noticeable also is the tariff path over past years, after the few years of energy reform in Mexico, one of whose motivations was to see electricity prices begin to decline, given more competition, improved technologies, more competitive renewable uptake, and less distortionary subsidies to the utility CFE. Such decline has not been achieved after 4 years of reform (from 2013 to 2018), mainly, as has been argued, because it takes around a minimum of 10–12 years or even more for a restructured market to align prices to marginal costs, as is evidenced by authors such as Borenstein et al. (2017), EIA (2020), Ibarra-Yunez et al. (2017), Pollitt (2018) and OECD (2018). Notice that while volume-weighted average prices (VWAP) fluctuated from around MX$680/MWh in mid-2016 to around MX$1,000 at the end of 2016, they peaked to close to MX$2,000 at the end of 2017, and then to MX$1,800 by the end of 2018 (recalculating prices in USD, they came to be USD$36.27 in mid-2016, USD$47.13 at the end of 2016, USD$107.30 at the end of 2017, and USD$91.56 at the end of 2018/MWh). A rough calculation shows an increase of 2.27 times in 2017, and a decline of 15% in 2018. Overall, since the end of 2016 until the end of 2018, the average price increase for electricity was 94.3%, an asymmetry with respect to ERCOT, or even CAISO, and also related to input (gas) prices (Fig. 1).

Note also that, in comparison, ERCOT equivalent average tariffs are much lower, and are aligned with gas prices reflected in combined cycle generation such that basic

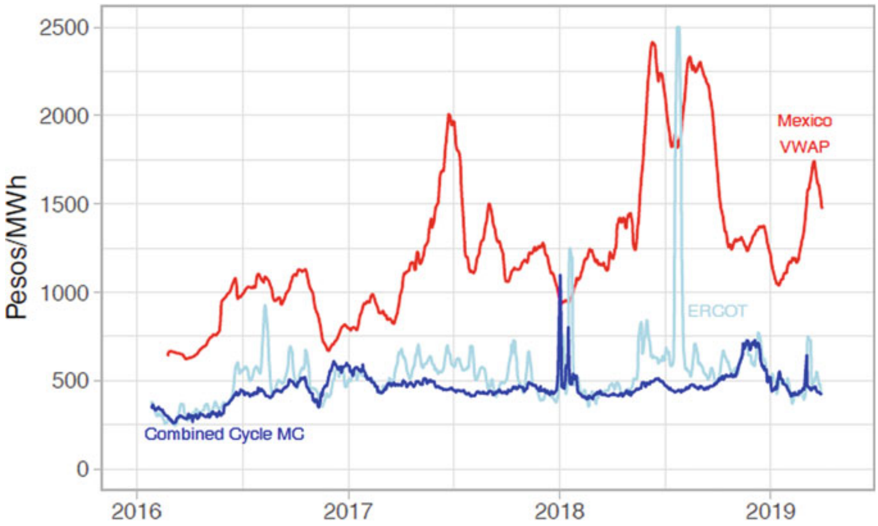

Fig. 1 Volume-weighted average electricity prices in Mexico. *Source* Taken from McRae, "market power in cost-based wholesale electricity markets", presentation, May 8, 2019. Mexico City, ITAM

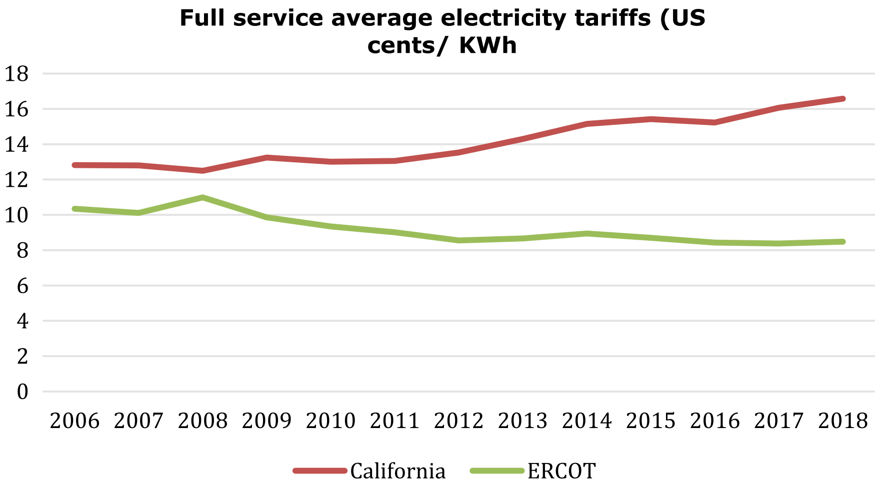

Fig. 2 Full-service electricity tariffs between California and Texas-Ercot. *Source* www.eia.gov avg. price annual, based on data from S&P global market intelligence, 2019

tariffs stayed stable at between MX$650–700 per MWh (with some congestion peaks in the winter seasons of both 2017 and 2018). So, in comparison, Mexico's (non-basic) tariffs have stayed between 171% higher, or 151% in MX pesos, as shown next.

Figure 2 compares California and Texas (the cheapest source of electricity in the US).

Now, in the case or Europe, market regulation has shifted its emphasis towards clear committed objectives of reducing the CO_2 footprint, and increasing the use and production of non-traditional sources of energy generation and load, or what is called a change in energy mix (or energy matrix), towards a target of more than 35% of renewables, and in some cases, more than 50% by 2024 (IEA 2019). Additionally, as a source of regulatory instruments, an emissions trading system in its new "vintage" has been observed and stressed as part of regulations.

For example, all EU countries with coal power plants have aimed at a reduction in their share of coal electricity. The total volume sank by 24%, or around 150 TWh in 2019. Relative to 2018, electricity generation from hard coal-fired power stations fell by 32% across Europe, while lignite-based electricity generation decreased by 16% (Agora-Energiewende 2020).

Taken as a leading one unit of measurement, Germany, Spain, the Netherlands, the United Kingdom, and Italy accounted for 80% of the decline in electricity from hard coal, leading to emission strategies against coal and Greenhouse Gas Emission commitments. For low quality lignite, more than 60% of the decline occurred in Germany and Poland alone. For its part, electricity from nuclear power plants declined slightly in 2019, falling by 1%, while gas-fired plants (combined cycle) were the only conventional power stations that produced more electricity than in the previous year, seeing a 12% rise in generation levels, mainly because of its cost, and gas prices and supply.

Turning back to the analysis of regulatory institutions, laws, and instruments, applied comparatively between the US regional markets and Mexico, one can trace back the regulatory compact in the United States, when the Federal Energy Regulatory Commission, or FERC, was created in 1977 as an outgrowth of the Federal Power Commission, dating back to 1920. In 1978, a key act; the Public Utility Regulatory Policy Act, the famous PURPA, was issued to promote the non-utility power sector, consisting mainly of cogeneration facilities and renewable energy sources for local utility, delivered under long-term contracts. Then the Energy Policy Act (EPA) was passed in 1992 to encourage non-utility generating facilities to become deregulated, meaning a first effort to separate monopoly from competitive market areas. This Act also intended the separation of generation from distribution, supply, load zones, and pricing of the regulated parts that faced no competition (wholesale and retail).

Also, expanding the Federal Energy Regulatory Commission or FERC endowments of regulation to open transmission to non-utilities in a non-discriminatory manner, were two critical pieces of regulation: FERC orders 888 and 889 (Joskow 2005). The first markets to see opening to competition were California, on the one hand, and some north-eastern states, such as Massachusetts, Rhode Island, and about a dozen states by 2000 (Joskow 2005). One can see that federal instruments and endowments of deregulation took more than 20 years and are continuously being updated.

In the case of Mexico, interested readers could trace back deregulation from 1993, where the Law for the Public Service of Electricity Use (Ley del Servicio Público de Energía Eléctrica, or LSPEE, 1993), separated energy facilities for public service (basic service for final consumers of residential and industrial, commercial, and agriculture segments). LSPEE also made space for private non-utility generators, explicitly destined for own use (auto-generation, cogeneration from industrial vapor and heat), large producers for exclusive sale to the utility CFE, called in Mexico Independent Power Producers, or PIEs, and imports, all under specific permits. By 2018 there were close to 2,000 private individual or conglomerate generation permits (Ibarra-Yunez et al. 2017).

Mexico's Constitutional change of 2013 turned the former monopoly state enterprises into the State Productive Enterprises (EPEs in Spanish). Then, during 2014 and 2018, a series of secondary regulations and administrative decisions, rulings, and tertiary administrative rulings were produced in a fast moving "downpour" of regulatory decisions. A wholesale market was also created as an autonomous institution, called CENACE (a regional transmission system operator, and the locus of wholesale transactions). In contrast to the US federal rulings, that have taken more than 20 years, the Mexican prospectus sought to implement change dramatically in just 4–5 years. (The main secondary laws of deregulation can be read in next Chap. 5).

A brief timeline of the FERC and the corresponding objectives of its orders can be outlned as follows:

2.1 FERC Legislation and Main Orders Shaping US Regulation

- 1992: FERC issued *Order No. 636* (The Restructuring Rule) that mandated unbundling of sales services from transportation services, providing customers with full choice of providers and opening these markets to competition. This Order has been ratified at state levels, via the corresponding Public Utilities Commissions (PUCs); in the case of California, it is called the CPUC, and for Texas it is the corresponding TPUC.
- Also in 1992, FERC *Order No. 637* further addressed inefficiencies in the capacity release market. It included both gas market and electricity submarket access.
- In April of 1996, key Order 888 was issued. It restructured the entire electricity sector, and emphasised unbundled transmission service obligations and planning, with no undue discrimination access to all generators and load entities, plus price exchange allowances to deepen transactions, mostly at wholesale level. Order 888-A, established rules for further open access electronic bulletin board OASIS (FERC 2020).
- In 1999, FERC issued Order 2000 to establish regional independent system operators, RTO/ISOs).

- The Energy Policy Act of 2005 established on its part, enhanced attribute and delegated responsibilities for the regulator, that emphasised, in addition to market deregulation, reliability security with non-discrimination standards for transmission along the grids, the promotion of transmission standards, interconnections across regional markets, and investment in the grids.
- NERC (National Energy Reliability Council) was established in 2006, to; oversee reliability, promote universal access, ensure tariff standards, coordinate rulings with those of regional and state standards, oversee adequacy of the bulk-power systems to regional needs, and, set up regional advisory boards in emerging matters of energy submarkets (Order 672).
- In October 2008, FERC acquired new responsibilities under Order 719, designed to improve the operation and strengthen the competitiveness of organised wholesale electricity markets via the use of demand response, and by encouraging long-term power contracts strengthen the role of market monitors, and enhance the regional transmission organization (RTO), and independent system operator (ISO) responsiveness.
- On the powers of the FERC in respect of an increasing investment in non-traditional renewable markets (for energy and capacity in some RTOs), the important orders are: Order 890 addresses cost allocation of diverse energy sources with transmission capabilities and planning; and, Order 1000, issued in 2011, for transmission planning in response to increasing numbers of energy sources located far away from load centres, such as solar-photo voltaic, and wind energy farms (FERC 2020).

I should be noted that US regional energy markets are characterised, not only by federal regulations, but also constitutionally by state Public Utility Commissions, or PUCs, which coexist to guarantee market development in respect of the Federal government and State legislatures. For example, at FERC level, the mandate is to guarantee a wholesale market of utilities and non-utilities, regional interconnection standards under transmission convergence and exchange, issuing hydroelectric permits (licenses), and natural gas pipeline certification. At state levels: PUCs have a mandate to issue rules for retail sales, set tariffs and state special taxes; intrastate transmission flows of power; certify new electric generation and transmission facilities in a coordinated manner, such that the phenomenon of "generation drives transmission", or "transmission drives generation", does not result in the negation of transmission services due to congestion, (e.g., the Texas case of renewable competitive energy zones, or CREZ planning); develop retail franchise areas; enforce quality and service standards; approve construction of non-hydro generation facilities; and, set rights of way in Texas (Bushnell et al. 2019).

At both federal and state-local levels, three sets of instruments to promote energy development and increasing uptake of renewables, at the same time that these instruments are applied in a level environment, can be distinguished between the financial, fiscal, and market promotion arenas. Many credit and loan instruments are rather important, mainly after around year 2000, in respect of direct subsidies to residential "prosumers" of solar panel installations, smart grid areas, distributed energy promotion activities, and so-called "behind-the meter" activities off-grid. Tax rebates, tax credits, and issuance of renewable credit certificates, and renewable energy credits (RCCs or RECs) have been a core promotion activity of the fiscal instruments. On the market promotion side, direct soft loans in Austin, Texas, or San Francisco, for quality standards at non-utility levels, called RPSs (Renewable Portfolio Standards) are noteworthy. These tie in renewables with the activities of carbon footprint reduction among final users. Some research has found strong correlation between RPS and renewable projects. Others have found that RPS reduces electricity prices, but only in a subset of cases, giving mixed success results (Upton and Snider 2017; Yin and Powers 2010; Zhao et al. 2013).

Turning now to Mexico, one needs to compare and complement this country's federal regulations in its response to new technology and markets at different aspects stages of the regulatory panorama, given that all energy subsectors have been in the process of opening up towards market-driven regulated segments of oil, petrochemicals, natural gas, and electricity. Various presentations by the Mexican Energy Regulatory Commission (CRE (Comisión Reguladora de Energía)), with its large array of laws, regulations, and administrative rulings, all give a good idea of the comprehensive set of regulatory compacts. CRE was launched in 2006 to oversee, in the case of electricity, the issuance of permits to private generators for self-supply, and co-generation, independent system operators IPPs that depended on long term purchase power agreements with the incumbent CFE (up to 30 and the 15 years). Under the new regulatory compact and wholesale market, beginning as an independent market clearing house, these became the so-called external legacy generators, that could let their contracts expire when finalised, or opt to become qualified producers, entitled to trade in the wholesale market under the National Centre for Energy Control, (CENACE).

The first set of laws restructured the electricity and gas sectors. The *Ley de la Industria Eléctrica* (LIE 2014), enacted in 2014, defined the following structures among various new players and opened the field to dozens of other rulings under the new regulatory compact: external legacy contracts (large private generating companies selling power to CFE, formerly defined as *Productores Independientes de Energía*; and, other legacy contracts among CFE subsidiaries, as mentioned above). On the demand side, LIE 2014 established load centres, similar to the US Load Service Entities (LSEs), for both basic service CFE, and private generators, commercialisation companies, and qualified private users. Also, on the demand side, the law defined qualified users (with a capacity larger than 0.5 MW), and basic service users (basically residences served by the utility CFE). For intermediation, the law defined suppliers who own load facilities or suppliers, and also traders with no facilities' ownership, or merchant entities (including aggregators), according to the secondary laws produced under the LIE 2014, plus rulings of the wholesale market operation under the independent system operator called CENACE, that was created by a specific Law of the National Centre for Energy Control (Mexico: Ley del Centro Nacional de Control de Energía, the CENACE), in 2013.

In the wholesale market, the following products were planned and regulated to be traded: power; capacity; ancillary services; financial transmission rights; renewable energy certificates or RECs; and, various other products to be defined. CENACE, Mexico's RTO/ISO, is under the oversight of the secretary of energy or SENER. Mexico's reform redefined policy making procedures and regulating agencies. A hierarchy of Mexican players and their mandates could be presented in summarized manner in the next description of main stakeholders, taken by this author from more than 50 documents and executive decisions (more than 3,000 pages of regulatory instruments produced in the course of five years (2013–2018):

2.2 *Mexico's Legislation, and Policy and Regulatory Makers*

Secretary of Energy (SENER)

- Launch of entire Energy Reform to oil, gas, and electricity sectors, voted in by Congress (December 2013).
- Definition of time frame to launch all "secondary laws," beginning in August 11, 2014.
- Launch and oversight of the Law of Electricity Industry (LIE), the main legal piece, and the law of CFE (also in August 2014).
- Set members of the boards of deregulated state productive enterprises (SPE) Pemex, and CFE, their subsidiaries and affiliates, and limits of ownership and unbundling.
- Approves five-year CFE expansion plans, called Plan Quinquenal de Energía, or Five-Year Energy Plan.
- Sets renewable (clean) energy provisions and requirements, as a key bridge between energy and environment regulations.
- In December 2015, an additional law was proposed by SENER and voted on; called the Ley de Transición Energética, or LTE. This is the Environmental Law that set targets (35% renewable consumption) of clean generation (consumption) by 2025, from a base of 17.9% in 2014. For that matter, SENER published guidelines before, for clean energy certificates (RECs) in October 2014.
- Sets minimum consumption limits to be considered as qualified users (0.5 MW installed load capacity), to eventually raise the limit to 1 MW.
- Hierarchical decrees from secondary laws, in layers as follows: (a) market bases; (b) market practices' manuals; (c) operating guides for all electrical markets and products; and, (d) Operating criteria. They extend beyond the equivalent US FERC Orders, because provisions could be separated from those requiring Regulatory Impact Analysis (RIA), and those that are published in the Federal Gazette with no RIA requirement under General Administrative Decisions.
- Arising from the former set of decrees, 28 new administrative provisions have been published and enacted under manuals for market practices (between 2014 and 2018). These provisions were separated into further layers. Note that most

of these provisions were postponed under the administration of Pres. López Obrador (2018–2024), who set presidential priorities, rather than those of other stakeholders.

Secretary of the Treasury (SHCP)

- Set regulated maximum prices for markets in transition (gasoline, oil liquids, natural gas, and basic utility services, the latter being a tripartite decision between SHCP, SENER, and CFE). Industrial tariffs with no subsidies, are set by CFE and are more market driven.
- Set final tariffs and prices for suppliers at load nodes (distributed geographically on a yearly basis along with SENER, after consultation with CRE).
- Fiscal treatment and adjustment to oil, gas, and electricity state productive enterprises "SPE" (Pemex and CFE), and its subsidiaries and affiliates).
- Co-participates in designation of members of boards in CFE and its subsidiaries an affiliates.

Energy Regulatory Commission (CRE)

- CRE was created in 2005 as an independent and autonomous energy regulator of non-utilities, like its counterpart, the federal U.S. regulator FERC.
- Under the Mexican Public Service Electricity Generation Law (Ley del Servicio Público de Energía Eléctrica, or LSPEE), was instituted in 1994 to be in charge of CRE, it inherited the following regulatory activities: administering all private contracts for generation (IPPs, auto-generation, cogeneration, imports, exports); regulating and liberalising gas transport and storage; and promote tendering through the so-called open seasons to incentivize renewable investment beginning in 2008.
- Administer permits and non-utility contracts, excluding state company CFE.
- With the Constitutional Reform (2013); Secondary Laws (August 2014), CRE was given new powers; extended legal and administrative endowments, new role to proceed towards overseeing de-regulated prices and participants, new grand-fathered contracts for generation and supply, and, administer contracts under the new LIE-2014 and other market rules (Market Bases, Bases del Mercado Eléctrico 2015).
- Under LIE, CRE sets contracting requirements in the vertically unbundled industry for generation, transmission, supply, trading, distribution, and commercialisation of electricity, and related wholesale products (for private permits in legacy and new contracts). Its regulatory arm touches on private permits for gas imports, pipelines, storage, and deregulation of sales.

National Utility Company (CFE)

- In accordance with the Constitutional changes in Arts. 25, 27, and 28, the Mexican state deregulated the two main State-Owned Enterprises; Petróleos Mexicanos (PEMEX), and Comisión Federal de Electricidad (CFE). They were renamed

State Productive Enterprises with new mandates, to produce social products and services for the public good, as they aim for economic value. The intent is for CFE to become a corporation, fully embodying corporate practices.

- Further, a new law called Ley de la Comisión Federal de Electricidad (LCFE, and the Ley de Petróleos Mexicanos), was published in July 2014, and came into operation in August 2014, that sets the vertical unbundling of an electricity company into generation for basic services, generation for non-basic services, separating transmission and distribution as subsidiaries for public service, plus supply activities at load centres, and trading activities, separated from the rest as new types of (privatised)economic activity.
- Further, the LCFE created a special regime in terms of: (a) subsidiaries and affiliates; (b) wages and remunerations; (c) acquisitions, rents and leases, services, and construction; (d) valuation and appropriation of goods and facilities; (e) responsibilities towards the state; and, (f) payments to the state.
- CFE corporate governance, and that of its subsidiaries and affiliates, was changed in the composition of their governing board into 10 council members from government (SENER, SHCP, 3 other designees by the federal government; 4 independents, 1 designated by the CFE union).
- The CEO of CFE manages, operates, and executes CFE objectives under the strategies, policies and orientation approved by the board of directors. The same principles apply to CFE's subsidiaries and affiliates.
- CFE's fiscal and budgetary regime was revamped as a corporation in practice, with an adjustment period between 2014 and 2016, and was covered temporarily, along with Pemex, by the federal budget. Beginning in 2017, CFE and its subsidiaries would follow corporate practices with no subsidies (in principle the fiscal and subsidy regimes transited towards such practice but needed fine tuning by 2018 under the new administration).
- Subsidiaries and affiliates were empowered to enter into contracts with other private companies, under the new LCFE, as so-called purchasing power agreements, or PPAs, but also via the wholesale market, that was also created (August 2014).
- Subsidiaries became SPEs with legal separation, and own capital, operating under their own board (consisting of 5–7 council members), with a designated director. Affiliates are not SPEs, but CFE participates directly or indirectly, having more than 50% of the equity, and they can be established with either Mexican or foreign legal status. This allowed CFE to create a company called CFE International in June 2016, along with CFE-Energía, to manage the gas business as a separate entity.
- Since 2014, many decrees and agreements were published in the National Gazette regarding tariffs, calculus methods for payments, rents, and regulated aspects of contracts.
- Further, within CFE restructuring process, a decision by the CFE board was revealed in March 2016, to be officially published in June 30, 2016, announcing CFE horizontal separation. Such separation was reverted to a centralised and concentrated form by the new administration of 2018–2024.

- Under CFE as a holding company, 4 generation facilities were dubbed "empresas productivas del estado", and these EPSs were to compete amongst themselves, and with private participants, in the wholesale market at CENACE. They were called CFE II, III, IV, and VI and were to become generating companies, using any technology to participate in the market.
- CFE I became a horizontally separated affiliate, called Intermediation Generation, to concentrate CFE legacy interconnection contracts, and to administer them, and trade in the wholesale market.
- CFE V became horizontally separated as an EPS to concentrate on, and be represented in the wholesale market (CENACE), all being former IPP producers.
- Finally, another EPS, called CFE Basic Services, operates under a special legal regime, with CRE supervision of its tariffs, for utility basic (residential) service.
- Two other EPSs, separated from CFE but under its corporate wing, are EPS Transmission, and EPS Distribution.

Additionally, and after key secondary regulations, the Electricity Industry Law (Ley de la Industria Eléctrica or LIE 2014), the CFE law (LCFE 2014), the Law for the National Centre of Energy Control (CENACE 2014), the Energy Transition Law (Mexico LTE 2015), are third level laws, established under the Electricity Market Bases (Bases del Mercado), that were spelled our during 2015–2018, with 19 bases to define procedures for all stakeholders, and other rulings. Chapter 5 accounts for the most important pieces of regulation for Mexico.

Among the rules, and the secondary and tertiary regulation, the first general rulings establish registries and guarantees for all market participants. Within the secondary rulings, operation of the wholesale market and the electrical system are spelled out, including guidelines for the reliability of systems, including small isolated systems. Then under the third general rulings all market procedures and dynamics are addressed, such as spot markets, day-ahead markets, and long-term markets for electricity, power balance submarkets, markets for RECs and financial transmission rights (FTRs), ancillary services, auction rulings, and payment systems.

Then in the fourth general rulings, that encompass information and oversight mechanisms, there are market information and measurement systems, market monitor obligations and rights, and fines, plus other mechanisms against irregular market conduct. Other general administrative rules include those related to basic services and their regulated user tariffs, interconnection rules, rules for isolated supply (abasto aislado), distributed energy determinations, transmission and distribution tariffs, among others (Bases del Mercado Eléctrico 2015).

To conclude this section, one should point out the provisions at both the US federal level and Mexico's level. Those in the former case are complemented by a myriad of local and state public utility commissions and authorities. A second and main lesson from the above treatment, is the fact that whereas in Mexico, the energy reform has proceeded rather quickly, it has taken more than 12–20 years for the California and Texas markets to evolve, while integrating new technologies, and the needs of all stakeholders of these very dynamic markets. Finally, whereas part of Mexico's energy reform sold the optimistic expectation that retail energy prices (and wholesale ones aligned to local marginal prices and costs) would decrease, electricity prices needed more time to converge. The last point has been taken by recent López Obrador administration officials, as a drawback and expose the negative results of the country's 2013–2018 reforms.

3 Regulation, International Convergence, and Connections

Regarding international regulatory convergence, one key difference between a long-term dynamic of regulatory adjustments in the United States, and a much more recent one in Mexico, is that market and technological dynamics have been integrated into regulatory instruments and institutions over a long time, in a pragmatic manner.

For example, rights of way have become a source of litigation and taken somewhat in a rush in Mexico, whereas in the Texas market, the Texas General Land Office has internalised rights of way permits, such that former owners and affected parties, can voice concerns and then agreements are reached with social acceptance, mostly with little conflict and litigation (given that all property has passed years of ownership scrutiny and owners are registered properly) see (https://glo.texas.gov/index.html). Another example is the planning process, adopted in 2007, to bring power generated far away from load centres, mainly from solar and wind farms, to the point of consumption. This large project, from the Texas Public Utility Commission (TPUC), instituted competitive renewable energy zones, or CREZ, meant to forecast and create transmission investment expansion for renewable energy. In California, a coordinated effort between the CPUC, the transmission owners, environmentalists, load servicing entities, generation planners, and even tribal representatives, focused on a way to transfer renewable energy from its source to the load zones. It thus focused around transmission expansion of intermittent energy, and to issue transmission permits along corridors. The process started in 2009 and is still active (see: https://www.nationalwind.org/wp-content/uploads/assets/blog/AnneGillette.pdf).

All stakeholders seem to be equally important in both Texas and California, which is a lesson to Mexico's recent regulatory process. Moreover, another critical aspect of the above more mature markets is that, in addition to the federal regulators FERC, the North American Electric Reliability Corporation or NERC, is in charge of the reliability, stability, compliance, security, and cyber-security of the grids, and their connections, not only interstate and across electrical regional systems, but including international connections with Canadian provinces, and with Northwest Mexico. Moreover, given Mexico´s recent energy reform of March 3, 2016, CRE commissioners approved Resolution RES/151/2016, containing the first Grid Code (Código de Red) in Mexico, as a critical regulation instrument to align the two countries in respect of transmission grid planning, including potential binational projects, such as those in Baja California (Baja California is part of the regional interconnection, named the Western Electricity Coordinating Council, or Western interconnection WECC).

Addressing the instruments of policy even more deeply, one could define incentives for investment and technology improvement, additionally to the commitment towards non-traditional renewable sources of energy (wind, photovoltaic-solar, biomass methane generation, residual biomass gasification, hydro electrical, efficient co-generation), into financial, fiscal, and promotional incentives. This is further addressed in Chap. 9, which deals with residual biomass and electricity generation.

3.1 Types of Incentives

One stark difference on the financial front, mainly of non-government budgetary sources, is that in developed and mature markets, financial instruments are rather varied and originate from banking loans, specialised green financing, government green bonds, as well as risk capital of all sorts (Lam and Law 2016; World Bank 2013). Some of the financing comes, not only from national financing mechanisms and institutions, but mainly from sub-national (state, local) sources. In cases such as Norway, as we have addressed above, state-owned enterprises have experienced years of deregulation, to the point that most firms became public, listed in main national and international capital markets, and equity ones. The above contrast with countries such as Mexico, and others in Latin America (Lam and Law 2016; Polzin, 2017).

In the above case of developing countries, where efforts are couched in terms of clean energy and non-traditional fossil fuels, financial instruments are rather simple or so-called shallow, since renewable energy projects pose a structurally higher risk than fossil fuel projects due to their relatively higher start-up capital costs, and, in some cases, their intermittency characteristics. For these reasons, financial promotion has to coexist with fiscal incentives, mainly to small size intermittent projects, as has been addressed by Ying et al. (2015).

Fiscal incentives include direct subsidies, as in the case of “feed-in tariffs”, in Germany. Other incentives include tax rebates, and tax deductions, in both the California and Texas markets. Still other incentives include accelerated depreciation of capital costs of energy in small solar installations, access (both obligatory and voluntary) to renewable energy certificates or credits RECs) (See IRENA 2020; NREL 2020). Many other fiscal incentives exist, not only in the energy field, but also in energy related projects. Examples are summarised in DSIRE (2020): (a) installation and equipment efficiency standards; building energy codes; corporate tax credits; corporate tax exemptions; stringent efficiency standards for public buildings; grants; green building incentives; and, offers of free energy evaluations for local governments.

In the area of pure promotion policies, one may note many efforts at local levels; for *prosumers* and investors in “behind the meter” installation with allowances for net metering, net billing, interconnection facilitation and permits, and, full merchant payments, and business models for energy, capacity, reserve management in small scale projects. The state receiving most incentives at present is California, with 218, then Oregon, and Texas, with respectively 145, and 142 (DSIRE 2020).

3.2 New Technologies and CAPEX and OPEX in Renewable Energy

A special case to be analysed here is how, in relation to fossil sources of energy generation, renewables face relative higher start-up costs (CAPEX), but once covered (without or with the incentives presented above), operation and maintenance costs are much lower (OPEX) than in fossil fuels. The main evidence against the claim that renewable projects are much more expensive than coal, gas, combined cycle, hydrogeneration as a reserve, is that the project costs of renewable energy has declined considerably in past years. Let us take some official statistics and maps from the widely accepted source, IRENA (2018):

IRENA's global calculation of the various emerging renewable technologies and their average costs, ranged, in 2017, from around US$2,000 for large photovoltaic-solar, to US$3,700 for small (below 0.5 MW)/kW. For wind projects, average costs range from US$1,200 to US$1,700/ kW. For combined cycle investment (CC-gas projects), it is around US$1,000/kW, while for hydropower it ranges from US$1,000 up to US$3,500 per kW. As can be seen, renewables have become rather competitive in installation costs, and cannot be seen as too expensive. Moreover, energy efficiency indexes have increased to around 20% which one piece of criticism to renewable projects.

Now, given the above costs of capital and installations, or CAPEX, the OPEX in 2017, according to the firm Lazard (2017), before subsidies and tax credits, wind comes in as the cheapest, with operating costs of between US$30–60/MWh, then comes large solar-photovoltaic OPEX at around US$43–53/MWh, while CC costs range from US$42 to US$78/ MWh, while coal is the least cost effective at US$ 60/MWh (Lazard 2017).

The main risks of renewables, as has been stressed in the present research, have to do with: the intermittency of renewable energy projects, or REPs, that increase the financial risks; and, the size of RE projects, that might stay small and thus not attain a minimum efficiency scale to attract partial funding, especially from the private sector. The most important sources of risk for REPs entering the market seem to arise from incumbent utilities with high market power that could discriminate against or even deny interconnection for renewable projects, mainly if the wholesale market participant is weak. Finally, another source of risk comes from regulatory failure, meaning that the regulator fails to provide predictable and clear regulatory instruments to promote the expansion of markets and investments (Ibarra-Yunez et. al. 2017).

Figures 3 and 4 show the reader the stark decline in Levelized Costs of Energy (LCOE) of new technologies.

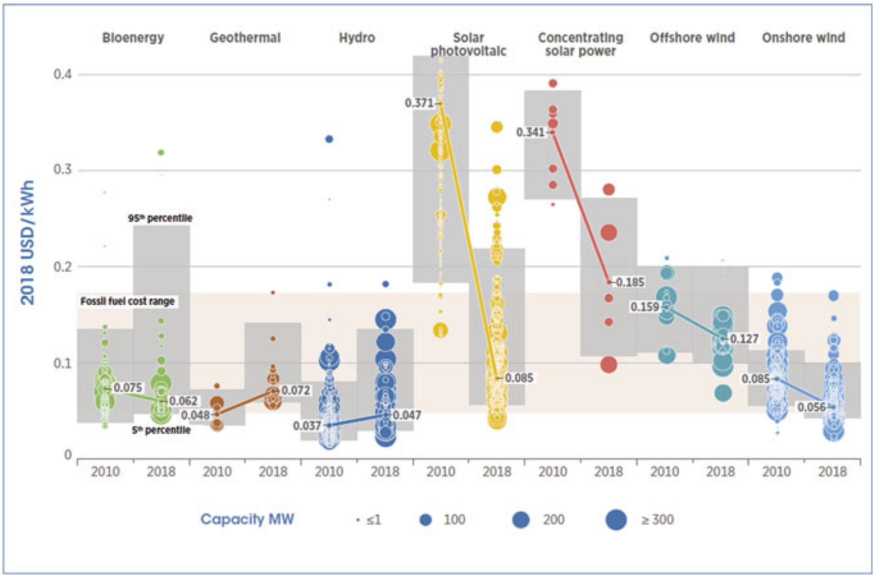

Fig. 3 Global LCOE of utility scale renewables 2010–2018. *Source* IRENA (2019). Data file renewable power generation costs. *Note* This data is for the year of commissioning. The diameter of the circle represents the size of the project, with its centre the value for the cost of each project on the Y axis. The thick lines are the global weighted-average LCOE value for plants commissioned in each year. Real weighted average cost of capital (WACC) is 7.5% for OECD countries and China and 10% for the rest of the world. The single band represents the fossil fuel-fired power generation cost range, while the bands for each technology and year represent the 5th and 9th percentile bands for renewable projects

3.3 *Connections and Facilitation or Restrictions.*

The California CAISO market has both interstate and international interconnections with neighbouring markets as part of WECC, so it is overseen by FERC legislation and rules. In contrast, ERCOT is an isolated system by design, with no FERC oversight mechanisms to adhere to, even if the Texas regional market follows such federal rules. The isolated Texas market has connections with Arkansas, Oklahoma, and Mexico, but only in emergencies, in asynchronous connections. Mexico has connections also to Belize and Guatemala (Fig. 5).

Taking away the Presidio-Ojinaga international interconnection in Chihuahua that is a lower than 69 kV, the oldest are the ones between Mexico's CFE Transmission and Ribereña-Ascárate, plus ANAPRA-Diablo at 120 kV. Then it is worth mentioning the Tijuana-San Miguel permanent connection, and the La Rosita-Imperial Valley out of Mexicali within WECC. They are high voltage synchronous ones (between 280 and 400 kV lines capacity). Then newer ones are Piedras Negras—Eagle Pass in the State of Coahuila, and then 5 back-to-back connections with the ERCOT regional system, in emergencies.

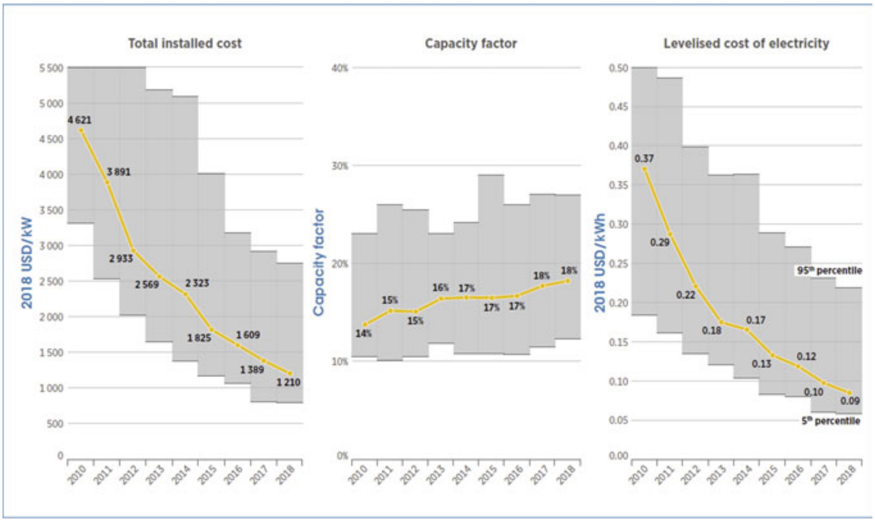

Fig. 4 Example of global weighted average total installed costs and LCOE in solar-PV. *Source* IRENA (2020). Data file renewable power generation costs. *Note* Solar PV. Unlike all other technologies in this report have their costs expressed per kilowatt direct current (DC) and their capacity factors are expressed as an AC-to-DC value

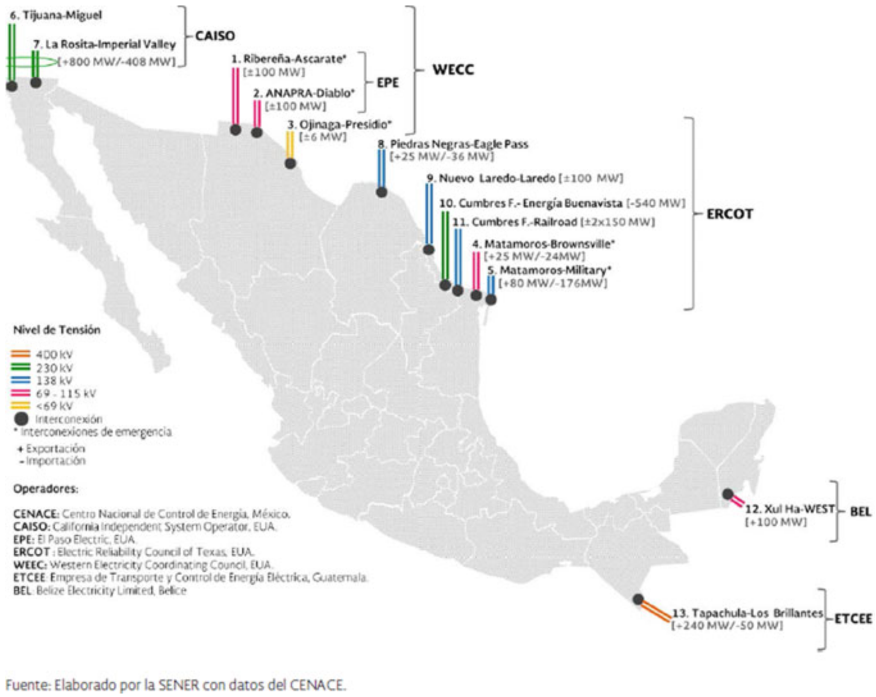

Fig. 5 Mexico: international interconnections. *Source* Sener, with data from CENACE 2019

Facilitation of these links has been put on hold, mainly because of the suspended auctions in Mexico's renewable energy sources since the beginning of 2019, and the lack of incentives by the state company CFE to expand the international lines needed for its strategic plan 2018–2033, as laid out in the National Development Programme for the Energy Sector, called PRODESEN 2018–2033 (México PRODESEN 2018).

CFE Transmission nowadays has a mandate; the maintenance and expansion of transmission lines in congested areas within Mexico. On its part, ERCOT has defined for many years that energy exports can be liberated, if domestic and local demand has been satisfied, and for which funded interconnections are a restriction. For Mexico, the regulator CRE offers permits for imports and exports, plus regulating interconnection contracts and obligations, and the trading of energy excess and energy transmission.

4 State of Submarkets Traded in Mexico's CENACE, CAISO and ERCOT

Part of the deepening of the wholesale market under the regional transmission organization, or rather the independent system operator, is the capacity to attract investors to the wholesale market, but also to develop various layers, or submarkets, to sustain an efficient, quality, reliable, secure, continuous, and sustainable electricity system. These products are energy, capacity, capacity balance, clean energy certificates (overall, renewable energy credits, RECs), financial transmission rights, traded directly or by auction, and an ancillary services submarket (not active until the present research in 2020). Auctions are also held, under CENACE's commitment, for clean energy projects (3-year contracts for energy and capacity, or medium term, and long-term auctions). On their part, legacy contracts for basic services, and external legacy contracts (the former large capacity exclusive contracts for generators to supply to the utility CFE, or PIEs), can be subject to bilateral contracts, or power purchase agreements (México Bases del Mercado Eléctrico 2015).

Moreover, under the new deregulated market, the wholesale market, under the aegis and obligation of CENACE, consists of:

(a) A short-term energy market, including a day ahead market (DA), and a real time market, plus, in a second stage, an hour ahead market;
(b) A balancing capacity sub-market;
(c) A CELs submarket under assignment (clean energy certificates);
(d) FTR auctions (operating in 2019 for legacy contracts of CFE plants);
(e) Incipient promoted distributed energy and social distributed energy projects.

Participants in the wholesale market need to be at least of 1 MW of capacity, and be separate from the supply side, as fossil, renewable, and clean energy generators; on the intermediation side, there are suppliers, acting as traders, but with no facilities in their control or ownership (pure intermediation); and, from the demand side, the qualifier users (LIE 2014). All detailed "general administrative decisions", called in Mexico DACG, are contained in the Bases del Mercado Eléctrico (op.cit. 2017).

Now, according to Mexico's official National Energy Balance Report (2018), the transitional market with CENACE as the locus of wholesale market activities, would have needed to show a move towards an increase the number of participants with modern and sophisticated technologies such as efficient co-generation, and the beginning of a change in the energy mix. According to the Balance Nacional (2018), the public generators represented 52% of all energy supply, while external legacy generators represented 26.7%, self-suppliers, 20.1%, and new permit holders, only 1.2% by the end of 2017 (Balance Nacional de Energía 2018), which shows a lagging energy mix. However, the latter producers were the most active in securing second auction results in projects and were predicted to grow to change the energy matrix, according to the Mexican government, to attain a large increase in clean and renewable energy production. According to other national generation figures, rather than generation distribution with producers, traders, and qualified users in CENACE, the energy mix by 2017 was 77% for fossil, while clean energies made up the rest. Of the latter: Hydro-electric generation remained at 10.5%; wind 4.6%; nuclear 3.6%; solar 0.1%; while efficient co-generation represented 2.3%; and, bioenergy and thermal contributed 1.1% each (México PRODESEN 2018).

Now, since the beginning of the Lopez Obrador administration, auctions were suspended to check for real investment efforts by those clean and renewable projects. Moreover, there was the intent by the incumbent utility to:

(a) Extend the assignment of RECs to legacy generating producers of facilities that existed before the new secondary laws of 2014; and,
(b) Set a limit of 46%, maximum, of the generating market for private projects, a turnaround of deregulation.

According to the present research, the RECs' shifts have been put on hold given strong opposition from private producers and their associations. The maximum limits have been proposed by the incumbent CFE, but no regulator's determination has been made public to date.

Let's turn now to the US regional product markets in CAISO and ERCOT. According to EIA (2020), a full-blown model of demand, coordinated, or schedule, supply arrivals, prices, and congestion, give rise to the submarkets in both these regional markets.

CAISO

In California's CAISO, a day ahead and real-time short-term market operates automatically with the most volumes, and bid-ask price settlements, including intra-hour market with high granularity of prices, locations, and participants. Then an ancillary services market operates to sustain reliability and balancing of markets, including regulation-up, regulation-down, and then spinning and non-spinning reserves. Regulation-up, and down, operate in an automatic way, while reserves are traded relative to the standby capacity that is synchronised with the grid (10-min ramps). A short-term balancing submarket is called a Congestion Revenue Rights market, similar to long term FTRs. Then there is market for demand response, or an interruptible contract market that operates both at the wholesale level, and also under bilateral PPAs between load centres and utilities and other generators. Finally, there is submarket capacity-adequacy trading (CAISO 2020).

One notable aspect of the California market is that it issues many performance-measure reports. Markets and incentives for renewables can both be treated as marketable products in this market, but they are also parcelled out in the incentives' mechanisms, before products are traded in CAISO. This means that promotion of renewables has two dimensions: *ex ante* and *ex post* investment maturity.

ERCOT

One has to point out that vertical separation of whole market participants was possible since the Senate Bill (SB7) from 1999 that liberalised the market by first requiring that all Investor Owned Utilities (IOUs) be unbundled into three kinds of companies (affiliation was allowed): Power generation companies (PGCs), similar to Mexico's "generadores obligados, participantes del Mercado", or GOs; then retail electricity providers (called REPs in ERCOT, not to be confused Mexico's REPs, as described before, and also cooperatives, that trade through ERCOT. Some cooperatives are load aggregators that trade in the wholesale ERCOT market, in order to extend and facilitate participation.

The ERCOT became the ISO, to which PGCs and REPs could affiliate, to provide both wholesale and retail services, the former of which is to be traded under ERCOT (being unregulated if they do so, since ERCOT has stayed as an isolated system, and not regulated by FERC). In such a case, power wholesale generators, and retailers could, and are, allowed to coordinate. (See Wolak 2005).

From the demand side, there is the number of Qualified Facility, or QFs, that can be either private participants, or a privately represented participants, similar to Mexico's traders with no owned facilities (called comercializadores, not suministradores in Spanish), or Load-Serving Entities (LSEs), or pure demand entities, similar to Mexico's centros de carga/usuarios calificados.

Products traded in ERCOT include a 'day ahead' market for bids and offers of energy, balancing short term, ancillary services at a particular location, and for a 'price within hours', while there is also a 'real time' (unregulated) market. Implicitly, there is also a balancing market, called point-to-point (PTP), bid-ask 'day ahead' market. Texas ERCOT is a regional energy-only market in the sense that there is no capacity market. There is also a regulated obligation for ERCOT to offer critical hours ancillary services, due to its lack of capacity submarkets. Much of ERCOT's work has moved towards the promotion of coordinated transmission extension, and renewable sources of energy, for which it has gained wide acceptance and repute. As for the rest, ERCOT, as a locus of market clearance, is a passive entity (ERCOT 2005).

To conclude the present section, one will notice, firstly, that wholesale markets, even if trading in similar products and services, are at various stages of development. Secondly, it seems apparent that each of the three ISOs referred to have aims beyond securing the operation of the wholesale market for their various products and services.

For example, Mexico's CENACE concentrates on encouraging participants to trade, while it also gives advice on transmission expansion, and services the electricity market to secure reliability, security, flow, and price convergence. CAISO, on the other hand, has moved beyond securing operation reliability, and has focused on the expansion of renewables, and other products more related to price stability, with incentives for products and connections, while ERCOT has moved to promote the coordination of transmission-generation of renewables in locations remote from load centres, and sought to maintain system stability in an energy-only market (Baldick and Niu 2005; Joskow 2005; Tierney 2008).

5 Conclusions and Framework for Further Analysis

Market evolution, as the chapter title intends to describe, implies time for adjustment at many levels for an electricity market in transition. A first lesson from this review and analysis of mature markets in the United States and, in passing, in Europe, shows that reforms have taken ten or more years to show results, in terms of market participants, settling of "rules of the game", the integration of more players than anyone could have expected at the end of the nineties in California, or Texas. Then there is the two referent cases of Mexico's recent experiment with energy reform that inaugurated its first four years of market liberalization. It seems apparent that policy makers in Mexico, have not seen such need to continuously modernise and upgrade regulations to respond to market and technological needs, or to embrace a true market with many participants along with the incumbent utility.

The second aspect addressed here, is that laws, regulations, administrative determinations, dockets, other rules of the market, and hence the adaptation of market participants constitute a heavy load of legal and institutional settings that need to first seek a level playing field for an increasing number of participants. Then, federal, but also state and local, levels of institutional change and upgrading, also take time to demonstrate beneficial results in price-to-cost alignment, congestion solutions, infrastructure to transmit and distribute energy, plus other products, and submarkets, to confront new challenges in this industry. Also, institutional change needs to internalise social awareness that includes affected parties and also present stakeholders, with new technologies adapted to market and institutional signals, along with coverage, security, and efficiency in the electricity market.

Now, let us derive a set of recommendations for the future, arising from the present chapter.

- First from the present analysis, it is clear from the beginning of the chapter, that technology, innovation, and awareness of the need to foresee a society with a new energy mix with a much higher weight of renewable energy, is a trend for which regulatory change has to adapt, that is, innovation and technology, come ahead of regulations.

- Secondly, as it has been stressed above, it takes years for this adaptation to take place, such that government styles and regulatory capture might shift more than once to finally respond to the market needs. For example, FERC orders in the United States have adapted many times since the first regulations in the eighties until now: more than 40 years, since 1977's PURPA. Hence, a long-term vision and readiness towards strong markets are necessary for the Mexican energy sector to reach best world practices. Going back in time to cancel shared governance amongst many players seems a way against worldly trends that have proven successful in mature markets.
- Another recommendation arisen from the analysis is that no matter the government style, being it disaggregated or centralised, the key part is to commit to complementary investment in various types of fossil and renewable energy sources, and many types of sub-markets, such as pure energy, but also capacity markets, ancillary services to embrace variable sources of energy, financial transmission rights, demand response management, but also creative sources of finance to new technologies, distributed energy, R&D in mobility and batteries, as the chapter has shown.
- A fourth critical recommendation in this analysis, is to clearly define the reach of regulatory change under financial support, fiscal treatment of the emerging markets, and promotional policies, such as pricing mechanisms, at the federal, state, and even local levels. Mature markets, in Germany, the UK, and regional markets in the United States (CAISO, PJM, ERCOT, MISO, among others), have clearly defined financial, fiscal, and deregulatory and promotion policies, that at the same time, create stability between the incumbent utilities with market power, and new investment efforts and emerging players with little market power. Moreover, markets need to promote innovation at the same time that basic services are guaranteed to all the population.
- Still another recommendation is for regulators to be evaluated by the strength, professionalization, and economic justification (via regulatory impact analysis or RIA) in each decision the agency reaches, as well as the administrative, jurisdictional, decision assets, and the institutional settings and endowments, but also by the quality if its instruments of regulation, and what they provoke as incentives for a strong and advanced market, with little uncertainties for all market participants. Moreover, regulation has to follow best practice also, being it convergent to international practices, since Mexico is an open economy with many international treaties and agreements.
- Another lesson from the chapter analysis has to do with the comparison Mexico faces regarding volume-weighted average electricity prices in contrast with much lower ones in both neighboring California's CAISO and ERCOT, even if the country has made efforts that tariffs reflect nodal costs and primary sources of energy generation. Price alignment is a strategy in electricity dispatch. In recent months when the present chapter is written, a rather contested decision by the Mexican system operator CENACE, has tried to dismiss that electricity should be dispatched first, from the cheapest producer, and then be orderly dispatch from cheapest to most expensive one, such as fuel, and carbon. In the case of Europe,

for example, there are rather committed plans to reduce countries' CO_2 footprint by moving away from coal and into non-traditional renewable sources, such as wind and solar, plus efficient co-generation, and efficiency and savings forceful plans on the side of consumers, something that obliges energy and climate change regulators to work hand-in-hand, something that Mexico should embrace more clearly.

- Moreover, as this chapter has demonstrated, the levelized cost of renewables has declined substantially since 2010 in the global markets, to be even cheaper than fossil energy sources, such as onshore wind, offshore wind, and geothermal. A recommendation is to bet that these sources will continue to be an increasing fraction of the energy mix in the foreseeable future, as well as other innovations in storage, and batteries for extended range transport.
- On the side of taking care that regulators and utilities do coordinate generation, supply, trading, with the grid expansion and maintenance, interconnection is critical and licensing should be integrated in the development strategy for the grid, such that no undue discrimination is provoked, that creates conditioning of investments. One section of this chapter refers to CREZ in ERCOT in Texas, where a clear strategy was implemented to extend the grid to be able to evacuate electricity from renewable sources in the west of the state, to far-away load centers and centers of consumption in the Gulf of Mexico (Houston), and central Texas.
- On its part, Mexico faces congested areas in the Gulf of California, and in the Yucatán peninsula, for which urgent transmission expansion seems apparent. The cancellation of a big HVDC transmission line from the state of Chiapas to the Mexico City area, and the one integrating the Baja California isolated grid with Mexico's mainland, sets the agenda back in time and wastes an opportunity for advancing the spread of resilient energy, and should be soon addressed again soon.
- Moreover, international interconnections should also be deepened, both with the US market and also Central America in the southern border, and auctions to call for investors are recommended to also be reinstituted, to guarantee that all stakeholders in this emerging market have a market space.

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Chapter 5
Market Restructuring Due to Renewable Sources Evolution and Penetration

Alejandro Ibarra-Yunez

Abstract This chapter is first focused on the institutional and multilateral analysis of renewable energy penetration, and its interface with energy reform. Then the vertical and horizontal separation of the utilities incumbent in the evolution of a true market driven sector, presents alternative sector restructuring, where an Independent System Operator (ISO: CENACE in Mexico's case), is crucial for the development of an electricity wholesale market and its various instruments, such as markets for power in the day-ahead and real market, capacity, clean energy certificates or credits, or the so-called CELs, financial transmission rights, ancillary services, and other emerging or new products. Then after reviewing all laws and secondary regulations in Mexico, an analysis of the "minimum functions" is applied to Mexico's CENACE. Finally, technological evolution as a driver of new energy sources is addressed.

Abbreviations

CEL	Clean energy certificates
CENACE	Centro Nacional de Energía
CENAGAS	Centro Nacional de Control de Gas Natural
CFE	Comisión Federal de Electricidad or Federal Electricity Commission
CNH	Comisión Nacional de Hidrocarburos
CONUEE	National Commission for the Efficient Use of Energy
COP	Conference of the Parties. UN Climate Change Conference
CRE	Energy Regultory Commission or Comisión Reguladora de Energía
ENTSO-e	European Network of Transmission System Operators
FERC	Federal Regulatory Energy Commission

A. Ibarra-Yunez (✉)
EGADE Business School, Tecnológico de Monterrey Rufino Tamayo y Eugenio,
Av. Eugenio Garza Lagüera, Valle Oriente, 66269 San Pedro Garza García, NL, Mexico
e-mail: aibarra@tec.mx

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FTR	Financial Transmission Rights
INDC	Intended Nationally Determined Contribution
ISO	Independent System Operator
LIE	Mexico's Energy Law or Ley de la Industria Eléctrica
LTE	Energy Transition Law
PUC	Public Utility Commission
RPS	Renewable Paortfolio Standards
SDG	Sustainable Development Goals (United Nations)
SEMARNAT	Secretary of the Environment
SEN	Sistema Eléctrico Nacional (México)
SLCP	Short-lived climate collutants
UCTE	Union for the Coordination of the Transmission of Electricity
UNCC	United Nations Climate Change initiative

1 Introduction and the Relevance of Renewable Energy

Much economic and policy effort has concentrated on increasing the use of non-traditional clean and renewable sources of energy at all levels of society. Interest began muted, but by the turn of the century, countries in Northern Europe, plus most of European energy market participants, some specific countries such as Spain and Portugal, and even at the subnational level (such as Hawaii, in the US Pacific, or California and Texas), have been involved in changing the energy mix towards renewable and clean sources (EIA 2020).

From electricity generation, to grid management and expansion, to distribution, supply, and trading of energy products, all have moved from the traditional model of a monopolist utility subject to regulation in its monopoly segments in respect of its consumer base, to market-driven models of energy that incorporate renewable sources. Also, the demand part of the electricity market has changed much, from a captured consumer base by the monopoly, to facing market-driven aspects for the supply, and even to market models in distributed energy and smart grids (Nuttall et al. 2019).

A relevant question for the present chapter is; what justifies looking at market restructuring and renewable sources? The answer seems to arise from two different but clear origins. First, market restructuring has arisen from the clear acceptance that the energy industry has evolved from natural monopoly, to a complex one, with some parts maintaining their monopoly characteristics (ex. transmission, some distribution, some basic retail services), while other parts of the market have evolved away from huge economies of scale requirements towards competitive markets (an example is traditional generation of combined cycles, generation of renewables, trading, last mile transmission expansion and interconnection, among others).

In consequence, the above calls for a redefinition and restructuring, not only of the electricity market, but also of its regulatory agencies, and their attributes and instruments. Secondly, the market restructuring arises from the increasing need to commit to a greener and better-quality energy, and the integration of clean and renewable non-traditional sources of energy (one refers to clean energy as the addition of hydrogeneration to non-traditional sources such as solar, wind, biomass, tidal, geothermal, clean combined cycles). The latter fostering a more sustainable energy market.

Not only does the market-plus-energy source shift call for a thorough analysis of the new realities, but the new market definition is increasingly in need of a much more detailed, disaggregated, and multi-agent market analysis (sometimes called "high granular" information), or the move towards prosumers and "behind the meter" models of demand management. Hence the transition calls for much more detailed analyses than ever before in the history of the energy sector, including new roles and restructuring of existing policy-making ministries, agencies, and regulating bodies.

The Chapter addresses these dynamics for restructuring. In the next section, a description of market evolution and changes in nowadays mature markets is presented, from the role of multilateral agencies and worldly objectives, and how emerging and transition markets are following up, or leapfrogging the mature ones. Then a section is needed to address the institutions, policy making bodies, regulatory agencies, and the set of laws and regulations that govern new markets in the transition towards a shift of the energy source mix towards renewables. A fourth section is dedicated to technological evolution and the innovation aspects that increasingly shape the energy markets. A final part derives lessons learned, together with policy considerations and conclusions.

2 From the Multilateral Vision and Paris Agreement, Regional Efforts at the International Energy Agency, to Dynamics of Electricity Markets

2.1 The Multilateral United Nations Efforts and the Paris COP Agreement of 2015

The United Nations Climate Change initiative (UNCC), was begun in the late 1990s to multilaterally involve and encourage the main developed countries to commit to measurable efforts against climate change accelerators, such as carbon dioxide emissions by the world's main sources, by type of sector and component effects (United National Framework Convention on Climate Change or UNFCCC 2019). Under the

UNFCCC, the Kyoto Protocol promoted measurable commitments around greenhouse-gas emissions, separating developed countries from non-obligatory commitments by other countrie.[1] The UNFCCC was abandoned with the end of the so-called Kyoto Protocol vintage 2, around 2012 (withdrawal of Canada, echoed the non-commitment of the USA).

Then the UNCC Initiative had to revive involvement by as many governments as possible. It is part of the United Nations' Sustainable Development Goals (SDGs), set in Monterrey, Mexico, in 2001. Since climate change is considered the most critical threat to sustainable development of the 17 SGDs, commitment is key not to allowing temperature to increase more than 2 °C by 2050. Three agendas arose after 2015 from the SDGs, as new targets after the demise of the Kyoto Protocol: (a) The Paris Agreement; (b) the 2030 c; and (c) the Sendai Framework for Disaster Risk Reduction (United Nations Climate Change 2019).

The Paris Agreement was formulated in 2015, with participation of 196 parties, but with commitments by the governments of only 30 developed countries (mainly the EU, plus Australia, and New Zealand), while increasingly involving single, medium-income emerging economies, such as China, India, Mexico, and Brazil. Its main objective is for all participants to lower all elements that could increase world temperature by 2 °C (and mostly closer to 1.5 °C) and reach the levels of the pre-industrial era (base year 1992, and target year 2050). The global temperature had already increased by around 1 °C by 2018, which is why the objectives of the Paris Agreement are now rather pressing. Note that the United States and Canada had still not signed the Agreement by the time of the present investigation (Fig. 1).

The impacts of climate change can indeed be very devastating, mainly for poorer countries. For that matter, the UNCC seeks to facilitate financial flows to these economies, along with enhancing opportunities for technological advance and making it possible for countries to develop capacities to benefit and disseminate new technologies. Bureaucracy, red tape, and unclear obligations for institutions designated to host UNCC projects, could become impediments to the improvement of climate change conditions. Furthermore, UNCC aims for all project actions to be transparent and subject to good governance. Again, obscure funding rules could give rise to corruption, as disclosed in various documents, after commission memoranda of the UNCC (2019).

Nationally determined contributions (NDCs) are self-committed measurable obligations by each country/member, updated and communicated yearly. COP 15 in 2019 was held in Santiago, Chile (UNCC 2019). Some of the relevant areas of NDCs include country leaders in committees for overseeing the following topics (ibid.).

[1] The Kyoto Protocol, also known as the Kyoto Accord, was launched in 1997 by the United Nations Framework Convention on Climate Change. It set mandatory limits on six greenhouse (GHG) emissions by developed countries. The United States did not sign, along with Somalia and Sudan. Countries in Annex I were all OECD countries as of 1992, plus Russia and other transition Eastern European countries, such as Baltic States (Annex II excluded economies in transition. They also correspond to the so-called Annex B countries with cap obligations. Non-Annex B countries are developing ones with no set obligations).

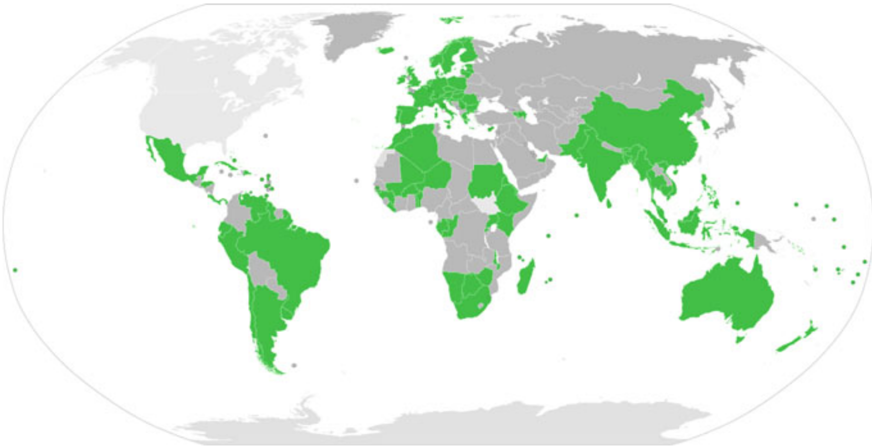

Fig. 1 Distribution of signing parties of the Paris Accord 2015. Doha Amendment to the Kyoto Protocol for Paris Accord (2019)

1. Mitigation
2. Social and Political Drivers
3. Youth and Public Mobilisation
4. Energy Transition
5. Industry Transition
6. Infrastructure, Cities, and Local Action
7. Nature-based Solutions
8. Resilience and Adaptation
9. Climate Finance and Carbon Markets.

In the past, projects were led, but then shared for multilateral yearly conferences, where governments offered measurable updated commitments, and declared a designated government agency, secretariat, or ministry to carry on the specific projects. In the case of Mexico, the Secretary of the Environment, called SEMARNAT, has been designated to lead the national inventories of pollutant agents, gases, and projects regarding the environmental agenda, with links to energy concerns. Now, given some developing countries' elections and political changes, some have reduced their commitment positions, or even the financing and governing of their climate change obligations, and their links with the energy transition agenda (Ibarra-Yunez 2016; Ibarra-Yunez et al. 2017).

2.2 *The International Energy Agency and Its Role in Bridging Gaps Between Climate and Energy*

Take the example of Mexico, which has seen its GHG emissions increase rapidly until 2011, mainly as the result of strong economic growth rates. According to the International Energy Agency (IEA), a world forum to discuss climate change, obligations, role of various energy markets, capacity for expanding and sharing energy development efforts with private parties. From 1990, energy-related CO_2 emissions grew by two-thirds to 431 million tonnes (Mt or Teragrams) in 2014, where fossil fuels account for 90% of Mexico's primary energy supply. Emissions increased more markedly in transportation services and electricity generation. It was anticipated, until Mexico's elections in 2018, that improvements in productivity, would motivate economic growth and energy demand.

According to the IEA, in its 2018 Report, power generation was expected to rise from around 300 Terawatt-hours (TWh) in 2017 to around 470 TWh in 2029, and over 500 TWh by 2040 (IEA 2018). Hence Mexico's new government needs to internalise the challenges to the energy system to become more competitive and more sustainable. Mexico has now embraced the idea of integrating climate change objectives into energy policy making, as evidenced by its Climate Change Law to reduce GHG emissions by 30% from the business-as-usual level in 2020, and 50% from 2020 to 2050, as shown in the IEA Country Report (2018). Measuring cost effects of objectives by all projects was a recommendation set by OECD/IEA, 2017. One drawback in Mexico's case is the fact that the new Energy Law, passed in 2014, was rather integral and detailed around swift changes to market and regulations (LIE 2014, published in the Official Gazette in August of that year: *dof Aug 14, 2014).* Many other Market Rules were set for all stakeholders in the electricity sector that promote private investment and participation. However, the so-called Energy Transition Law, the "green agenda", was separated from the electricity law, and came into force afterwards, in December 2016.

As an example of the weak links between the energy and climate change agendas, Table 1 helps to understand such a weakness, for which renewed efforts should be adopted to increase coordination of the two agendas. Unfortunately, for this economy, the incoming administration of Pres. Lopez Obrador, in its National Development Plan, and voted on in Congress in May, 2019, little or no mention is made of climate change commitments, or that guarantees are clearly provided for market development.

The IEA, in its declaration of intended nationally determined contribution (INDC), includes the goal to reduce the emissions of short-lived climate pollutants (SLCPs). Integrating climate policy and air pollution policy brings synergies, as reducing SLCPs has a direct impact on air quality and the health of the population. The IEA then urges the government to strengthen national air quality policy to provide a solid basis for limiting air pollution. The above requires that all signatories to the IEA vision, present clear measurable objectives for achieving; energy subsectors in the hydrocarbons industry, facility for gas transportation, warehousing, and

Table 1 Scope and objectives of Mexico's Energy Law (LIE) and Energy Transition Law (LTE)

LIE	LTE
Clean energy goals compliance (obligations, fines for non-compliance, by the energy regulatory commission CRE)	Emissions reduction compliance (obligations and fines for non-compliance, by National Commission for the Efficient Use of Energy CONUEE, and also the Secretary of the Environment SEMARNAT
Clean energy certificates (CELs) issuance and obligations to a quota (35% by 2024)	Emissions national registry by type of GHG, particles, and by type of producer
Oversight of wholesale market participants to use the wholesale market for energy, capacity, CELs, ancillary services, transmission financial rights, other products (pro-competition segment)	Direct mandate for GHG emission reductions
CEL market must link to carbon market	Register advances in the clean energy targets 2018, 2020–2024, and further
Promotion of distributed energy (generation), with no obligations	Eventually launch a cap-trade market mechanism linked to the carbon market, and the CEL market
Indirectly contribute to reduction in GHG emissions in electricity sector	

Source Taken from Table 2 of Ibarra-Yunez et al. (2017)

commercialization, and that the electricity industry, including renewables, appoint responsible entities, and promote markets. At the time of this analysis, it is unclear if all requirements are, or will be, met by the incoming Mexican government.

Given a return to centralised government in the electricity and oil sectors, Mexico's emissions may actually increase from today's levels, with an apparent minimisation or disregard, by the new presidential administration, of Mexico's compulsory position in multilateral forums. Additionally, from pure population growth, the projected increase in transport may have worrisome implications for emissions. This calls for urgent strengthening of sectoral policies, especially in transport, and for developing a comprehensive policy approach for all sectors. That Mexico's current administration will take these concerns seriously is unclear, at the moment. Some clear efforts can be seen in specific urban projects abroad, such as those for London, Paris, Montreal, Berlin, Valencia, Austin, and Curitiba in Brazil, to name salient efforts by some smart communities.

Smart city initiatives are a clear and challenging part of IEA's goals because they involve many actors in the energy and climate change panorama. Mexico, for example, a major energy producer, has experienced its energy policy as traditionally focused on the supply side rather than on the demand side, with some muted administrative decisions over distributed energy projects. The same has applied to climate-related policies. Noticeable is the challenge to coordinate government efforts by the Secretaries of Energy and the Environment, Economic Promotion by the Secretary of the Economy, including agencies such as the Energy Regulatory Commission, and

Table 2 Legislation in Mexico's energy reform 2014–2018

1.	Law of hydrocarbons (LH)
2.	Law of foreign investment
3.	Law of mining
4.	Law of public and private associations
5.	Law of the electric industry (LIE)
6.	Law of geothermal energy
7.	Law of national waters
8.	Law of national agency for industrial safety and environmental protection for the hydrocarbons sector
9.	Law of Petróleos Mexicanos
10.	Law of Comisión Federal de Electricidad
11.	Law of parastatal entities
12.	Law of acquisitions, leases and services of the public sector
13.	Law of public works and related services
14.	Law of coordinated energy regulatory bodies
15.	Organic law of the federal public administration
16.	Law on hydrocarbons revenues
17.	Federal law of income rights
18.	Law of fiscal coordination
19.	Law of the Mexican petroleum fund for the stabilization and development
20.	Law of federal budget and fiscal responsibility
21.	General law of public debt
22.	After these 21 laws, then market bases rulings was passed, and all codes, market rules, interconnection, rulings on distributed energy, along many other operational rulings, published in the National Gazette (*Diario Oficial de la Federación*)

Source Own generation with a review of all legislation between 2013 and the end of 2018

all institutional settings to guarantee loci wholesaling of electricity and its derivative sub-markets, gas, and oil (named CENACE, CENAGAS, and CNH). As the IEA notes, *"In general, energy efficiency and clean transport are important, as are cost-effective policy levers that could play a stronger role in a comprehensive clean energy and climate change plan"*.

2.3 Electricity Sector Evolution Dynamics

Markets are stimulated by deregulation, re-regulation, and technological innovation. One can see the first market changes becoming widespread in Nordic countries, where, from centralised utilities, Finland, Sweden, Denmark, and later Norway, all moved to separating the competitive side of the markets from the monopoly parts, subject to regulations. International interconnections were part of the dynamic market alignments, for which the Nordel regional market set rules for electricity generation, transmission, and distribution, but they also progressed to align the prices of energy across the countries, and embrace transmission expansion to integrate renewable sources of generation and demand.

Then the so-called European market UCTE integrated many international Western European electricity interconnections into a market, where electricity in all its forms (including renewables) was transformed, from a utility towards a tradeable good and service. The market includes Austria, Belgium, France, Germany, Greece, Italy, Luxemburg, Netherlands, Portugal, Spain, and Switzerland. Since 2011, this interconnection market has adopted a new community name, the ENTSO-e, and it guarantees total convergence of trans-border transmission tariffs. Moreover, the European Commission on Energy has launched a trans-European plan for a 2050 carbon neutral energy market (European Commission 2018).[2]

How do energy markets look in their transition, and how are the parts separated from being unified and centralised in their policy and administration, towards being decentralised, segmented, and competitive, and where policy and administration operate under shared ownership and collective decision-making, and not ‘the government’ only. Figure 2 could be useful to the understanding of such an evolution, which is where most countries have moved, with few exceptions, in the world.

As one will notice, the Independent System Operator (ISO), is the centrepiece of the wholesale market and locus for market clearance. Some markets such as NGC in the UK, Alberta in Canada, California in US, ERCOT in Texas, the case of Norway, and finally other comparative markets, such as VPX in Australia, PJM, and New York NYPP are also shown in the above figure.

The segments of the markets that are of interest are various components of the emerging electricity market configured as generators (G), power marketers (PM), power exchanges (PX), transmission owners (TO), the independent system operator (ISO), ancillary service providers (AS), scheduling coordinators (SC), retail service providers (R), and distribution service providers (D). Note the diversity of roles the ISO has in the various management models, such that in some markets like the UK’s NGC, the ISO integrates transmission and power exchange decisions, while in Norway, the ISO integrates with transmission services and infrastructure, while in most of the relevant mature markets, power exchange decisions and management are an integral part of the ISO. ERCOT, Alberta, and notably California are examples of totally disaggregated or market-oriented sectors, with multiple independent players in the electricity ecosystem. All integrate renewables (Srivastava et al. 2011).

An additional critical aspect of market segmentation, that the energy sector has experienced, is cost allocation, hence pricing across all segments of the industry to ascertain sustainability. Moreover, some segments have given rise to new players

[2] See https://ec.europa.eu/info/news/commissioner-arias-canete-germany-discuss-integrated-national-energy-and-climate-plan-2019-jun-24_en.

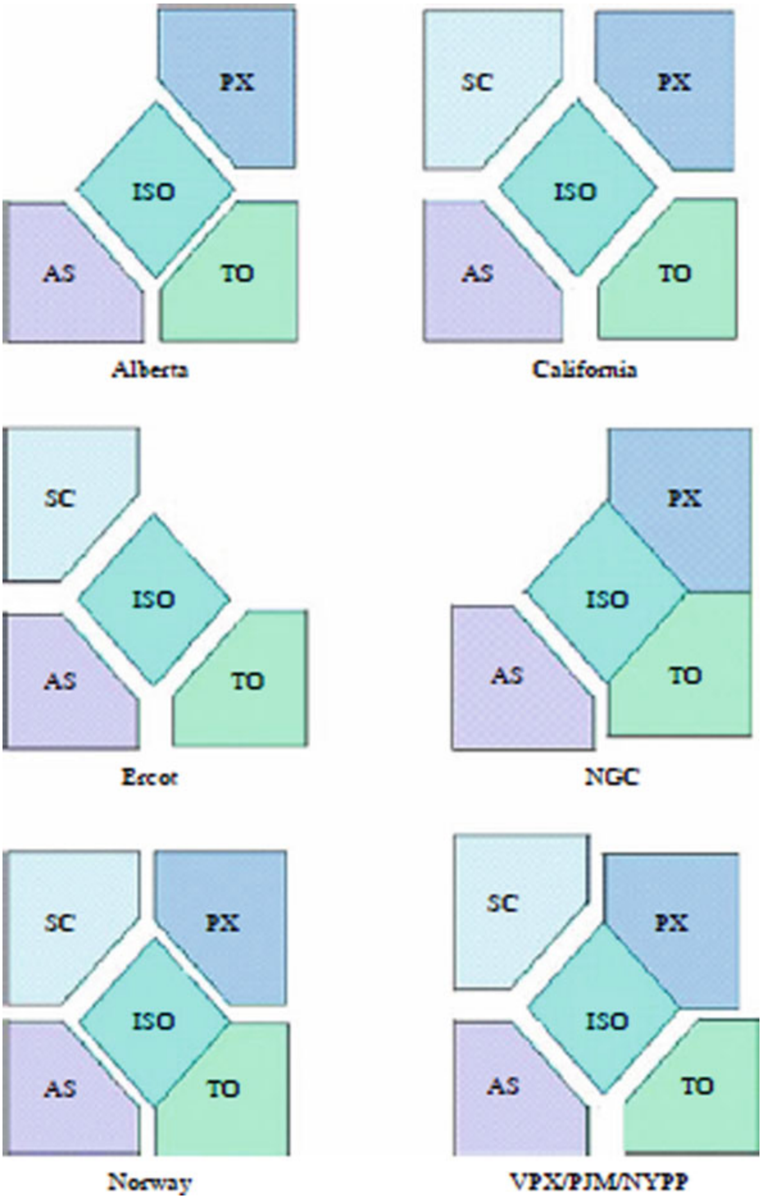

Fig. 2 Alternative restructuring of electricity markets. ISO: Independent System Operator; AS: Ancillary Service Providers; PX: Power Exchanges; SC: Scheduling Coordinators; TO: Transmission Owners. *Source* Taken from Srivastava et al. (2011)

(aggregators, traders, service engineering, financing, among others, as well as products additional to only-energy, but that include submarkets for capacity, balance, financial transmission rights, clean energy certificates or credits, and other submarkets), for which one has to accept that new markets are, nowadays, deep and complex.

The present chapter gives a brief but complete idea of the dynamics of the electricity sector; the role of multilateral agendas under UNFCCC-then UNCC, for example, the Paris Accords, role of the IEA in promoting renewables and governance of the energy sector under new market conditions for many stakeholders and interest groups in the industry, and then briefly and visually present alternative market structures across the main mature markets. The next section will address the institutional and regulatory settings across some energy markets, with emphasis on Mexico's recent changes in commitments, agencies, and the legal impacts of the deepest and most integral energy reform.

3 Institutions, Policy Making Bodies, Regulatory Agencies, and Their Updated Roles

In Mexico, arising out of the Constitutional changes that occurred in December, 2013, so-called secondary laws were enacted, starting in mid-2014, by the Mexican Congress, These included at least 22 new laws whose objective was a long-awaited de-regulatory stance, that also promoted private investors as needed complements of the three main energy submarkets: hydrocarbons, natural gas, its infrastructure, storage, and commercialization, and electricity, in both its basic services and wholesale markets. In the latter, a specific law established the breath of the ISO called Centro Nacional de Control de Energía, or CENACE, as the central pillar of the new market.[3]

Before describing and analysing the crucial role of CENACE, suffice it to list all relevant legislation, executive orders, administrative rulings, and regulatory decisions to end this section.

The Law of the Electric Industry (Ley de la Industria Eléctrica), Chapter II, Arts. 107–112, established that CENACE would become an independent public organisation, with juridical independence and its own funding. Stated objectives included that it: (a) be the operative control of the national electrical system (SEN); (b) be the locus of all operations of the electricity wholesale market; (c) guarantee open access, with no undue discrimination, to the national transmission and distribution networks, among the ones spelled out in the Law (Art. 107); and (d) guarantee the operation of

[3] Basic services and the operation of the incumbent state oil Company PEMEX, and the electricity utility CFE, were changed both in the Constitutional changes (Chap. 28), and by the National Laws of Hydrocarbons (LNH), and National Electricity, (LIE), to the new designation, State Productive Enterprises, or *Empresas Productivas del Estado*, with a clear mandate to operate with corporate culture and management. Both were subject to strong regulation as powerful incumbents.

the whole system, within the parameters of efficiency, quality, reliability, continuity, security, and sustainability (Art. 109). Later, CENACE was administratively established by a decree published on August 28, 2014, in the National Gazette (*Dof Aug 28, 2014).*

Two critical mandates were placed on CENACE. First, in order to align the objectives of increasing generation and the supply of renewable sources of energy, auctions were to be scheduled to occur at least once a year, beginning in 2015. Three such renewable energy auctions were successful in opening up a market for long term commitment of renewable markets for energy, power, and clean energy certificates, until 2018. In the first auction, 11 projects were adjudicated (6 were in operation by 2018, mainly in the Yucatán peninsula in southern Mexico); in the second, 20 projects received permits (4 were operating by the end of 2018); in the third, 10 projects were adjudicated (by the end of 2018, none of them was operating).

It is important to note that the auction mechanisms were successful in attracting competitive players to the market. At the same time as investment was committed to renewable wind and solar project capacity, hydroelectric projects were set up in the States of Chihuahua, Hidalgo, Jalisco, México, Oaxaca, Puebla, Sinaloa, and Veracruz; together with geo-thermal contracts in Jalisco, Michoacán, and Nayarit, plus one biomass project in the State of Chiapas (García Alcocer 2018; Ramirez-Cabrera 2019). According to the Energy Regulatory Commission, USD$2.5 billion ($10^9$USD) were committed in the first auction, while USD$4 billion were committed in the second, and USD$ 2.4 billion in the third (García-Alcocer 2018).

45 countries have used renewable energy auctions as a transparent vehicle to promote new players and new sources. As the main results, one can posit the following:

(1) Generation costs have declined, which creates substantial savings to the incumbent state enterprise CFE-Basic services.
(2) Auctions create a diversification of the energy matrix, as renewable energy projects are incentivised.
(3) Auctions promote investment away from the incumbent CFE which, during the transition, had not enough resources to embark on creating a new market itself. Committed investments, as shown above, reached almost USD$ 9 billion, with no risk to the state.
(4) Success at the auctions creates positive externalities, as more investors are drawn to subsequent auctions.

A second critical mandate was for CENACE to establish clear rules for: the short term electricity market (day-ahead, and real time), medium term, and long term (latter pending); technical interconnection (network codes, market rules); a capacity submarket; a market for renewable energy certificates and allocation (somewhat pending); ancillary services; financial transmission rights; and, other submarkets. At the time of the present analysis, some of the latter parts have been put on hold by the new administration of Pres. Lopez Obrador, which could hinder the wholesale market and its participants (SENER 2019).

How does CENACE compare with the United States' markets, after three years of operation, with around ten years of review and the boost of a host of modern regulations, and taking into account the brief report of the Federal Regulatory Energy Commission (FERC) on ISO's performance, and, to begin with, FERC order 2000, which established a similar mandate for the operation of the crucial Independent System Operator, with its so-called "minimum functions"?

By the end of 1999, FERC defined the "minimum functions" of an RTO/ISO in Docket No. RM99-2-000, Order No. 2000. FERC based these minimum functions on lessons learned by the regulator since FERC Order No. 888, which provided a basis for the first U.S. RTOs in 1996. In Table 3, FERC's minimum functions are applied in the context of Mexico's CENACE as a basis for evaluating the system operator's development to date. These RTO/ISO minimum functions are listed and defined in the first two columns, and their strengths and weaknesses are evaluated in the following columns (Table 3).

While CENACE is on track to fulfil most of the minimum functions outlined in this table (Table 3) in the medium term, the table shows lack of progress in some submarkets, such as in ancillary services development. Other areas that will be especially important for CENACE to address in terms of encouraging renewables uptake, include encouraging congestion management and parallel path flow improvements to provide flexibility that an increasingly renewables-driven grid demands (Mohler and Sowder 2017, p. 285). As it plans grid expansion and interregional coordination of control areas, CENACE can develop strategies to harness renewable resources in areas with high wind, solar, and/or geothermal generation potential, whilst also considering critical transmission points across regions that may arise due to high-renewable generation scenarios, although these might change due to the stalling of renewable and wholesale market promotion.

CENACE's capacity as a market monitor and tariff designer also positions it well to continue to open the wholesale market to new participants and provide a fair platform for their participation, reducing costs through greater competition in generation, and transparency in pricing. CENACE's continued role in serving as the sole provider of transmission services is also a key feature of ensuring non-discriminatory access to new generators, renewable or otherwise (FERC 1999, p. 330).

For the transitional market in Mexico, an additional dimension is the speed of moving from a centralised governance CENACE model, towards a true market with minimal central intervention. However, the new administration of Pres. López Obrador, and overall policy by the Secretary of Energy in Mexico, seem to be at odds with the concept of markets. Additionally, CENACE, in an increasing mature market, would be moving towards a neutral-passive role in the market clearing processes. Speed and a strategy of increased implementation of market functions is critical for success, especially as it pertains to rapidly developing approaches that support renewable uptake and utilization.

Given the rapidly changing nature of Mexico's electricity system, and CENACE's identified need for performance assessment (and metrics for its performance in the transition), the application of minimum market functions to CENACE's third and following years would be an important step towards building a continually evolving assessment framework. Given that the functions of wholesale markets continually develop, market operators and monitors can establish new minimum functions as

Table 3 Minimum functions and CENACE's strengths and weaknesses afster its third year in operation 2018

Minimum FERC function	Minimum function definition	CENACE strengths	CENACE weaknesses
Tariff administration and design of wholesale prices	In the interest of reliability, implement efficient prices for transmission asset access, as well as for related markets	Day-ahead and real-time tariffs set, including imbalance market, capacity	Financial transmission rights applicable to incumbent CFE only Other projected FTRs suspended
Congestion management	Congestion pricing structured to minimise congestion costs. Monitor for abuse of monopoly power in constrained areas	FTRs set for incumbent. Information system for loads and marginal local prices (MLPs), demand and supply in real time	Basic service tariffs established as reference only, in the summer of 2018
Parallel path flow to guarantee network security	Ensure that system allows electricity to access a single network node via multiple routes. Network with necessary redundancies to be able to handle outages	Grid efficiency, reliability, etc., in place and improving	Coverage is less than total 100%
Ancillary services	E.g., load following reserves, markets for energy imbalances, voltage control, and black start capability	Five ancillary services included in the market bases, and operators are collecting data on prices before market rollout	Ancillary market not implemented, and prices not established as of autumn 2018 (lags in implementation)
Non-discriminatory, open access	Transmission access via universal, non-discriminatory platform. ISO responsible for oversight and operation of platform	Included under market bases	Implementation and participation both by participants in the supply and load-final demand sides only marginal and incipient by the end of 2018 Projects take time, but some have been stalled in 2019

(continued)

Table 3 (continued)

Minimum FERC function	Minimum function definition	CENACE strengths	CENACE weaknesses
Market monitoring	ISO monitors geographic sub-markets formed by local congestion. ISO seeks to minimise cost of market abuse to system	In CENACE's endowments, with tariffs totally socialised (postage stamp), expansion planning, and signing of contracts	Oversight of incipient market participants' operations, with no market standard yet implemented to check for market abuse Market monitor with little power
Grid expansion	ISO coordinates and evaluates future investment in transmission network	Coverage of OPEX/CAPEX to TO/DO; rules for private subcontracting in place	Expansion and access to distant sources of energy (renewable) not in place
Interregional coordination of control areas and nodes (nodal management)	ISO manages flows of electricity across multiple control areas and internationally, with other ISOs	Operational	Integration to national grid, from Baja California (BC) and Baja California Sur (BCS) pending. Large DC projects originally planned were suspended in early 2019
Dynamics and speed	N/A (Not defined by FERC), important to include in a transition market to check for speed of entry and market display	Market for day-ahead (DAM), real market working, and medium-term contracts	Only a small fraction of total permit holders is participating in market at the end of 2018

Sources Adjusted from Pollitt (2012); SENER (2017); CENACE (2015 and 2017), and CRE (2018)

needed, which can be used additional with the minimum functions presented above. From the established minimum market functions, market operators can go into further detail to create measurable indicators of success, or performance metrics. However, the path is additionally complicated by technology changes in the sector.

4 Technology Drivers of Renewable Transitions

The present section provides a literature review to help assess technological developments and advances in renewable energy technologies for electricity markets. Technological developments are traditionally classified with respect to; generation, transmission, and final consumption. This section assesses aspects, such as installed capacity, and the costs of key technologies in each of the subsections (generation, transmission, and final consumption) that enable a more reliable and secure grid. Highlighted U.S. trends and policy drivers for each technology are also summarised.

In 2016, the contribution of US renewable energy sources to the energy mix experienced its largest growth, ever, especially in the global electricity sector, according to IRENA (2017a), when generation from renewables increased by 6% (IEA 2017). Generation capacity increased from 1,845 to 2,006 GW between 2015 and 2016, an addition of 161 GW (IRENA 2017c). Wind and solar photovoltaics (PV) have been the technologies making the greatest contribution, and accounting for 51 GW and 71 GW, respectively, again, according to IRENA (2017b).

Growth in the United States markets apparently has grown more than has the total worldwide. Thus the 6% yearly US growth in the past decade, compares to an average worldwide growth of 3.6% (IEA 2017). For renewable power capacity, growth rates were around 4% in the early 2000's. By 2015, however, growth rates had increased, almost to 10% (IRENA 2017d).

Now, regarding installed capacity for generation, per technology, hydropower is still the main technology (International Energy Agency 2016a). However, it does not compare to what are now the dominant "modern renewables", since, in addition, hydropower generating capacity has been decreasing (International Energy Agency 2016b). Modern renewables, such as solar PV (photovoltaic) and wind-generated energy have experienced relevant growth in 2016. Solar PV capacity increased to around 70–75 GW. Onshore wind capacity's growth was 15% less compared to 2015, with 50 GW of new installed capacity compared to 70 GW installed in 2015. As for offshore wind, new installed capacity accounted for 2 GW, compared to 3 GW of additional capacity installed in 2015 (IEA 2017; International Energy Agency 2016b; Ibarra-Yunez et al. 2017).

The renewable agenda in the United States arises from incentives at federal level, but mostly at state and local levels. They could be described in terms of the following levels: de-regulation and re-regulation incentives; fiscal incentives; and, financial incentives. DSIREusa.org, presents the three levels of incentives at the zip code level, for; individual projects at residential generation, self-supply, distributed generation, projects for self-sufficiency, including, among others, construction standards. Additionally, information and incentives are readily available for non-residential efficiency, renewable energy uptake, and dissemination of new technologies. Such as the Renewable Portfolio Standards in many states (RPS), and at regional transmission organisation levels, arising mostly from the state's Public Utility Commissions (PUCs), as well as by regional market agencies, such as CAISO in California, the Southwestern Power Pool (SPP), ERCOT in the majority of Texas, the Midwestern interconnection regional market (MISO), the PJM regional market, NYISO, New England interconnection (NE ISO), and others.

For Mexico, renewable energy uptake has been motivated by two main drivers: on the one hand, the Energy Reform, its legal compact, and its institutions both emanated from the reform itself; but also from the Law of Energy Transition (meaning the green agenda and the agenda for the setting of standards and norms, similar to the quest of the Renewable Portfolio Standards mentioned above). These have been the key boost for renewable energy projects, along with a commitment to Mexico's objectives of 35% renewable generation, and load, by 2024. Agencies in charge of incentivising these are the Commission for the Efficient Use of Energy (CONUEE), the ASEA with special overseeing competences on hydrocarbons, together with some residual competences by the national energy regulator CRE, similar to the US FERC, and the North American Electricity Reliability Corporation (NERC), dedicated to overseeing reliability standards, and interconnections (NERC.com).

Secondly, and in a different but related issue for renewables, the drive also comes from technological developments, to which we can now turn. One can visualise the different technological changes, both from pure innovation, but mainly from intent applied to the different parts of the electricity markets, as is shown in the next sections.

4.1 Solar-Photovoltaic Generation Technology

Solar-Photovoltaic power capacity grew from 39 GW in 2010 to 295 GW in 2016, a dramatic change in the United States. Between 2015 and 2016 solar power capacity reached a new record with the addition of approximately 70 GW. It is the first time that solar-photovoltaic additions surpass wind additions (IEA, 2017). This represents an approximate growth rate of 40% (IRENA 2016b, d). Also in 2016, solar-photovoltaic represented about 15% of total renewable generating capacity.

Now, the averaged capacity weighted cost of solar generation (LCOE, meaning the net present value of the unit-cost of an installation over its lifetime), fell around 60%, between 2015 and 2017, according to IRENA (IRENA 2017e). This means that costs have become rather competitive in relation to fossil fuel, even gas combined cycle. Part of the explanation for such an expansion of solar-photovoltaic generation investment, has been tax credits of 30%, along with the so-called state Renewable Portfolio Standards RPS (IRENA 2017b, Delmans and Montes-Sancho 2011).

For a solar-photovoltaic installation to succeed as a renewable alternative, two elements should be present in the market: (a) smart net metering; and (b) third party resale of electricity at retail prices back to the utility, taking care to keep the latter economically viable. In many markets, the solar-photovoltaic uptake has been less than surprising, since badly designed mechanisms have been ousted in favour of "prosumers". Rate design is critical. In the case of Mexico, some of the above critical aspects are yet to be settled. Moreover, a slight but critical issue is that of designing individual project net metering/net billing, and that at community net metering for cases of distributed energy, and even urban "smart" developments, these aspects extend well beyond energy prosumer capacities (Durkay 2016).

4.2 Wind Generation

By the end of 2016, power generating capacity derived from renewables amounted to over 2,000 GW. Of this, 23% was attributable to wind technologies (IRENA 2017c). Global installed wind-generating capacity increased from 7.5 GW in 1997 to more than 465 GW in 2016, for both onshore and offshore wind (IRENA 2017c; IRENA and IEA-ETSAP 2016). One of the most promising technologies is offshore wind production, and by the end of 2014 installed capacity worldwide was 8.8 GW (Global Wind Energy Council 2015). Most wind offshore farms in developed economies, could learn from experiences in the UK (Scotland, England, and Wales), The Netherlands, Germany, China, and Denmark (farms with around 400–600 MW capacity, according to the Siemens and Siemens Gamesa company webpages, the largest project developers in 2015–2018).

The average cost of energy, for both onshore and offshore wind has experienced a large decline. In 2010, the average LCOE for onshore wind was 0.071 USD/kWh, while in 2016 it decreased to 0.056 USD/kWh. As for offshore wind, LCOE in 2010 corresponded to 0.133 USD/kWh but has decreased to 0.123 USD/kWh in 2016. Between these technologies, onshore wind is still the most competitive against fossil fuels, which costs approximately 0.045 USD/kWh (IRENA 2017b).

On a US federal level, wind development has been stimulated by the $0.024/kwh subsidy known as the Production Tax Credit. Accelerated depreciation, which allows owners to write off capital costs, is another federal policy that has contributed to the growth of the industry (DOE 2015). In the US case, Texas leads wind generation across the country, with 18 GW capacity and growing steadily. One critical aspect for the success of this technology, is the siting facilitation and fast community consultation for rights of way. The other critical aspect is to coordinate wind projects and uptake in zones far away from load and consumer nodes and zones, with transmission expansion to evacuate energy towards consumption centres. One notable success story is the Texas-ERCOT programme for establishing "Competitive Renewable Energy Zones" (CREZ). (see https://www.oncor.com/en/Pages/CREZ.aspx).

4.3 Distributed Generation

On the side of generation developments, distributed energy has been recently present as an innovating way of solving generation in rural and distant areas, but increasingly so in urban developments, with a recent emphasis on how spaces can be opened for isolated supply projects, or in Spanish, projects in "Abasto Aislado". The Mexican regulator has produced documents to incentivise distributed generation along with planning of a back-up basic electricity supply by the utility CFE. However, projects are moving slowly.

Currently, over 1 billion people in the world lack electricity access, and another billion have an unreliable supply (IRENA 2017d). Distributed generation, or off-grid systems, allow access to electricity for distant communities. Despite the population still lacking electricity access, off-grid systems have grown significantly in recent years. Off-grid systems can be classified into two types, depending on how they produce electricity: conventional systems; and, renewable off-grid systems.

Renewable off-grid systems are the most economical option for off-grid electrification (IRENA 2017d). Conventional systems use fuel and gas generators to produce electricity. Currently, installed capacity of diesel generators is 400 GW. However, from 50 to 250 GW of the total installed diesel capacity could be hybridised, according to Kempener et al. (2015). Renewable off-grid systems use small renewable sources to produce electricity. Almost 26 million households benefit from off-grid renewable systems worldwide. Approximately 20 million households have solar home systems, and another 5 million households use renewable-based micro-grids. Even more, 0.8 (% of) worldwide households use small wind turbines (Kempener et al. 2015).

Distributed generation also includes technologies such as fuel cells, and energy storage systems. Small-scale solar-photovoltaic is the most common distributed technology in the U.S., while the net capacity from the residential, industrial, and commercial photo-voltaic sector was over 13 GW as of February 2017 (EIA 2020) 0.102 Property Assessed Clean Energy (PACE), which finances residential and commercial energy efficiency and renewable installations through a property lien or retention right, has financed $1.37 billion in residential renewable energy installations from 2010 to 2016. In addition to access to end-user financing, distributed generation requirements, streamlined permitting processes, and clearly defined interconnection procedures are all policies needed for the growth of distributed energy technologies. They are still a lesson for Mexico to put in place. Let us now turn to the area of transmission innovation, and technological developments.

4.4 Transmission Areas of Opportunity for Development

A pressing challenge is how to move from evaluating demand, balancing, and congestion in a grid with high demand growth and integrating renewables in a neutral way, meaning a system that does not affect decisions for generating locations, or consumption centres, or what is called solving the problem of ‘generation drives, transmission’, as opposed to ‘transmission drives generation’. The above implies that planning and incentive investments must be aligned for transmission with new sources of generation and large consumption nodes.

Moreover, one needs to separate transmission maintenance needs, from transmission expansion, with the existence of new technologies. Moreover, in mature markets, there is a way of looking at energy, not only as a public service in many cases, but also as a tradeable good that incentivises interconnection by regions, but also connects across borders. Mexico’s CFE Transmisión is a subsidiary of the CFE headquarters, but where financing of maintenance, last-mile expansion projects with private investment participants are allowed by regulations, but where little or no thought has been developed for long transmission (even the High Voltage DC Transmission), or for transmission across the US and Mexico borders (such as with California. See Rosellón et al. 2017, 2018).

Another source of innovation in transmission is the area of smart grids. Smart grid technology—or digital technology that enables two-way communication between a utility, it is the transmission and distribution system, and the end-user—includes technologies such as advanced metering infrastructure, voltage regulation equipment, power flow controllers, and equipment health sensors to balance the demand and supply of markets. IT technology is a critical component of smart grid deployment.

While early smart grid solutions were targeted toward distribution, given that they were applied close to consumers at low voltages, there has been an increasing incorporation of smart technologies in switches, substations and transformers, allowing for two-way flow and increased transmission flexibility. The increase in electricity generation from variable renewable energies (VRE) poses several challenges for the grid, including the need to rapidly synchronise supply and demand. This has become more of an issue in grid management, since the peaks of VRE are more pronounced. Therefore, grids need to become smarter and more flexible (IRENA 2016c).

Moreover, demand response, consumer efficiency, and energy management have become areas of high expectations for energy intensive industries, but also for small and medium enterprises that, given that they cannot reach the minimal required load of, say 1 MW of capacity demand, have begun to promote the role of aggregators, which become another vertical link in the energy market (at wholesale levels). Such have been studied recently for Mexico (Ibarra-Yunez et al. 2019).

Advanced metering infrastructure (AMI) developments intend to capitalise on "big data" (International Energy Agency 2016b). This has increased the relevance of joint information technology and operation technology (IT/OT) solutions. The IT/OT solutions market grew approximately 65% per year and is expected to grow by 600% by 2023 (Navigant 2014). IT/OT solutions will allow utilities to have control over all connected devices, and therefore have a "real time" management of supply and demand (IRENA 2016c). Investment in smart grid technology, which incorporates IT/OT systems, increased by 12% in 2015. Moreover, new business models, such as virtual power plants (VPPs) are also expanding (International Energy Agency 2016b). Over the next twenty years, experts predict that \$17 to \$24 billion, on average, will be invested yearly in smart grid upgrades.

One last point about IT/OY solutions is their application in urban areas, mainly in the case of public transportation and traffic congestion management, but with clear expansions aimed at reducing pollution in metropolitan areas, such as London, Paris, Valencia, Curitiba-Brazil, or Los Angeles. Innovation can be integrated into new business models.

4.5 Storage

Electricity storage plays a critical role in the integration of VRE to the grid. The extent to which the power generated during the peak production hours can be stored is crucial for full exploitation of renewable energies. Storage is also crucial for increasing operating system flexibility (IRENA 2017d).

The most developed storage technology is pumped hydropower. This technology currently has over 145 GW in operation, accounting for the majority of energy storage worldwide. In the case of Mexico, the new vision is for traditional hydropower to gain importance over the next 5–10 years, although little is known of new business models that integrate storage with balancing markets at intraday, seasonal, or emergency management in respect of virtual versus physical capacity.

According to IRENA, pumped storage hydropower will increase from 150 to 352 GW by 2030. On its part, battery storage is the subsector with the most important recent growth. In 2014, 400 additional MW were added, thereby doubling 2013 installations (International Energy Agency 2016b). Battery storage is expected to increase from 0.8 to 250 GW by 2030 (IRENA 2015). Currently, lithium-ion batteries dominate the electricity storage market, which is a significant shift from prior decades when sodium sulphur batteries were the dominant technology (IRENA 2017d). The market for this type of battery grew by 50% per year, helped by the commercialization of the Tesla Powerwall, a 10 kWh lithium-ion battery. (International Energy Agency 2016b).

Energy storage technologies are becoming increasingly cost-efficient. In 2005, costs for lithium-ion batteries were around US$1,500/kWh. In 2016 costs were around US$350/kWh (New York Battery and Energy Storage Technology Consortium, 2016). Moreover, between 2015 and 2016, the cost of batteries at grid scale, fell 12% for Peaker plant replacement, and by 24% in the case of transmission (Lazard 2016). Finally, it is expected that battery prices will continue to fall; forecasts suggest a 50% decline by 2019 (Wilkinson 2015).

4.6 Electric Vehicles and Smart Buildings

Let us finish this section with a note on electric vehicles and smart building technology developments. Electric vehicles today can be classified into two main technologies, battery electric vehicles (BEV), and plug-in hybrid electric vehicles (PHEV). BEVs only use batteries to store energy, and therefore, they must be plugged-in in order to recharge (IRENA 2017a). New discussions at the utility level, have tried to calculate the stress on the electricity distribution grid of these new developments. Moreover, a related issue concerns consumer habits in charging BEVs during the day in commercial or office outlets during semi-base or peak tariffs, or at home, at night, at basic electrical tariff, with full recognition of electricity consumption in electricity bills; a case of free riding, or not free riding.

For their part, PHVEs use batteries as well as liquid-fuel storage. Moreover, liquid fuel can be replenished, allowing for greater ranges of travel (IRENA 2017a). A new discussion has arisen about public transport vehicles, whether they should be BEV or PHEV. Worldwide, the number of electric vehicles reached one million in 2015, and surpassed 2 million by 2016 (ibid. IRENA, 2017a). In 2015, 477,000 electric passenger cars were sold worldwide, according to the International Energy Agency(2016b). Typically, BEVs have dominated sales. However, PHEVs have been gaining strength, mainly as a more levelled option, mainly for buses, but also for electric tramways and more massive transportation.

Beyond light electric vehicles, a market exists for the two-wheeled variety. These types of vehicles are sold mainly in Asia, but one can see electric mopeds (and the Segway, now banned in many cities) in many US and European cities, or even some highly congested traffic cities in Mexico. Over the last ten years or so, over 200 million units have been sold (Cherry 2016). Only in 2015, almost 40 million vehicles were sold mainly in China and Japan (IRENA 2017a).

Now, regarding smart buildings and smart building materials, in order to reduce energy consumption in installations where demand for heating and cooling forms almost one third of energy demand, several countries have developed building energy codes and energy efficiency policies. As a result, global building energy performance has improved 1.5% (International Energy Agency 2016b).

Global markets for smart buildings in urban areas are growing. The estimated value of the market was USD 4.8 billion in 2012, however; value is expected to rise to more than USD 35 billion by 2020. Moreover, sales for smart appliances are also rising. Sales in 2015 accounted for USD 5 billion, and they are expected to reach the USD 34 billion by 2020. According to energy efficiency codes, such as Mexico's CONUEE's norms, government buildings are first to adopt energy efficient materials for construction, but many government facilities use old buildings, which sets a big challenge for enacting the CONUEE's building materials codes. In any case, the process of using technologies to integrate smart buildings in all their electricity, gas, and water use is ongoing. In the United States, per FERC Order 745, energy efficiency and demand response are marketable, and must be compensated at the same locational marginal price as an energy generator. However, it is state level policy that drives energy efficiency, and therefore smart building technology.

5 Conclusions and Recommendations for the Future of Energy Markets, Regulations, and Best Practice

The present analysis of the status of both the energy and climate change agendas, first, has shown that both are fundamental ingredients towards reaching an increasingly needed energy sector in its overall economic importance, at the same time that countries adhere and commit to their environmental concerns and include them in all government and private sector planning.

However, as the chapter emphasises, the institutional and regulatory agendas for the case of Mexico, have departed from different bases, for which the links between the two objectives seem weak at the least. One example is the link between the legal promotion of renewable and clean (including hydrogeneration) sources of energy via the clean energy certificates (credits), or CELs as they are called in Mexico, their assignment through long term auctions between 2016 when they started, and 2018, after which they have been put on hold by the new presidential administration.

Moreover, market regulatory change during 2013 and 2018 was rather profound and included 21 changes in laws and regulations, additional to more than one hundred administrative orders that opened the electricity sector to private participants in all but natural monopoly parts of the sector, and a wholesale market was launched in 2014: the National Center for Energy Control as the Independent System Operator ISO, or *Centro Nacional de Control de Energia, CENACE*. As it is argued in this chapter, the role of ISO's in most mature markets in the world, is central to promote wholesale trade of energy, capacity, clean energy certificates, ancillary services, financial transmission rights in short, medium term, and long-term trades.

For a new restructured energy sector such as Mexico's, some parts of these markets are still in the planning process, and not all sub-markets are operating at present. Moreover, the new administration has found itself undefined if a more profound market-driven electricity sector, including renewable energy and a quantitative-measurable target of lowering the carbon footprint for this economy, or more centralised, top-down government intervention is a preferred model (going back to the old model). In such a decision-making uncertainty, the key CENACE locus of wholesale market clearing, planning, and leadership, has seen its role somewhat diminished, at the same time that lack of performance measures has characterized this independent system operator. Moreover, the chapter presents the reader with the methodology of "minimum functions," that are derived from FERC Order 2000 of 1999, and other market experiences. Indeed, the minimum required functions are spelled out in their critical parts towards a mature, well-behaved wholesale market, with many participants (except electricity basic services, subject to asymmetric regulation).

Then the chapter compared the experiences from international institutions, such as the United Nations and its evolution of the climate change objectives and institutions and agencies. Also, in the analysis, other institutions are reviewed in their aims and representativeness, such as the Paris COP Agreement and its targets, and the International Energy Agency, from which Mexico has been welcomed as a new member. All of the clean energy objectives and commitments by governments, and their agencies pertain to all signatories, including Mexico, additional to the country's Secretariats and agencies in charge of overseeing norms and standards towards reaching the clean energy and climate change targets: Secretary of the Environment SEMARNAT, and agencies such as CONUEE for norms and standards of clean energy, and ASEA for hydrocarbons.

Finally, one has to bear in mind, that public policy, sectoral regulation, ex post competition policy regulation all come later than technology advances. The final part of the present analysis summarises main technology concerns and advances in the energy sector, as we divide it for technological analysis into generation: solar-photovoltaic, wind, and distributed generation; then transmission: AC, DC-HDC, last mile private complementarities, interconnections; then storage and batteries; and finally electric and hybrid vehicles and smart buildings. With the above, the reader is able to clearly locate areas of opportunity for the electricity and renewable energy industry in Mexico, in comparison with other experiences in the world.

- As a series of policy and industry recommendations for the future, first, Mexico is member and has committed to international obligations related with the multilateral climate change agenda that sets the clear path to deepen this country's international commitments. Moreover, even the recent launch of the USMCA (United States- Mexico-Canada trade agreement) contains in its articles, jointly agreed upon, trilateral and regional binding obligations related to energy, energy markets, energy regulations, and energy security that complement the multilateral obligations. Those set the international framework of maintained obligations and commitments.
- At the national level, the 21 secondary laws set the market commitments at various levels and sub-markets that need to be maintained. Recent decisions at the Secretary of Energy, CENACE, the Energy Regulatory Commission (CRE), regarding stability of the grid, prefer the incumbent utility CFE to increase its monopoly powers against other market participants from the generation, supply, intermediation, trading, load centers, and innovative prosumers, has set a bad precedent to attract investment efforts in an energy market and the environment agenda, and needs to be recaptured.
- In case efforts are continued by the present administration, to dismantle the present operative energy reforms, it will create costly litigious environment and could move Mexico to a welfare reducing position. The recommendation here is that being the social and economic cost much larger than the social and economic benefits of true sub-markets, all stakeholders in the short term and large term sub-markets (energy, capacity, renewable energy certificates (CELs), ancillary services, and qualified users of energy, load centers, and even prosumers) should push for deepening commitments, one way or another.
- On the regulatory front, the main recommendation is that CRE, as an independent and autonomous entity, clearly and forcefully separate regulatory quality with asymmetric regulations between the monopoly parts and the competitive parts of the market, observe best practice elsewhere in the world, and promote parts of the market that so far have not been implemented as shown throughout this chapter.

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Chapter 6
Energy Efficiency for the Current Use of Fossil Fuels

Carlos I. Rivera-Solorio, Alejandro J. García-Cuéllar, José L. López-Salinas, and José I. Huertas

Abstract Higher energy demand is related to the increased economic activity in all countries of the world. However, the current dependence on fossil fuels causes great pressure from the sustainability standpoint, particularly when considering the associated carbon emissions that cause climate change. Hence, increased process efficiency is essential in the abatement of these harmful emissions. In this chapter, a general outlook is presented regarding the current situation of energy demand in North America. Thermodynamics is then called upon to give an engineering answer to the question of quantifying, comparing, and optimising the energy performance of processes. Next, energy generation and transportation are studied in more detail since these two sectors are among the main energy consumers. Then, renewable energies are also considered, given their potential to produce a substantial reduction in carbon emissions. Solar thermal energy is presented as a solution to provide process heat. Moreover, waste heat reduction and reutilisation are identified as pivotal in increasing efficiency and sustainability indicators. In closing, general recommendations are presented for better decision making in the public and private sectors when considering the goal of achieving more sustainable processes.

C. I. Rivera-Solorio · A. J. García-Cuéllar · J. L. López-Salinas · J. I. Huertas (✉)
Tecnologico de Monterrey, Escuela de Ingeniería y Ciencias, Ave. Eugenio Garza Sada 2501, 64849 Monterrey, Nuevo Leon, Mexico
e-mail: jhuertas@tec.mx

C. I. Rivera-Solorio
e-mail: rivera.carlos@tec.mx

A. J. García-Cuéllar
e-mail: ajgarcia@tec.mx

J. L. López-Salinas
e-mail: jllopezs@tec.mx

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Abbreviations

CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
CONUEE	National Commission for the Efficient Use of Energy (Mexico)
FE	Fuel consumption expressed in km/L
GDP	Gross Domestic Product
HD	Heavy Duty vehicles
IEA	International Energy Agency
LD	Light Duty vehicles
LGE	Energy consumption as litres of gasoline or petrol equivalent
LPG	Liquefied Petroleum Gas
LPV/T	Low concentrating Photovoltaic Thermal
masl	Metres above sea level
NOx	Nitrogen oxides
OBD	On-Board diagnosis systems
PTC	Parabolic through collectors
PV	Photovoltaic
SEMARNAT	Secretaría de Medio Ambiente y Recursos Naturales (Mexican national environmental ministry)
SFC	Specific Fuel consumption expressed in L/100 km
TPS	Ratio of total primary energy supply

1 Introduction

Whilst the world trend and climate reality call for strong sustainable policies, mainly related to energy transition and energy efficiency, fossil fuels will remain the dominant energy sources in this century. This chapter will provide a discussion of efficiency in the use of available fossil fuels in Mexico and the USA, by economic sector.

The World economy is based on energy use, specifically from fossil fuels. Developed countries are consumers of a large amount of energy. In each good produced or service rendered, there is embedded a certain amount of energy. As presented in Chap. 1, Table 1, material flows of fossil fuels have the same order of magnitude as iron ore but are between 1 and 2 orders of magnitude higher compared to fertilisers.

As discussed by Holliday (2014) on providing sustainable energy for human life there is a need to improve present energy efficiency, as well as access to energy services for all, and increasing the use of renewable energy.

For a transition towards a future with sustainable energy, where renewable sources prevail, there is a period to reach that goal. For 2017, fossil fuels represented 85% of World consumption (BP 2018), while hydroelectricity, solar and wind sources

Table 1 Energy consumption in Mexico and the US for global sectors in 2016

Consumption (% total)		
For 2016	Mexico (%)	USA (%)
Industry	28.8	17.6
Transport	43.5	40.3
Other	23.3	15.7
Non-energy use	4.4	26.4

reached 9.4%. Hence the gap is wide, but there is a responsibility toward future generations to start the transition. World energy consumption trends have been presented in Chap. 1.

From the perspective of Eco-efficiency (Stigson 1999; Lehni 2000; Verfaillie and Bidwell 2000) one action to improve a company's eco-efficiency is "to reduce the energy intensity of goods and services". The latter implies that for a certain amount of sales, upon reducing energy consumption the energy metric will improve (Keffer et al. 1999).

The International Energy Agency (IEA 2019c) comments that "*For instance, something is more energy efficient if it delivers more services for the same energy input, or the same services for less energy input*". From the eco-efficiency perspective, as stated in Chap. 3, as well as the preceding paragraph, "*minimising the intensity of energy in goods and services*" is similar to the IEA efficiency concept.

IEA presents data at country level, as well as for specific sectors of the economy, using the energy intensity concept: "the ratio of the total primary energy supply (TPES) divided by the gross domestic product (GDP) of the country" (IEA 2014). But at sector level, the economic concept used is the energy intensity per value added[1] to the goods and services.

Energy consumption per sector was discussed in Chap. 1; for Mexico and the US, Table 1 shows their percentage contribution to the whole. For both countries transport represents the largest contribution, followed by industry, and then other types.

Assessing energy efficiency through time allows focusing in sectors where special attention has to be applied in order to improve them. Figure 1 shows manufacturing energy intensity in Mexico, across the sectors. Producing coke and refined petroleum goods has the largest energy intensity, which has increased between 2000 and 2017, compared to non-metallic materials and chemicals, the latter having a decreased energy intensity from 2000 to 2017. Figure 2 shows a slightly different behaviour for the US; the energy intensity for chemicals has decreased between 2000 and 2009 but has risen again from 2009 to 2017. Meanwhile, the energy intensity for coke and refined petroleum products has decreased until 2005, only to oscillate around increase/decrease from then onwards. The only sector, as presented in Fig. 2, to show a decrease since 2000 was non-metallic minerals. Presenting energy intensity, as in

[1] Value added is the difference between the price of product or service and the cost of producing it. (Investopedia, no date).

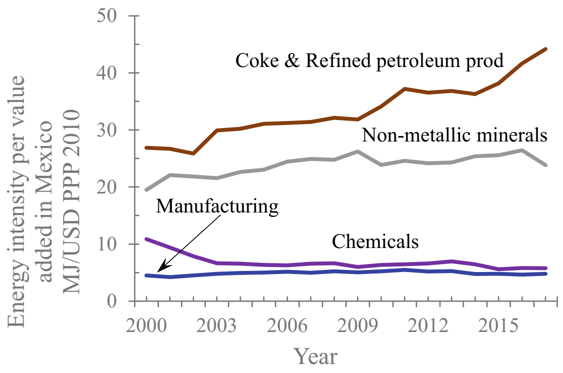


Fig. 1 Energy intensity in Mexico for total manufacturing and some sectors

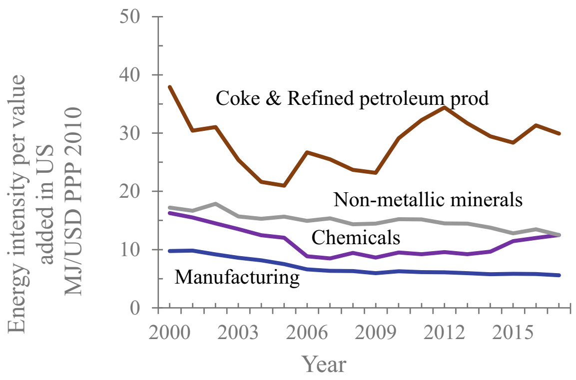


Fig. 2 Energy intensity in the US for total manufacturing and some other sectors

Figs. 1 and 2, has the effect of lumping together the sectors with lower values at the bottom of the graph.

Using 'instead' indexes (IEA 2018b, 2019c) and taking as a base the year 2000, disaggregates data visually. In Fig. 3, data for Mexico shows that the chemical, and the paper and pulp, sectors decreased their energy intensity, while basic metals and agriculture, forestry and fishing increased slightly, as did mining and non-metallic minerals. However, overall manufacturing energy intensity in Mexico remained constant for the period 2000–2017. Hence, improvements in energy efficiency for Mexico's manufacturing are needed, coupled with specific sector programmes and public policy support. For the latter, CONUEE (National Commission for the Efficient Use of Energy) (CONUEE 2017; CEPAL 2018), a governmental body dedicated to energy efficiency, has been addressing these issues and themes.

The US indexes are presented in Fig. 4, showing that paper and pulp, non-metallic minerals, basic metals, and the mining sectors show a marked decrease in their energy intensity. But agriculture, forestry, and fishing show an increase, and then a slight decrease in the index. Finally, chemicals show a marked decrease just below 60 until 2014, then an increase close to 80 in 2017.

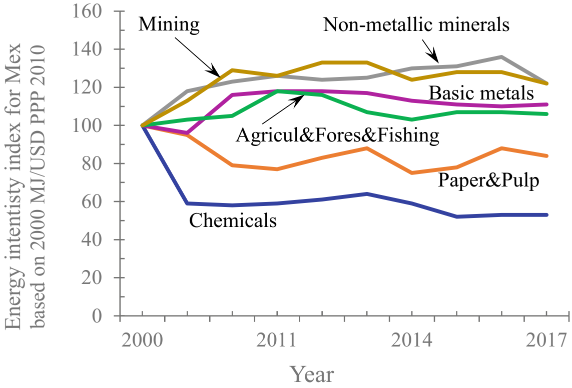


Fig. 3 Energy Intensity Index for several manufacturing sectors in Mexico [*Source* (IEA 2019b)]

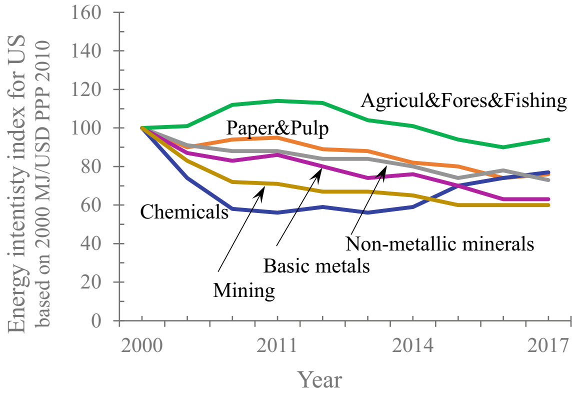


Fig. 4 Energy Intensity Index for several manufacturing sectors in the US [*Source* (IEA 2019b)]

The transport energy efficiency indicators for Mexico and the US, presented in Fig. 5, are in tonnes-km per capita (Mg-km/capita), and show a slight increase for Mexico, while for the US, from 2000 to 2007, there is no change, but from there onwards the indicator shows a decrease.

In the residential sector, the energy efficiency indicator selected (for Mexico and the US) is energy per floor area, as presented in Fig. 6. Mexico's behaviour shows a marked improvement; decreasing all along, while the US indicator decreased from 2000 to 2006, but increased from then onwards, taking year 2000 as a reference.

But nature has set certain limits to efficiency, the laws thermodynamics can be used to understand and calculate the theoretical maximum efficiency that can be achieved. Upon transforming energy sources, either fossil fuels or renewables, through various technologies there is a need to calculate those limits.

Fig. 5 Total freight transport energy efficiency indicators for Mexico and the US in Tonnes-km/capita

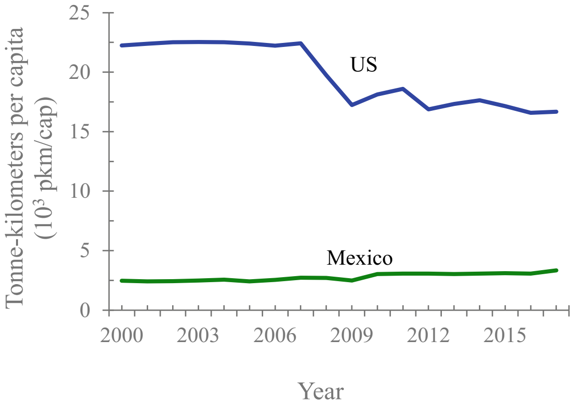
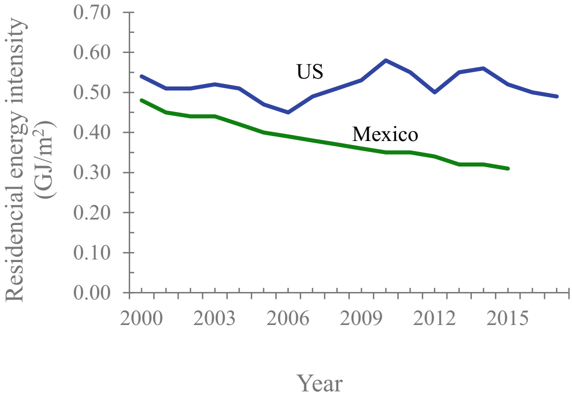


Fig. 6 Total residential energy intensity per floor area for Mexico and the US



2 Thermodynamics Fundamentals Associated to Energy Conversion Efficiency

2.1 The Carnot Efficiency Limit, and Efficiency Limits of Other Technologies

The efficiency limit of a thermal engine or device/technology to produce power from heat source or thermal energy reservoir is called Carnot efficiency, and was coined by Nicolas Léonard Sadi Carnot at the beginning of the XIX century. Carnot was one of the first scientists in giving an expression to predict the limits of transformation of heat into work. Scientists and engineers had worked out creative practical and theoretical devices that may reach the limit of Carnot's findings, and in some other scenarios they have found simplified mathematical formulas to predict the limits of energy transformation. Some of these expressions are in Table 1 where you can

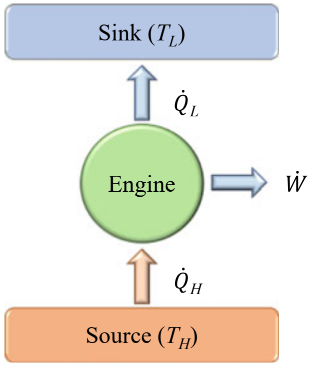


Fig. 7 Conceptualisation of a heat thermal engine

review the thermodynamic limit of different technologies that allow us to predict the performance of these devices under ideal operating conditions. The Carnot engine can be conceptualised as a device depicted in Fig. 7.

Carnot defined a heat engine as a closed device that operates under steady state, taking heat rate from a source at high temperature T_H and producing power across a boundary, either by moving elements, or rotating shaft, and releasing waste heat rate into a sink at temperature T_L. Application of the first and second law of thermodynamics on such devices give you Eq. 1, of the form (Demirel 2016):

$$\eta = \frac{\dot{W}}{\dot{Q}_H} = 1 - \frac{T_L}{T_H} \tag{1}$$

In order to quantify the performance of any transformation, the efficiency or process yield represents the ratio of output to input. Efficiency is the useful power output, divided by the heat rate input that implies a cost. For this conceptual heat engine, the ratio of power and supplied heat rate from the high temperature zone.

There are practical engines that their ideal limit approaches this Carnot efficiency, these engines or cycles are the Ericsson and the Stirling. The first one is a Brayton or gas turbine type cycle with multistage intercooled compressor and a multistage turbine expansion with reheat and regeneration, and being an internal combustion engine. The Stirling cycle in contrast to the Ericsson cycle is an external combustion engine, but they both share the same efficiency limit (Wood 1991).

In this chapter we discuss briefly how to measure the efficiencies of energy transformation, of some practical devices used to produce energy, and will elaborate in the methodology of a steam engine type process.

Most of the actual energy transformation technologies were designed in order to be close to some of the theoretical thermodynamics' cycles or processes, in the following table we list some of the most common ones, and how to estimate the thermodynamic limit of these transformations (Table 2).

Most of the efficiency equations listed in this table were obtained applying systematically first and second law of thermodynamics, and the working fluid was treated

Table 2 Maximum (ideal) efficiencies that could be obtained converting heat energy into work by means of diffferent thermal engines

Cycle type	Cycle efficiency	Nomenclature
Carnot, Stirlling and Ericsson	$\eta = 1 - \frac{T_L}{T_H}$	$\boldsymbol{T_L}$= is the lowest temperature of the process, this is the temperature of the sink. $\boldsymbol{T_H}$= is the highest process temperature, or the temperature of heat source
Spark ignition Engine or Otto	$\eta = 1 - \frac{1}{r_v^{k-1}}$	$\boldsymbol{r_v}$ = Compression ratio, which is a design parameter of the engine, this is the relationship of the volume at the bottom dead center and the volume at the top dead center $\boldsymbol{k}$ = specific heat capacity ratio of the working gas, ***cp/cv***
Diesel	$\eta = 1 - \frac{1}{r_v^{k-1}}\left[\frac{\beta^k - 1}{k(\beta - 1)}\right]$	$\boldsymbol{r_c}$ = Compression ratio, β = cut-off ratio, this is the volume ratio of the volume when the diesel stops being injected and the volume at the top dead center
Brayton	$\eta = 1 - \frac{1}{r_p^{(k-1)/k}}$	$\boldsymbol{r_p}$ = compression ratio, pressure after the compression stage divided by the intake pressure
Atkinson	$\eta = 1 - \frac{k}{r_v^{k-1}}\left[\frac{r_d^{1/k} - 1}{r_d - 1}\right]$	$\boldsymbol{r_d}$ = constant volume pressure ratio, this is the pressure change after the combustion

as an ideal gas, assuming specific heat capacities being constant. As a device to produce energy the gas turbine using natural gas, may be treated to work close to a Brayton cycle. Gas turbines operate in a process similar to the process sketched in Fig. 8. Backup energy plants, usually use Diesel technology, but in some other

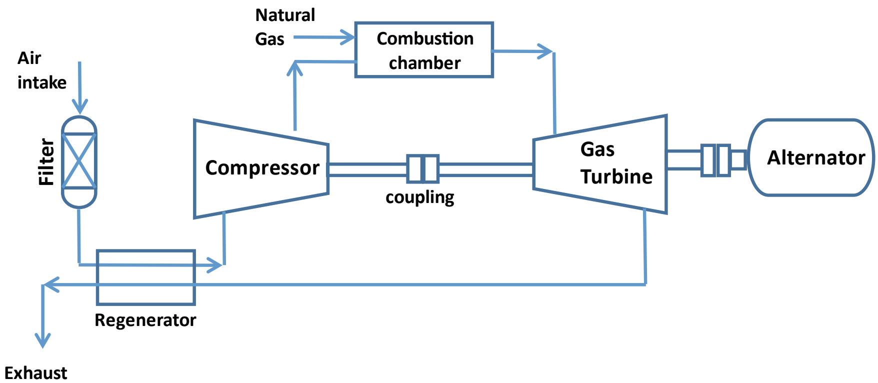


Fig. 8 Gas turbine with an arrangement that operates close to a Brayton cycle

technologies you may see engines trying to operate close to any of the listed cycles, so these efficiencies can be used as guide to compare different technologies, and to take decisions.

The main objective of listing the equations of efficiency is to realise that the performance of such technologies is related with operation conditions of such devices, like temperature differences, pressure ratio, volume ratio, and so on.

To know the actual process efficiencies, each technology has to be analysed using the conservation equations (Bird et al. 2002; Wood 1991), and incorporating the equation of state that best describes the working fluid. If during the energy transformation a phase change occurs, a more elaborated methodology is needed, and the thermodynamic properties of the working fluid play an important role.

The thermodynamic properties of the working fluids in energy technologies approximating the cycles described in Table 1 are not as important as in the technologies working with steam turbines, and the only important information regarding the fluid properties was that the working fluid was made-up of either monoatomic, diatomic, triatomic o polyatomic gas that determines the cp/cv ratio (Levenspiel 1996). In most of the actual technologies, working gases have high concentration of diatomic gases, setting the specific capacity ratio to a value of 7/5 ($k = 1.4$) (Levenspiel 1996).

2.2 *The Steam Power Plants*

To illustrate the importance of thermodynamic properties of fluid in steam power cycles, and to compare technologies that produce power using thermal energy resources, lets analyse a basic Rankine process. These systems may operate in different arrangements, in order to increase efficiency, but the simplest one consists of at least four components (Fig. 9).

The main boiler, which is a unit where heat is added, in this component a high pressure stream of liquid water (E) is converted into a steam (B), in a continuous manner at almost constant pressure, or at least pressure drop is negligible because these units typically consist of parallel tubes, in order to minimise pressure drop. These tubes are in a unit where combustion gases provide the energy by heat exchange. Then, the heat rate supplied to the boiler must equal the change in the flow of enthalpy within the boiler.

The working fluid leaving the boiler (B), is directed towards an adiabatic expansion turbine (i.e. a turbine with minimal or no heat exchange at all), That equipment, made of a series of streamlined blades allow the seam to be expanded (C), transforming part of the flow and internal energy (this is the enthalpy) into work. The expansion process is made in stages, in a gradual expansion process, under these conditions the process is close to be reversible, this is, minimal or no entropy generation. Then the change in flow of enthalpy is caused by the production of power by the turbine, and the entropy change is negligible or minimal.

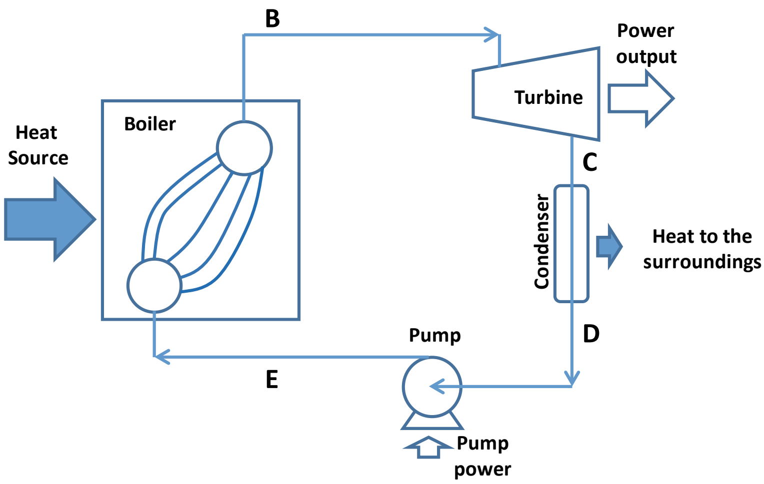


Fig. 9 Rankine cycle to produce work

Once the fluid is exhausted (C), losing most of the potential to drive a shaft for work, because of its lower pressure, the stream is condensed (D), using a heat exchanger. Typically removing the excess of energy that cannot be converted into work, in order to restore the conditions to send it back to the boiler, the fluid is condensed, and then sent to the pump in order to increase its pressure. The change in flow of enthalpy is compensated by the heat rate exchanged with the environment, directly (i.e. using atmospheric condensers) or indirectly (with a heat exchanger interconnected with a cooling tower) (Fig. 9).

The last element is a small pump, that has the task to take the liquid leaving the condenser (D) and increase its pressure, and send back the working fluid to the boiler (A). These devices work with a motor, that runs a shaft connected to an impeller, made of streamlined blades, to minimize entropy generation. Then the required powers equal the change of flowing enthalpy.

In conclusion, the thermodynamic limits of the transformation process, or the energy production process, will depend on the design, operating conditions of the technology, the technology per se, the constraints, and the properties of the working fluids.

2.3 Examples of Thermodynamic Limits, and Comparison Between Technologies

A typical power plant operating under ideal conditions will behave as an ideal Rankine cycle. Lets analyse a power plant that operates with water as a working fluid, under a temperature range between 138 and 550 °C. This temperature range will give us a Carnot efficiency of 50%, but using the basic elements of a power plant will result in less efficiency. Under the assumption that the maximum pressure of this technology is 1,380 kPa, the properties of the process are the ones shown in Table 3.

Calculating the efficiency for this cycle under ideal conditions result in: 15.02%, this is only the 30% of the maximum given by Carnot limit.

If the same, analysis is made over an organic Rankine cycle as illustrated in Fig. 10, with R245fa (1,1,1,3,3-Pentafluoropropane) as working fluid, the same upper pressure, but instead of extracting the energy from burning fossil fuels, the energy is collected from the sun, the temperature range will change, and the performance as well. In this case a temperature 10 °C higher than the ambient (temperature in a hot day of 40 °C) in the condenser, in order to condense the fluid in a compact heat exchanger using the atmospheric air (Table 4).

In this particular organic Rankine cycle, the temperature limits are lower, and the temperature difference as well, then the Carnot efficiency limit is 23.67%, and the

Table 3 Example of the thermodynamic properties of water at each state of a Rankine cycle

State	*T* (°C)	*P* (kPa)	*h* (kJ/kg)	*s* (kJ/kg-K)	*x*
B	550	1,380	3,585	7.749	SH
C	331.4	343.5	3,133	7.749	SH
D	138.2	343.5	581.4	1.721	0
A	138.3	1,380	582.6	1.721	CL

h = represents the enthalpy, i.e. the flowing energy of each stream, **x** = represents quality or fraction of vapor present in a fluid mixture (SH = superheated vapor, CL = subcooled liquid), ***s*** = represents entropy (Sandler 2006)

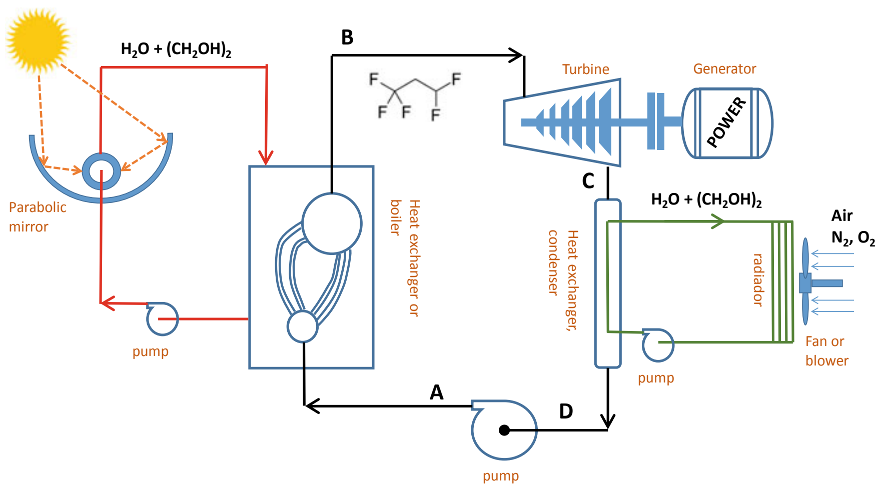


Fig. 10 Organic rankine cycle

Table 4 Example of the thermodynamic properties of the refrigerant at each state of the organic Rankine cycle

State	*T* (°C)	*P* (kPa)	*h* (kJ/kg)	*s* (kJ/kg-K)	*x*
B	150 °C	1,380	534.6	1.939	SH
C	104.8	343.2	503	1.939	SH
D	50	343.2	166.3	1.222	0
A	50.45	1,380	267.1	1.222	CL

ideal Organic Rankine efficiency of 11.51%. In a nutshell that technology is capable to obtain 49% of the Carnot limit.

Under the same pressure ratio, a gas turbine will have an efficiency 32.79% (Table 5).

With the three examples seen, we had verified that the performance of each technology depends on the configuration of the equipment, the working fluid, and of course of the working conditions of pressure and temperature.

With the previous analysis, we can see that the actual efficiency of a process, even working within the same pressure limits, strongly depends on the working fluid properties, also in the second process, the technology was relative closer to the thermodynamic limit of a Carnot engine, even working with lower temperatures. There are strategies to improve the performance of these processes by energy recovery techniques like regeneration and reheat, but that will imply more equipment and the cost of the apparatus will increase.

These three technologies have pros and cons. For instance, the steam power plant has the advantage of being versatile regarding the energy source. The fuel and burners can be replaced for different options, while the working fluid in this case water, remains the same, and most of the moving parts and seals need no replacement if changes of fuel is made.

The scenario of the gas turbine has more constraints regarding the fuel, because the moving parts are in contact with the fuel, and combustions gases. If the fuel is changed, some modifications are required on the materials, and design, and the performance is affected drastically.

The last scenario of the Organic Rankine cycle, uses the same concept as the steam power plant, but requires no fuel. This process works with the energy of the sun, and the working fluid is a hydrofluorocarbon, producing no CO_2 neither directly nor indirectly, being a process without carbon footprint.

Table 5 Comparisson of the thermodynamic efficiency of different cycles to produce work with the Carnot cycle efficiency

Technology	Efficiency (%) η_1	Carnot efficiency η_2	η_1/η_2
Steam power plant (Rankine cycle)	15.02	50.0	0.30
Organic Rankine cycle	11.51	23.6	0.49
Brayton cycle	32.79	70.0	0.47

In general, the message of this numerical exercise is to clarify that the comparison among processes requires knowing in detail, the technology of power production, the operating conditions, the values of the environmental conditions, and costs in order to decide which technology should be consider for a specific application.

3 Energy Efficiency in the Transport Sector

Land transportation is essential to the Mexican economy. However, it is also the largest energy consumer with ~46.5% of the country energy consumption, which has remained stable over the last years (SENER 2020). Figure 11a, b show that gasoline is the most used fuel for light-duty (LD) vehicles in Mexico with a share of 65.5%, followed by diesel for heavy-duty (HD) vehicles with 23.8% share. The use of natural gas or liquefied petroleum gas (LPG) for land transportation is negligible (Fig. 11b). Land transportation sector is also the largest emitter of air pollutants. It is accountable for approximately half of all energy-related nitrogen oxides (NOx) emissions, which was about 56 Mt (Million metric tons or Teragrams) in 2015, and it is an important source of primary particulate matter (85% of total PM emitted) (IEA 2016).

The measurement of the instant fuel consumption in vehicles used to be a challenging an expensive task due to the high fluctuations of the pressure fuel lines. Currently, the electronic fuel injection technology, and the on-board diagnosis systems (OBD) allows obtaining reliable data of instant fuel consumption in both gasoline and diesel vehicles. Nowadays, most vehicle models report in the dashboard an average value of their real fuel consumption expressed as SFC [L/100 km] or FE [km/L].

Traditionally, energy efficiency in the transport sector is measured in terms of those metrics:

- Specific fuel consumption (SFC) or volume of fuel consumed per traveled kilometre. This metric is appropriate for light vehicles, where weight variation due to passengers is insignificant compared to the total weight of the vehicle (weight variation greatly influences the fuel consumption). However, this metric does not allow the comparison between vehicles of different sizes. Instead, we recommend the use of SFC per passenger transported or per metric ton transported as a more suitable variable to measure energy efficiency in vehicles.
- Fuel economy (FE) or the inverse of SFC (kilometres travelled per volume of consumed fuel). It is also frequently used as a metric of energy efficiency in land transportation, especially for HD vehicles.

To compare the performance of vehicles powered by different fuels, it is customary to express fuel or energy consumption as litres of gasoline equivalent (LGE). This the volume of gasoline (V) with the same energy content as the actual fuel consumed (mf). In Eq. 2, LHV and LHV_f are the low heating value of the gasoline and the actual fuel, respectively, and ρ is the gasoline density.

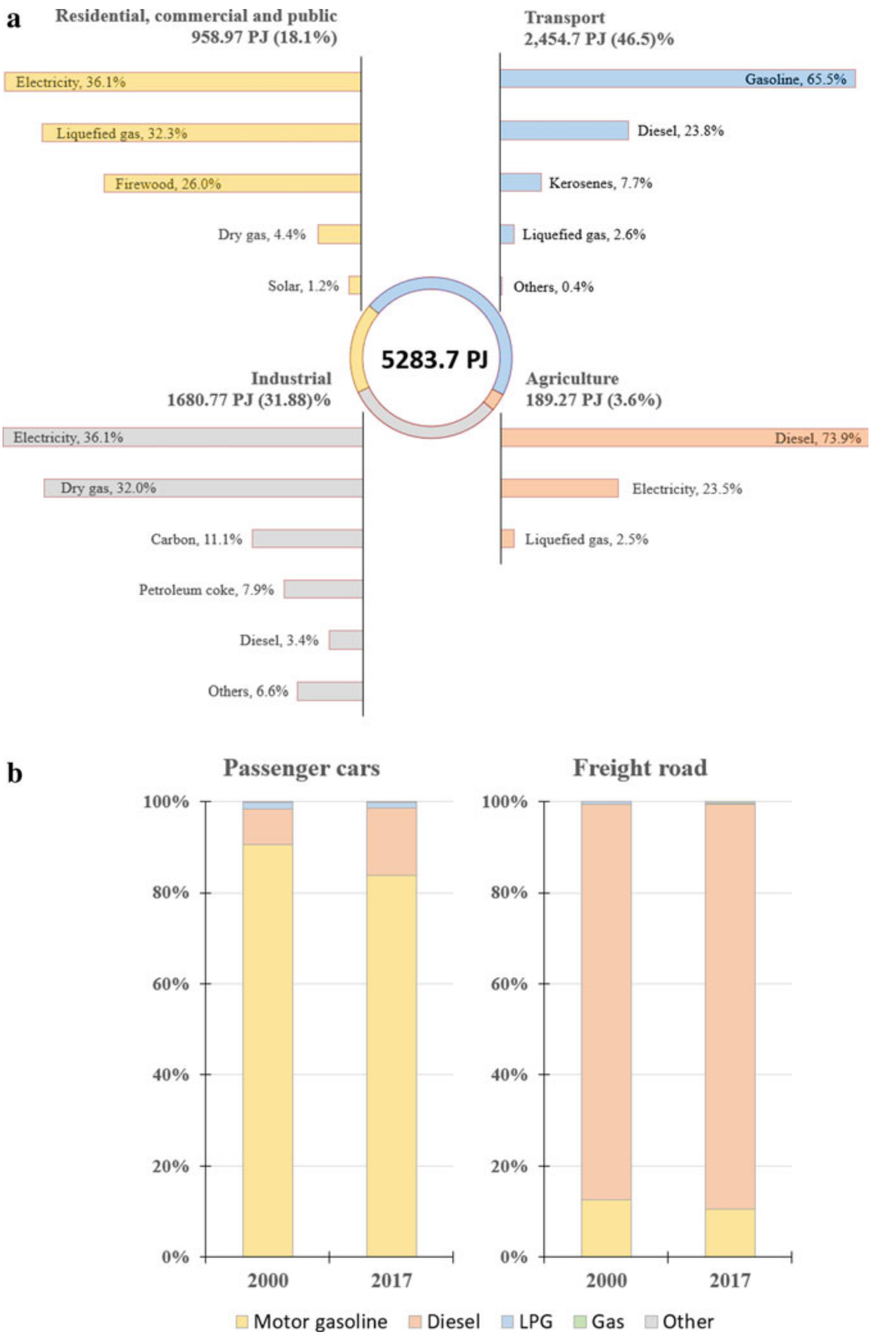


Fig. 11 Transport sector as the main energy consumer in Mexico. **a** Energy consumption in Mexico by sector and source (SENER 2020). **b** Comparison of energy consumption by vehicle type (IEA 2019c)

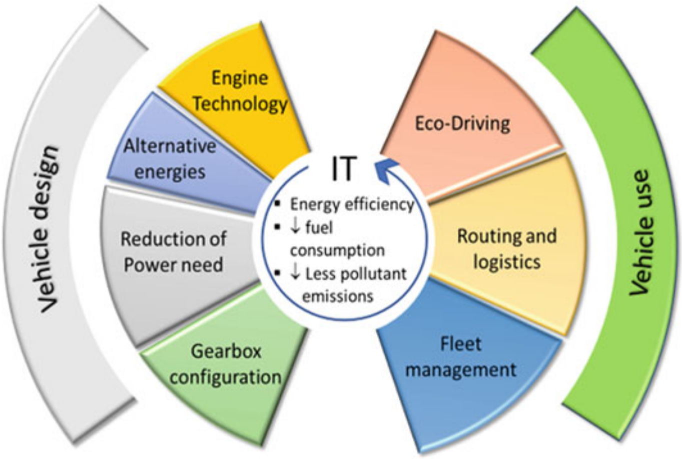


Fig. 12 Alternatives to reduce fuel consumption in vehicles

$$V = m_f LHV_f / \rho LHV \tag{2}$$

Besides the vehicle's technology, the SFC also depends on driving habits and external conditions. Mexico has highly populated regions, such as Mexico City, located over 2,500 masl, reducing the energy efficiency of the vehicles. It also has extensive regions with intensive hot seasons, which increases the fuel consumption to 30% up, due to the use of air conditioning inside the vehicles. Figure 12 illustrates the alternatives to reduce fuel consumption in vehicles. They can be classified as related to vehicle technology and to vehicle use.

Within the first family of alternatives, fuel consumption can be reduced by improving the performance of the engine through new technologies that enable to increase the engine compression ratio, including turbochargers. It also includes the possibility of using lighter engines with less power for the same tasks. The cost associated to fuel consumption can also be reduced by incorporating new sources of energy. Chapter 3 discussed the current possibilities of using alternative sources of energy for vehicles in Mexico. Fuel consumption can also be reduced by reducing the power needed to move the vehicle. This can be achieved by reducing vehicle weight. The automotive industry has focused on the replacement of metal by polymer or composite materials to make their LD vehicles lighter and with less fuel consumption and manufacturing cost. An incremental but constant rate of vehicle weight reduction has been achieved. In this aspect, the body of the HD vehicles used for urban freight distribution or passenger transport still has large opportunities. Weight reduction of HD vehicles can be achieved by incorporating best practices of the automotive manufacturing into this still artisanal and labor-intensive industry. The improvement of the aerodynamic shape of the vehicle also reduces fuel consumption. However small improvements can be achieved in the already optimised body shape of the LD vehicles. Opportunities are still present for the case of long-distance hauling. Improving the aerodynamic shape of HD vehicles for the urban passenger transportation or freight distribution is not of interest, due to the low speeds under which these vehicles move inside the city. Finally, it is also possible to reduce fuel consumption by reconsidering the gearbox configuration in HD vehicles. The current design of gearboxes has an acceptable performance of the vehicle under all operating conditions. Nevertheless, as will be shown later, vehicles end up demanding less than 25% of the engine available torque, where the engine exhibits its lowest efficiency. Increasing engine torque increase engine efficiency. We propose to save fuel by identifying the narrow set of operating conditions (specific route) where the vehicle works most of the time and configure the vehicle gearbox in the way that the engine operates in the region of torque-RPM of maximum efficiency.

The second set of alternatives to reduce fuel consumption focus on how the vehicles are used. This strategy offers potentially large fuel savings. The first alternative within this family is the well-known eco-driving. Companies with large vehicular fleets in Mexico have implemented eco-driving programs along with incentive programs for their drivers with the best performance saving fuel. The main challenge for these companies is to come up with a methodology to, fairly, compare the performance of drivers who use vehicles with different technology, model-year, running along roads with different conditions and varied topography. Another possibility is improving the planning (logistics and routing) designed by these companies to transport people and freight. Even though there are plenty of engineering tools to optimise that planning, as well as company awareness of those tools, they are seldom used. In that regard, the lack of knowledge of how to run the software for their specific needs and circumstances, as well as cultural issues are the limiting reasons. Finally, the correct management of the fleet can save fuel. Maintenance has a high impact in fuel consumption. With the proper maintenance, up to some extent, vehicle age has a negligible impact in fuel consumption. However, vehicles need to be renewed because the maintenance of old vehicles become expensive and, in most cases, vehicle manufacturers improve the efficiency of their vehicles year after year.

3.1 Real Fuel Consumption of Light Duty Vehicles

In this section, the efficiency in the use of fossil fuels for LD vehicles (1–1.5 GVW and 100–180 HP) is described. LD vehicles make up the largest vehicle group in Mexico (73%) (INEGI 2018a), are gasoline fueled and are used mainly for individual transportation. For the purpose of describing their energy efficiency in Mexico, we present first their technologies and ages.

LD vehicles in Mexico: the distribution of LD vehicles per category corresponding to the registered vehicles of the four major Mexican regions: Mexico City (CDMex), State of Mexico (EdoMex), Jalisco and Monterrey (MTY), is shown in Fig. 13a. In 2018, the Transport Secretary of Monterrey reported 2.2 million registered vehicles; 73% were automobiles and 3.25% were motorcycles. The number of vehicles registered in Mexico City, State of Mexico and Jalisco in 2014 was 4.7, 5.2 and 3.1 million

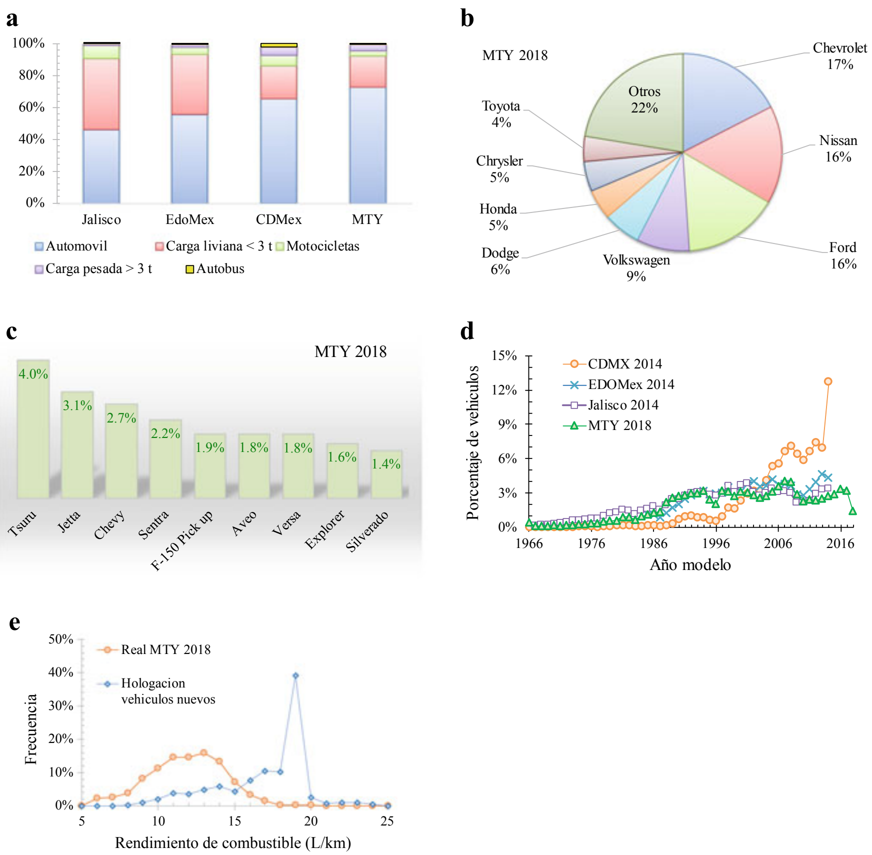


Fig. 13 **a** Composition of vehicular fleets in the four regions as of June 2018 for Monterrey and June 2014 for the other regions. b Brand participation in Monterrey in 2018. **c** Model participation in Monterrey 2018. **d** Distributions by model-year in each region. **e** Comparison of real fuel consumption in Monterrey and consumption in approval tests reported by manufacturers

respectively (INEGI 2018b). These three regions showed similar vehicular composition, where most of their vehicles are automobiles, then light freight vehicles and finally motorcycles. As to brands, Chevrolet and Nissan are dominant in Monterrey with 17% and 16% of participation respectively (Fig. 13b), while Tsuru, Jetta, Chevy and Sentra are the main models (Fig. 13c). Electric and hybrid vehicles are almost null (0.026%). Similar figures are reported for the other regions in Mexico. Fuel consumption and tailpipe emissions depend on the vehicle's technology. Thus, one indicator of vehicles' energy efficiency in a city is the vehicles' average age, which is expressed as the average model year. Figure 13d shows that the distribution of LD vehicles per model-year does not adjust to a normal distribution, making the average not a good descriptor of the fleet's age. It is preferable to use the median, which in 2014 was 12 years, for the case of Monterrey, and 7, 10 and 16 years for Mexico City, State of Mexico and Jalisco, respectively. In 2015 Monterrey's Metropolitan Area had 4;437,643 citizens, Mexico City had 8,918,653, State of Mexico 16,187,608 and Jalisco 7,844,830 (INEGI 2015). This means that on average there were ~0.5 vehicles per person in the main urban areas of Mexico.

Real fuel consumption of light duty vehicles: there is a substantial difference between the fuel consumption reported by manufacturers and the real fuel consumption that users experience. Aiming to dig deeper into the real consumption of LD vehicles, in 2018 a campaign was developed in the Metropolitan Monterrey Area, where the dashboard of 411 random vehicles was photographed to obtain the average fuel consumption, kilometres travelled and license plate. Using the latter as input data, we obtained the vehicle technical characteristics from the vehicle state registration database (REPUVE). The fuel economy, reported by manufacturers, was obtained from Ecovehículos, which is a database published by the national environmental ministry (SEMARNAT). Out of 411 vehicles, 372 were identified with complete valid data. Figure 13e shows the real and reported fuel consumptions. As expected, the data did not show a normal distribution. The average real FE was 11.42 ± 4.96 km/L while the manufacturer reported 16.46 km/L. Similarly, the frequency distribution of kilometres travelled was obtained. It did fit a normal distribution with a mean of 14,240 km/year.

Energy consumption *of electric versus fuel vehicles:* for the last three years, Mexicans have adopted the use of light electric vehicles. The number of electric vehicles sold in Mexico has increased from 201 in 2018 to 305 vehicles in 2019 (INEGI 2019), being Nissan the dominant brand (INEGI 2020). To evaluate their performance under the Mexican conditions, a comparative study was made between an electric vehicle of a premium brand and similar gasoline -fueled model, both tested in the central region of the country. As seen in Fig. 14a, the energy consumption of an electric vehicle increases proportionally to the vehicle speed, while the engine-powered version is more inefficient at a low velocity (Fig. 14b). It was also found that the real energy consumption of an electric vehicle under normal use is 0.12 kWh/km. When the charger efficiency is incorporated, the user's effective energy consumption is 0.20 kWh/km. This represents an increment of 63% to the manufacturer's report. Under the current electricity and gasoline prices (0.14 USD/kw h and 0.77 USD/L) (CFE

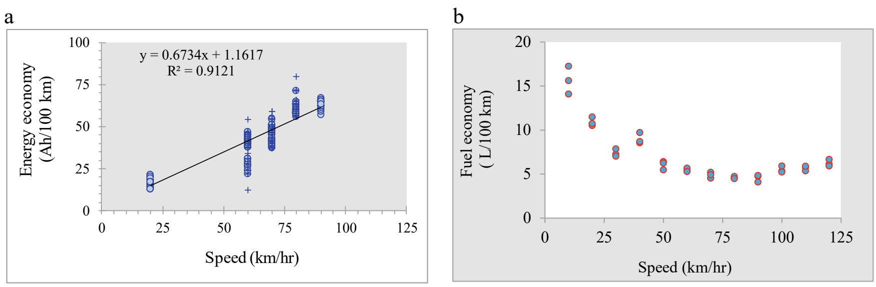


Fig. 14 **a** Performance of electric vehicles in Mexico. **b** Performance of gasoline fueled vehicles in Mexico

2018; CRE 2020) in the residential sector, 0.04 USD/km are saved. Nonetheless, this monetary savings in the daily operation of electric vehicles do not compensate yet the initial over cost of the electric vehicles.

3.2 Real Fuel Consumption in the Public Passenger Transport

In Mexico, most of the intercity and urban trips are done by bus. Therefore, the public passenger transportation industry is dominant. It is currently controlled by few companies with large fleets of buses (>5,000 units) powered by diesel engines. These circumstances favour the possibilities of implementing strategies for the reduction of fuel consumption. Figure 15a shows the average annual consumption of a sample of 500 buses classified by the model-year. These 20 tons buses transported ~50 passengers through interurban and urban routes in northern Mexico from January 2014 to July 2017. The FE was approximately 3.5 km/L and increased 0.077 km/L with each model-year, showing the relevancy of renewing the bus fleet regularly. Additionally, this figure shows that the consumption of each operating year is similar; meaning that providing a proper mechanical maintenance to the buses, the normal deterioration of the vehicles has a negligible effect on buses fuel consumption. Nonetheless, the improvement in the performance of the buses depends on the manufacturer. Figure 15a also shows a second manufacturer that does not improve the FE of its buses.

The companies that operate these buses reported the operative costs shown in Fig. 15b, which shows that fuel consumption represents 47% of variable costs. These buses travel on average 100,000 km per year, therefore any increment in the efficiency represents a significant economic saving for these companies.

For deepening in the study of energy efficiency in the public passenger transport sector, the regular operation of a 500 buses fleet with the same technology (20-ton GVW, 60 passengers, Engine EPA, (EPA 2004) was monitored in central Mexico

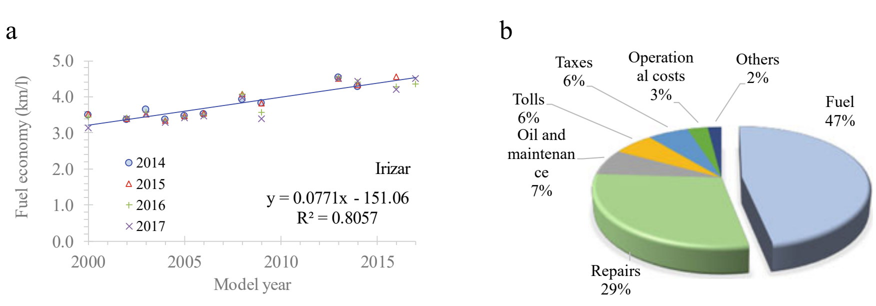


Fig. 15 **a** FE of a fleet of 500 buses travelling ~100,000 km/year in northern Mexico. **b** Variable costs in a public transportation company in central Mexico

Table 6 Average values of the characteristic parameters (CPs), and their 95% confidence interval, that describe the driving patterns exhibited by the buses' drivers in Mexico

CP	Units	Regions			
		General	Urban 1	Urban 2	Mountain
Average speed	m/s	12.2 ± 0.9	8.5 ± 1.5	9.7 ± 1.2	17.0 ± 1.5
Maximum speed	m/s	28.2 ± 0.7	22.1 ± 1.2	25.4 ± 0.9	28.1 ± 0.7
Positive kinetic energy per distance travelled	m/s^2	0.25 ± 0.01	0.36 ± 0.02	0.31 ± 0.02	0.19 ± 0.01
Percentage of idling time	%	7.6 ± 2.1	11.1 ± 6.2	10.3 ± 2.9	1.4 ± 1.1
Percentage of cruising time	%	45.3 ± 6.6	37.6 ± 9.6	39.3 ± 8.1	55.0 ± 4.2
Average positive acceleration	m/s^2	0.03 ± 0.06	0.02 ± 0.07	0.03 ± 0.06	0.02 ± 0.05

during 2014. The buses followed a route connecting Mexico City and Toluca City. This route includes 15 km inside Mexico City and 14 in Toluca. Both cities are in flat regions at 2400 and 2500 masl respectively, with high vehicular traffic. Moreover, it includes 43 km of an intermunicipal highway that goes up to 3500 masl. The driving patterns followed by the drivers during the monitoring period are shown in Table 6.

Tools for vehicle emissions inventories (such as MOVES or COPERT), or vehicle routing (Route4me), describe driving patterns as the percentage of the time vehicles spent in bins of speed, VSP-speed or speed-acceleration. Other algorithms could even use bins of engine load (torque)-RPM. Figure 16a, b shows the percentage of time all monitored buses spent at each bin of speed per region during the on-road tests. In the urban regions, vehicles spent a long time (16–22%) idling. Furthermore, buses mostly were driven at low engine loads (Fig. 16c) where the engines exhibit their lowest efficiencies (Fig. 16d).

The integrated values of SFC per trip adjust to a normal distribution with *p*-values >0.12, for all regions, using an Anderson–Darling goodness-of-fit test. Table 7 reports the average SFC, with a 95% confidence interval, of the monitored fleet. They showed an average SFC of 0.41 ± 0.04 and 0.37 ± 0.02 L/km in the Urban 1 and Urban 2 regions, respectively. Since Urban 1 region has a higher traffic of vehicles, a greater fuel consumption was expected. The fleet showed an SFC of 0.37 ± 0.03 L/km when travelling in the General region. These values are close to the reported by IPCC of ~0.40 L/km for similar vehicles in the US and Europe with different emissions control: advanced control (AC), moderate control (MC) and uncontrolled (UC), as well as the ones reported by Wu et al. (2015) (0.42 L/km) and Liu et al. (2011) (0.40 L/km) for urban diesel buses. The values obtained in central Mexico are lower than in northern Mexico due to a higher altitude above sea level, but also because they take urban routes while buses in the north usually operate on interurban routes.

In eco-routing studies, it is customary the use of fuel consumption per bins of speed or speed-acceleration (Díaz-Ramírez et al. 2017; Huertas et al. 2018). Figure 17a

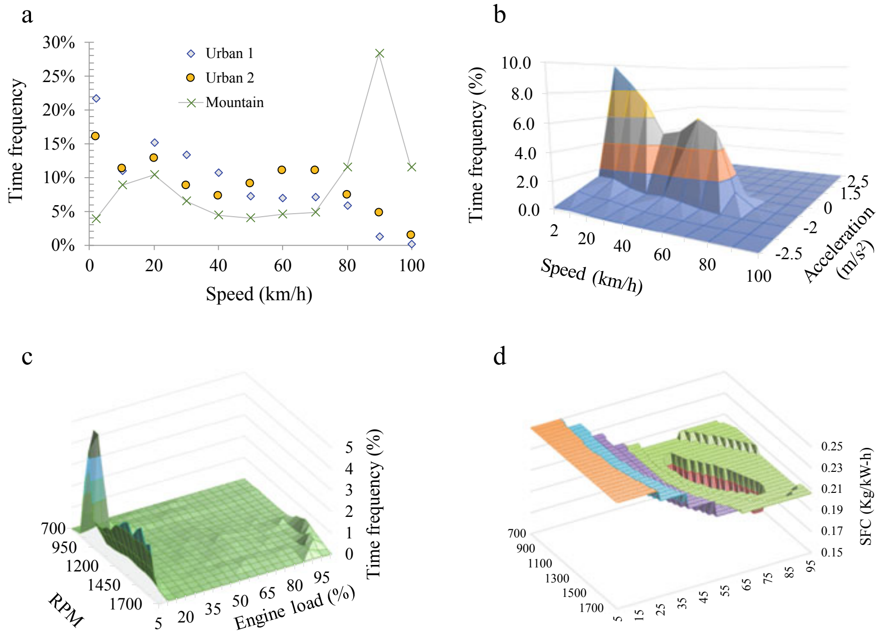


Fig. 16 Driving patterns expressed as the percentage of time the vehicles were driven at a set of bins of **a** speed, **b** engine speed-acceleration, and **c** engine load-RPM. **d** Engine efficiency in kg of fuel per kw-h at the engine axel

Table 7 Fuel consumption measured in a USEPA 2004 bus fleet operating at high altitude under local conditions in Mexico

Parameter	Unit	Urban 1	Uphill	Mountain	Urban 2	General
SFC	L/km	0.41 ± 0.04	0.62 ± 0.03	0.36 ± 0.04	0.37 ± 0.02	0.37 ± 0.03
FE	km/L	2.48 ± 0.22	1.62 ± 0.07	2.89 ± 0.31	2.71 ± 0.14	2.75 ± 0.22

show the results of the average fuel consumption rates obtained per region, considering all buses and all trips in both directions. We stress that the reported values are simple average values and that the distribution of data within each bin does not follow a normal or any well-known distribution. Figure 17b shows the fuel consumption behaviour measured for the case of Urban 1 during the on-road tests as averages values for all buses. We obtained similar results for all regions considered in this study. For the same purpose and in a similar way, we determined the average, fuel consumption rate per bin of speed and acceleration. Figure 17c shows that all regions exhibit a similar profile of average SFC versus speed.

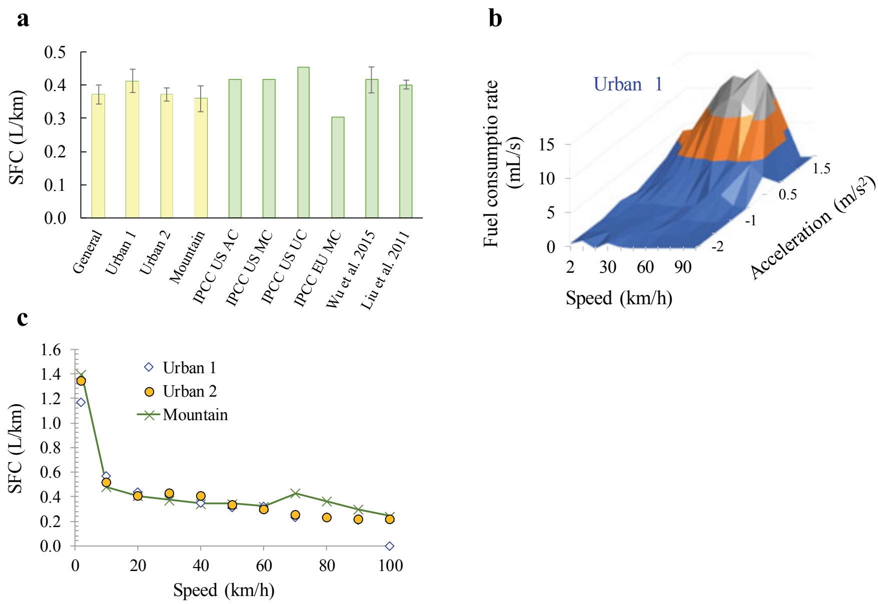


Fig. 17 **a** Comparison of average SFC observed in buses operating at high altitude in Mexico city, against similar studies reported in the literature of buses with different types of emission control: advanced control (AC), moderate control (MC) and uncontrolled (UC). **b** Average fuel consumption rate as a function of speed and acceleration. **c** Specific fuel consumption as a function of speed

4 Analysis of the Consumption of Fuel Fossils and Renewable Energies to Produce Heat for Industrial Processes in Mexico and the United States

In the last decades, the energy consumption worldwide has increased considerably to satisfy the demand of the industry. The International Energy Agency (IEA) reported that most of this energy was obtained from fuel fossils such as gas, coal and oil with a percentage of 22%, 30% and 12%, respectively (IEA 2018a). The emission of CO_2 gases due to the combustion of these fossil fuels has been an important contribution to the global warming (about 20% of world emissions) Bloomberg 2019).

The energy demanded by the industry can be classified as electrical and thermal. Power stations have been employed to produce electricity by burning fuel fossils contributing to the emission of greenhouse gases. Cleaner technologies such as hydro-electric power stations and renewables, specifically aero-generators and photovoltaics (PV) solar collectors, have also been employed to provide electricity to the industry on a smaller scale. There are also other friendly environment technologies such as concentrating solar power systems where the solar radiation is concentrated to increase the thermal energy of a fluid that is employed to provide energy to drive a turbine that generates electricity. Examples of concentrated solar technologies to produce electricity at a large scale are power solar tower and parabolic trough solar collectors. Solar power tower systems consist of a large number of flat mirrors (heliostats) located on the floor with a tracking mechanism that reflects the solar radiation to a receiver in the upper zone of a tower to heat a working fluid (steam or molten salts). Parabolic trough collectors (PTC) use parabolic surfaces with very high reflectance to concentrate the solar radiation in a pipe located at their focus to increase the thermal energy of the working fluid (oil or steam). For both types of concentrating technologies, the working fluid provides thermal energy to produce electricity through a thermodynamic cycle. Solar power plants (PTC or Solar Towers) are systems that require a large investment to be economically feasible.

For the case of thermal energy, fuel fossils such as natural gas, coal and oil are burned to provide heat for industrial processes in different forms. For example, boilers are employed to produce hot water or steam for a chemical or food processes. Direct heating can be provided to transform a material. The thermal energy demanded by the industry globally for heating processes is larger (about two thirds of the total energy) than the consumption of electrical energy. The application of renewable energies to produce thermal energy for industrial processes is not as large as the case of the electrical energy, however it has favorable conditions to flourish in the United States and in Mexico. In this section, an analysis of the consumption of fuel fossils and renewable energy to produce heat for industrial processes in the United States and Mexico is presented.

First, it is needed to understand the form that the industry is classified by the demand of energy and the level of heat required. An industry is specified as Intensive Energy Industry when the demand of energy is high and continuous. Intensive Energy Industries such as chemical, oil refining, food processing, metal and cement manufacturing, among others, require about three quarters of the total energy consumed to produce heat for their thermal processes. Depending on the levels of temperature required by the industrial process, the heat consumed can be classified (Venerus and Ottinger 2018) as heat for high temperatures (above 400 °C), medium temperatures (between 150 and 400 °C) and low temperatures (below 150 °C). For the intensive industries in developed countries, about half of this thermal energy is required as heat for processes with high levels of temperature, while the rest is for low and medium levels of temperatures (Solar Payback 2017).

In the United States, the manufacturing sector demands a huge amount of energy obtained from fuel fossils for process heating, process cooling and refrigeration. In 2010, approximately 7,204 TBtu/year (70% of process energy) were employed for process heating, where about 64% was obtained by consuming fuel to produce heat directly and 31% by consuming fuel to generate steam (indirect consumption) (Kurup and Turchi 2015). Different types of fossil fuels such as natural gas, coal, distillate fuel oil and diesel, residual fuel, liquefied petroleum gas and natural gas liquids are consumed by the manufacturing industry to produce energy for their processes. In 2010, Natural Gas was the fuel most employed (56%) followed by coal with a 9% (Kurup and Turchi 2015). The end user consumption by the manufacture industry in the United States of the annual energy consumed for process heating, conventional boiler use, combined heat and power (CHP) and cogeneration from natural gas and

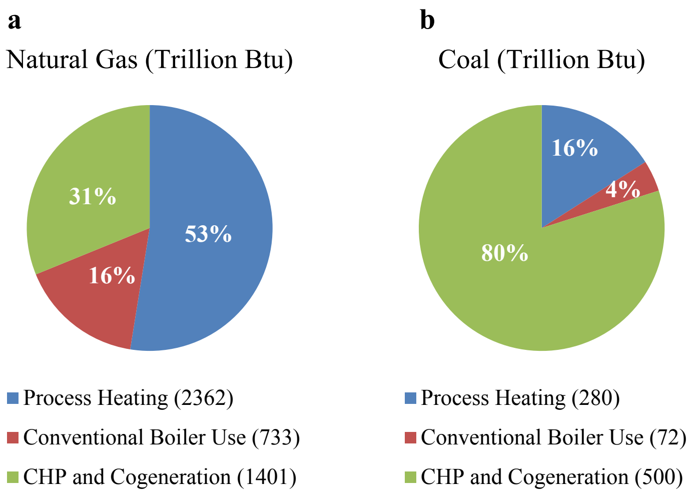


Fig. 18 Fuel consumption of natural gas and coal for the US Manufacturing industry in 2010 for process heating and indirect end use for **a** natural gas and **b** coal (Plot elaborated with information from Kurup and Turchi 2015)

coal are show in Fig. 18. Natural gas is the fuel that is most used for process heating followed by CHP and cogeneration. Coal is more used for CHP and cogeneration followed by process heating. However, the amount of energy consumed for natural gas for heat process is about 8 times larger than the one from the coal.

From the information presented, it can be concluded that there is a large opportunity to use solar energy technologies to provide thermal energy for process heating for the manufacturing sector in the US, especially in the states that are located at the South and that have a good level of solar radiation. The type of solar technology recommended depends on the range of temperature required for the industrial process. Kurup and Turchi (2015) estimated that about 627,000 GWh_{th} of thermal energy from natural gas was demanded by the food, chemical, petroleum, paper and primary metals sectors for direct process heating and boiler use for low and medium temperatures below 260 °C. For these applications and range of temperatures, solar concentrating technologies are recommended. Mc Millan and Ruth (2019) presented a more complete study, where the number of industries analyzed increases to 14 and the range of temperatures for industrial heat process is extended up to 1,500 °C. In addition to the solar technologies, they considered geothermal and nuclear reactors as an alternative to generate heat for the industry and an estimation of the reduction of the fuel consumption and greenhouse emissions due to the application of these technology was performed.

In Mexico in 2016, about one third of the total energy was consumed by the industry, where 67% corresponds to thermal energy and 33% to electrical energy (CONUEE 2018). The heat produced for the industry was obtained mainly by burning fuel fossil (about 96%), where natural gas was the dominant fuel with 58%, followed by oil (27%) and coal (11%). Only 3% was obtained from fuel bagasse cane and 1% from solar technologies. From this heat, about 49% corresponds to applications for industrial processes that demands thermal energy at high temperature levels, while 51% are for application with medium and low temperature levels (CONUEE 2018). Although the participation of renewables energies (mainly solar) to produce heat for industrial processes in Mexico is still very small, it has a lot of potential to grow for the following reasons. First, Mexico is located in a privileged region that receives a great amount of solar radiation during the whole year. Second, there is an important local industry that manufactures different types of solar collectors that can provide air, water and steam at temperatures that are in the range of values of heat for low and medium temperatures.

The type of collectors that are manufactured and commercialised in Mexico for solar industrial heating applications are the flat solar collector, the evacuated heat pipe collector and the parabolic trough solar collector. Flat solar collectors are employed mainly to provide heat for low temperatures (40–100 °C) (Kumar et al. 2019). This type of collector consists of an array of parallel tubes integrated to a metallic flat plate coated with a layer of material with high absorbance. Water that circulates through the pipes is heated by the solar radiation absorbed and conducted by the plate. Some of these collectors have a glass cover on the upper surface to reduce the heat losses to the ambient. The hot water can be stored in a tank or can be sent to a heat exchanger to transfer the thermal energy to the industrial process. Evacuated heat pipes are used to provide hot water for industrial applications that requires heat for low and medium temperatures (up to 150 °C) (Kumar et al. 2019). These collectors consist of a set of inclined evacuated tubes composed of a metallic pipe surrounded by a cylindrical wall made of glass to reduce the heat losses by convection and radiation to the ambient. The absorber pipe contains a fluid that is heated with the energy from the solar radiation and by natural convection the thermal energy is transported to the upper part of the tube, where heat is transfer to the water for the industrial process with a heat exchanger. The parabolic trough collectors (PTC) manufactured in Mexico are smaller than the ones employed for the solar power plant for the generation of electricity described above. The PTC used in Mexico are mainly for industrial applications that demands heat for low and medium temperatures (Fig. 19).

The appropriate selection of the solar collector technology to provide heat for industrial processes in Mexico depends on several factors. For example, using less surface area, the PTC can achieve higher temperatures than the ones obtained with flat solar collectors and evacuated tube collectors, however their cost per square meter installed is higher. Also, an economic analysis is required to evaluate if the heat provided by the solar collectors for industrial processes can compete with the heat generated by burning fuel fossils.

In Mexico, there is an important sector of the industry (chemical, food and beverage, machinery, mining, textile and wood) that demands heat at low and medium temperature (AEE INTEC 2019). Boiling, pasteurisation, drying, sterilisation, cleaning, bleaching are examples of industrial processes of heat at low temperature. Distillation, vapor generation, separation, dyeing are processes that requires heat at medium temperatures. Unfortunately, the heat demanded by these processes

Fig. 19 Parabolic trough solar collector installed in the solar energy laboratory of Tecnologico de Monterrey

in Mexico is obtained mainly by burning fuel fossils, even though there are available solar technologies that could provide this heat without releasing pollutants to the atmosphere. The most employed fuel is natural gas followed by oil and coal.

Even though there are not incentives in Mexico for industry to apply renewables technologies to produce heat for industrial applications, several projects have been developed in Mexico. In this type of projects, there are companies in Mexico that are specialised to provide service to the industry to install solar collectors of different types to produce heat for their processes. The service includes the technical and economic analysis, installation, setup and operation of the solar collectors. More than 80 projects have been implemented in the industry in Mexico to provide heat for their industrial processes. The number of solar projects for the industry is dominated by the flat solar collectors, followed by the parabolic trough solar collector and the evacuated tubes as shown in Fig. 20 (AEE INTEC 2019).

Different innovations have been investigated in the Energy and Climate Change Research Group at Tecnologico de Monterrey to increase the performance of solar collectors so that they can be more competitive. An example of one of these innovations is the applications of nanofluids in thermal systems. Experiments were conducted by Bretado de los Rios et al. (2018) to evaluate for different incidence angles the effect on the efficiency of a commercial PTC due to the use of Al_2O_3/Water nanofluid with a volume concentration of 1 and 3%. The nanofluids were produced

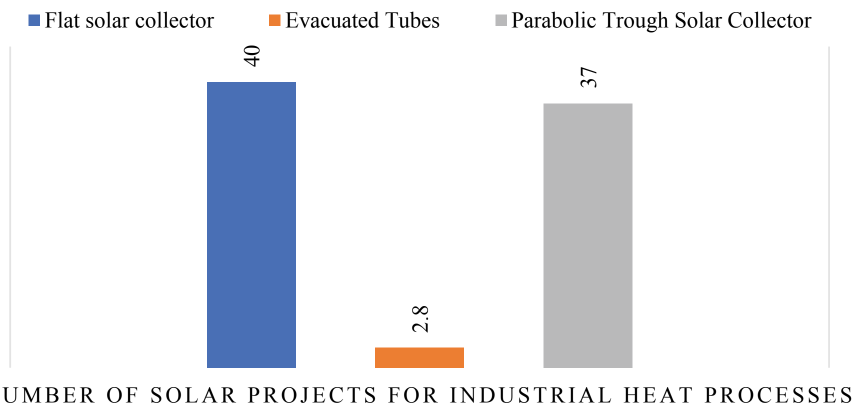


Fig. 20 Technology and number of solar projects installed in Mexico that provide heat for industrial processes (Plot elaborated with information from AEE INTEC 2019)

and characterized in our group with specialised equipment obtained from the binational lab project (Tecnologico de Monterrey 2018). The efficiency of the PTC increased by more than 20% when nanofluids were employed instead of water as a heating fluid for all the incidence angles and volume concentration considered. A computational model based on energy balances was developed by Tagle-Salazar et al. (2018) to predict the performance of PTC for different types of fluids, including nanofluids. Ramírez-Tijerina, et al. (2019) performed computational fluid dynamics (CFD) simulations to study the heat transfer in a pipe for nanofluids produced by dispersing five different types of nanoparticles in water, ethyl glycol and turbine oil. The information of this study is important to improve the thermal operation of the PTC since the receiver of this parabolic collector is a straight pipe and the working fluid usually employed is water or oil. Another innovation that is being explored is the development of a low concentrating photovoltaic thermal (LPV/T) collector that can generate simultaneously thermal and electrical energy. In this type of hybrid collector, PV cells are attached to the receiver of a parabolic trough collector with two main purposes. First, the solar radiation received by the PV cells is increased due to the concentrating effect. Second, the fluid that circulates in the receiver, reduces the temperature of the PV cells increasing its efficiency. Acosta-Pazmiño et al. (2017) developed and evaluated the performance of an LPV/T with PV cells located in a triangular receiver. For this hybrid collector, it was obtained an electrical and thermal efficiency of 55% and 12%, respectively.

4.1 Main Perspectives for Solar Energy Technologies in North America

From the analysis performed in this study it can be concluded the following. There is an important demand of the industry in Mexico and the United States for thermal energy for process heating. Most of this energy is provided by consuming fuel fossils, mainly natural gas. There is a great potential to reduce the consumption of fossils fuels by using solar energy technologies. Concentrating parabolic solar technologies are suitable for process heat applications of medium and low temperature. Although several solar projects have been developed in the last decade to provide thermal energy for process heating, their contribution to reduce the emission of greenhouse gases is still very small since the consumption of fuel fossils to generate heat dominates the industry. More research and stronger environmental regulations are needed in order that the application of solar technologies can be a representative option to reduce the consumption of fuel fossil in the industry of Mexico and United States.

5 Conclusions and Recommendations

There exists a great dependence on fossil fuel consumption for satisfying the immense demand of thermal and electrical energy of different industrial sectors in Mexico and the United States. Natural gas, followed by oil, are the preferred fuels employed to generate thermal energy to meet the heat demand of the process industry. Out of the total thermal energy required by industry in Mexico, about half corresponds to processes that require heat for medium and low temperature applications. The combustion of these fossil fuels to satisfy the thermal energy demands of industry produces greenhouse gas emissions that contribute to global warming.

There is a great opportunity for Mexico and the United States to reduce these greenhouse gas emissions due to the favorable conditions that both countries have for the development of renewable energies. First, there is an abundant solar resource due to the privileged geographical locations of these countries. Second, there is an important demand for heat by the industry for their thermal processes. Third, there is an important local manufacturing industry with mature solar technology that can provide solutions to industrial thermal energy demand.

Renewable energy resources (solar, wind, etc.) in Mexico are abundant and should be better utilised. The wide adoption of renewable energy applications could be achieved by coordinating the efforts of government, private enterprise, and society. The examples discussed in this chapter should motivate the discussion amongst these sectors, and ways that could facilitate the launching of projects that reap the benefits of renewable energy should continue to be devised. The technical aspects of this challenge are in continuous development and improvement. Economic and regulatory aspects must meet and drive the implementation of these sustainable solutions.

To this end, we recommend the following:

(a) Different energy production processes use different technologies and energy sources. In order to compare them and make the best decisions, then it is necessary not only to understand the thermodynamic framework, but also the multiple costs, resource availability, and environmental impact.
(b) A survey is required to identify and quantify the industrial processes that demand thermal energy of low and medium temperature. This information is useful to evaluate the potential and to identify the type of solar collector that can be employed to satisfy the demand of heat of the industry.
(c) Specialised energy agencies can provide these services to the industry, including energy audits and the evaluation of renewable energy potential. It is important that practicing engineers in the industry receive continuing education and training in energy efficiency and renewable energies to help identify areas of opportunity.
(d) Government officials must regulate, certify and support local the industry that manufactures solar collectors. In Mexico, there is a mature industry that manufacture a wide variety of solar collectors to satisfy the demands for thermal energy of different industrial sectors in Mexico.

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Chapter 7
Micro-grid an Integral Approach to Long-Term Sustainability

Luis Ibarra, Pedro Ponce, Arturo Molina, and Antonio Rosales

Abstract This chapter shows a complete review of micro-grids as the main intelligent blocks in new electric grids, which are essential part of smart grids. Hence, it presents the micro-grids from their economic, environmental, social, and technological requirements, objectives, and impacts. The paradigmatic changes now imposed to the conventional grid are emphasised and contrasted with the micro-grid capabilities and benefits. Then, bidirectional power flow, local and centralised control, and the active participation of consumers are introduced and described. Given that most of micro-grid potentials are enabled by power electronics, a full section is devoted to the power converters used and their common control strategies, introduced from a qualitative viewpoint. Also, the main obstacles hindering micro-grids implementation are analysed, demystifying the "green" label normally associated with renewable energy sources and the expectance of them being plug-n-play systems. Then, a section dealing with grid protection systems and their technical incompatibility with distributed generation is also presented. Finally, a list of recommendations for implementing micro-grids in the Mexican context is provided, considering social, technical, economic, environmental, and policy factors.

L. Ibarra (✉) · P. Ponce · A. Molina
School of Engineering and Sciences, Tecnologico de Monterrey, Puente 222, Ejidos de Huipulco, Tlalpan, 14380 Mexico City, Mexico
e-mail: ibarra.luis@tec.mx

P. Ponce
e-mail: pedro.ponce@tec.mx

A. Molina
e-mail: armolina@tec.mx

A. Rosales
Department of Applied Physics and Electronics, Umeå University, 901 87 Umeå, Sweden
e-mail: jarm@ieee.org

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Abbreviations

CB	Circuit breaker
CSI	Current source inverter
DER	Distributed energy resource
DSO	Distribution system operator
EMS	Energy management system
FiPs	Feed-in premiums
FiTs	Feed-in tariffs
MC	Management controllers
MG	Micro-grid
MPPT	Maximum power point tracking
NO_x	Nitrogen oxides
PCC	Micro-grid, point of common coupling
PD	Protective device
SB	Switchboard
So_x	Sulfur oxides
VSI	Voltage source inverter

1 Introduction Micro-grid Concept and Challenges

Micro-grids (MG) come as a response to a wide variety of problems about the power system in general. The electric grid is comprised of many cooperating—even redundant—subsystems and, mostly due to its progressive deployment, they have become an intricate, poorly automated service over which high stakes are set in terms of power quality. Also, energy demand is on the rise while fossil fuels are depleting; nuclear power could not hold for much longer after them, and the aging and environmental issues the grid is subjected do not put forward the idea of a bright horizon (Ding et al. 2009). The modernisation of the power grid is a recurrent topic when approaching these issues, being the renewable sources an alleged significant contribution to the overall enhancement of the power grid.

Renewable power sources yield a direct solution to the final collapse of traditional energies; however, different, indirect benefits have been foreseen, and, simultaneously, novel challenges emerged. In order to trim down the required grid investments and reduce transmission losses, alternative sources are mainly planned to be inserted at the distribution level, locally. Such distributed energy resources (DER) also come with negative impacts related to the weakness of the grid at the distribution level (Lu and Wang 2017), and the desired plug-n-play capacity, implying installation randomness and variable—sometimes uncontrollable—operation. In the pursue of preserving the benefits while minimising the DER's problems, the micro-grid concept was proposed (O'Neill-Carrillo et al. 2018).

Likewise, today's grid architecture—top-down radial transmission system—assumes that energy is distributed to strictly passive loads, with no generation or storage capabilities. As new storage and generation technologies are being put to service, this approach is becoming obsolete (Asmus 2014). Moreover, new markets now favor business models based on local availability and timing instead of estimate-based centralised generation (Asmus 2014; Vanadzina et al. 2019). Such topological changes have paved the way for new proposals to be designed and tested.

The micro-grid (MG) concept is sometimes broadly defined as an energy supply and network management technology that deals precisely with DERs, enabling demand-side energy management (Ding et al. 2009). Such a local grid may contain many DERs, energy storage systems (ESS), local loads: it is a grid on itself that can operate either connected to the main grid or stand-alone, switching seamlessly between them both (Ding et al. 2009). Its pursued objectives are efficiency, sustainability, reliability, energy cost reduction, and resiliency (Alam et al. 2019; Parag and Ainspan 2019). Hence, those problems brought by DERs are to be solved locally (O'Neill-Carrillo et al. 2018) by taking a closer eye into fewer systems, also empowering the demand-side by enabling a new local energy market (Vanadzina et al. 2019).

However, taking the overall picture to reality imposes soaring technical requirements. For instance, one concern is the categorical need of a support grid to amend the variability of renewable resources (Fu et al. 2013)—customarily assumed to be a reliable, traditional one. Moreover, the uncertainty brought by installation randomness—e.g., grid reconfigurations and protection against faults (Lu and Wang 2017; Vukojevic et al. 2020)—and the electronic contamination of an already weak grid are supposed to be tackled naturally. Similarly, finding a solution for a partially/fully automated and communicated intra-MG operation is not necessarily sufficient as many MGs are supposed to be integrated over a common grid. Interacting MGs pose further problems mostly pointing toward stability, protection, coordination, privacy of private and community information and the threat of cyberattacks (Alam et al. 2019).

Similarly, interacting with the main grid is risky and must be in line with the utility interests. Utility stands as an obstacle in MGs adoption inside existent grids, normally demanding excessive requirements for interconnection (Burr et al. 2014). In the context of a non-changing, indispensable electric grid, disruptive technologies are not expected to find an organic growth path, requiring some first-adopters to increase the MGs credibility of the skeptical, standards-accustomed electric industry (O'Neill-Carrillo et al. 2018). Such a process is like the paradigm change in the telecommunications area that led to the internet itself, for which the military and universities were pioneers (Burr et al. 2014).

Such a context has modified the expected integration of MGs which have, in turn, found successful case-studies in remote communities and developing countries unable to establish a traditional power infrastructure (O'Neill-Carrillo et al. 2018). Likewise, other success cases are related with emergencies in which users experienced grid unavailability (Ravindra et al. 2014). The expected transformation of the existent grid has taken a step aside to ultimately deal with extreme weather, vulnerable and aging electrical infrastructures, changing transportation needs, and socioeconomic disparities, making the MGs stand-alone operation capability and ad hoc design their most valuable current assets (Cuzner 2018; Vukojevic et al. 2020).

Then, major changes in the electric grid are foreseeable; however, they will come at a different rate and with particular characteristics depending on the dominant contexts where MGs are deployed. Up to this day, MGs have passed the reliability and resiliency tests as stand-alone "safe havens" during emergencies (Shahidehpour and Pullins 2014) and as enablers of better life quality for some communities in need. Indeed, there are technical, financial, social, and governance challenges to solve before observing the definitive development of the future power grid.

One of the remaining benefits of a micro-grid can be assessed by (Parag and Ainspan 2019): the addition of economic, reliability, environmental, deferred transmission minus distribution- generation and construction. In fact, the micro-grid is a controlled entity in the main electric grid that can be seen as a single aggregated load. Moreover, it can store energy in order to handle the market prices of electrical power in a local or global condition.

A general classification of micro-grids is based on AC and DC types. The DC micro-grid has an excellent short circuit protection system, and the efficiency is good enough for local generation in low and medium electrical loads. On the other hand, the AC micro-grids can be connected to the main electric grid, and they are reliable for the end-user. Still, they have a sophisticated control system strategy for synchronisation with the main electrical grid to be a stable system (Gao 2015). In this chapter only AC micro-grids are presented since they can accomplish an excellent demand-response when the electric load is swiftly changing.

Briefly, a micro-grid can be defined as a set of interconnected micro resources, flexible loads, and storage systems in a local distribution system. The form of operating characterises the micro-grid since it can connect and disconnect to the main grid. The micro-grid operation, when it is disconnected to the main grid, is called island or stand-alone mode, and when it is connected to the main grid is named grid-connected mode. The operation in both methods increase the functionality and provide benefits to the primary grid. The micro-grids are constructed by microgeneration, such as solar energy, wind energy, fuel cells, etc., storage devices as batteries, energy capacitors and flywheels, and flexible and controllable loads.

1.1 Economic Impact

One of the main benefits of installed micro-grid is the economic impact that is generated since the investment of transmission and distribution cost is reduced; thus, the conventional bulk transmission and distribution systems are eliminated from the electric topology. In micro-grids, the load centers are next to the generation systems, so the cost of transmission is not considered. Also, the micro-grid is a flexible topology that allows reconfiguring its components according to the electric load, renewable energy demands, and so on. Hence, the concept of option value system is applied to it. This option value concept removes the risks since it can continue, adapt, or abandon an investment. In the micro-grid, which is an adaptable system that can be re-configured, the option value concept is applied to reduce the economic risk (Ruotolo 2018). In the case of renewable energy, the micro-grid can be adapted according to the increment of electric load under a programmed structure that permits to reconfigure and to add new electric generation modules.

On the other hand, the economic impact of micro-grids also depends on the type of connection that is used: islanded or grid-connected. Usually, the type of electric connection of the micro-grid determines the demand response program that is implanted, so the dispatchable or non-dispatchable price program varies the price rates. This kind of program motivates the end consumers to try increment their electric consumption when off pike period of electric demand is reached and decrement the electrical consumption when higher peaks of electric load demand are achieved. This consumer's behaviour flattens the demand curve so the prices can be reduced. As a result, the costs can be divided as the time of use, critical peak pricing, and real-time pricing. Sometimes extra rates are added because the rates are changing continuously, and they reflect the total sales price. When a high demand response is needed, the end consumers are informed about the electric price one hour/day ahead. If the demand response is not critical, participation based on incentives could be implemented. In addition, the micro-grid can store energy, so the micro-grid regulates the energy import. Thus, the congestion of the electrical network at peak demands is also reduced, and the physical capabilities of the electrical grid are not overloaded. Therefore, the quality of energy and reliability of electricity is kept.

Moreover, the inequality provision of energy is mitigated, as well as the replacement cost linked to non-programmed maintenance (Gui et al. 2017). In fact, the investment for developing micro-grids integrates energy efficiency and generating smart technologies. Besides, the optimal configuration of a micro-grid is also defined by economic incentives, for instance, a 50% tax credit of investment cost for renewable energy promotes the adoption of wind energy more than a 30% tax credit. Besides, this kind of incentives increment the total amount of electric power generated by renewable energy and can accelerate its implementation (Zachar et al. 2015). It was shown that the cost of developing a micro-grid is around the following percentages: 15% for the controller, 50% generation, 35% remaining costs (Astriani et al. 2019). Besides, investment of small micro-grids into a community depends also on idiosyncratic activities since micro-grid operation requires specific equipment, a substantial investment has to be made in the community, and the participation of end consumers who are not part of the community for this investment is small (Gui et al. 2017). For estimating the cost of a micro-grid, the main characteristics have to be defined as shown by (Parag and Ainspan 2019):

- Installed capacity
- Structure of that capacity
- Costs associated with building, operating, maintaining the micro-grid

Using these characteristics, a comparison between the cost of fossil-based and renewable technologies can be done using Eq. (1) to find the levelized cost of electricity

$$LCOE = \frac{\sum_{i=0}^{n} \frac{I_i + O_i + F_i + ITC_i - PTC_i}{(1+r)^i}}{\sum_{i=0}^{n} \frac{E_i}{(1+r)^i}} \quad (1)$$

where I_i is the investment cost in year i, O_i is the operation cost in year i, ITC_i is the investment tax credit in year i, F_i fuel cost in year i, PTC_i is the production tax credits in year i, E_i is the energy generated in year i, r is the Weighted Average Cost of Capital and n is the life time of project (years).

It is essential to mention that carbon taxation does not make a difference regarding the technology deployed in the micro-grid with or without carbon taxation since the cost of carbon is too low (Milis et al. 2018).

1.2 Environmental Impact

To achieve an entire structure of the micro-grid that considers the environmental protection and economic dispatch into a decentralised generation system, the micro-grid has to be adjusted to find the minimum generating cost and the minimum greenhouse emissions cost. Also, power balance and load demand are reached (Liao 2012).

The environmental impact can be assessed using the emissions avoided monthly using a typical emission curve, as shown in Eq. (2) presented by (Hatziargyriou et al. 2009).

$$p(h, m, po) = \frac{\sum_{i=1}^{n} fc(h, m)_i * em(po)}{days(m)} \quad (2)$$

where: n is the number of units that may be affected by applying distributed generation, fc is the frequency at which unit i expects a critical value for the month m and the hour h, and em is the emission factor of the pollutant po for the unit i, and $days$ is the number of days in month m.

1.3 Social Impact

A couple of years ago, an estimate of almost 4 billion people, mostly in developing countries and isolated communities, had no reliable access to electricity, whereas 1.1 billion had no access whatsoever (Cuzner 2018; Podmore et al. 2016). Electricity represents not only the possibility of artificial lighting, but the access to a better life quality as it can be thoughtfully coupled with the community prosperity (Shahidehpour and Pullins 2015; Podmore et al. 2016). Not surprisingly, electrification has been recently outlined as one of the United Nations Sustainable Development Goals, among clean water, sanitation, access to education, medical services, and communication technologies (Anderson et al. 2017; Anderson and Suryanarayanan 2018). Undoubtedly, those goals are empowered, if not entirely enabled, by providing access to electricity, which also drives job creation, agriculture, and transportation, to name a few.

Providing energy through distant, isolated MGs is regularly preferred over expanding the existing grid, if any. The main drivers are, perhaps, the short-term applicability and its lower cost; however, MGs exhibit additional benefits that help such societies further. Indeed, every community is different and MGs can be designed specifically for their present needs and foreseen expansion; they generate value with local available resources, taking into account their variability, considering definite timing and potential social and governance issues (Ravindra et al. 2014). The direct participation of the electric industry would find difficulties due to the potential lack of existent technical standards and regulatory certainty (O'Neill-Carrillo et al. 2018).

On the other hand, the usefulness of MGs on existent grids has been advocated mainly due to their independence from a main grid prone to faults under emergency conditions. For instance, the hurricane Maria on Puerto Rico brought to light that the availability of electricity is a life or death matter, i.e., a proper human right (Cuzner 2018). MGs are, in the end, not a step toward the modern, traditional electric architecture but value-based entities, able to interact with the main grid if necessary or possible (Ravindra et al. 2014).

However, as beneficial as MGs may be in the socioeconomical context, they face challenges far from technical applicability. Ravindra et al. (2014) present a list of common obstacles of MGs implementation that have been summarised here under three categories:

- Financial issues
  - Affordability, financing, insurance, and return of investment
  - Application procedures and planning
  - Cost and pricing models, including further interaction of consumers and providers (exit fees, feed-in tariffs, load retention rates, interconnection, and standby fees)
- Social
  - Ignorance/lack of interest of stakeholders and consumers
  - Cultural dimensions in terms of usage of energy technologies
  - The growing rich-poor division
- Governance
  - Stakeholders lack of commitment, harmony, and trust
  - Lack of coordinated efforts and accountability
  - Political interference and lack of regulatory and policy frameworks.

1.4 Sustainability Impact

The sustainability in micro-grids could be measured by several indicators that comprise economic, social, and environmental conditions, so an adaptation of the sustainable factors presented by (Evans et al. 2009) is described in Table 1.

When a micro-grid has renewable energy included the greenhouse emissions are calculated during the entire operating life. Hence, the starting point is the manufacturing emissions of the plant. The greenhouse emissions are measured as grams of CO_2. Thus, solar and wind energy have a maximum emission value during the manufacturing process. The best generation energy in terms of availability, reliability, and flexibility is the hydropower (Egre and Milewski 2002). However, hydropower does not have a constant footprint, and the topography is not uniform in each location, so the land use is significant: around 73 km^2/TWh (Gagnon and Vate 1997).

An evaluation of sustainable indicators to generation technologies was presented by (Evans et al. 2009) in which each renewable generation technology is evaluated. As a result, photovoltaic technology is the worst technology in terms of price and the best is geothermal, wind energy is the best in terms of CO_2 emissions and the worst is the geothermal, hydro technology is the best one in terms of efficiency and photovoltaics is the worst, hydro is the worst in terms of land use and photovoltaics is the best, geothermal is the worst for water consumption and the best is the wind, hydro is the worst in terms of social impact, and the best technology is wind energy. Finally, the best technology in terms of availability and limitations is hydro and the worst photovoltaics. In a nutshell, photovoltaics and geothermal lead the rankings

Table 1 Sustainable factors in micro-grids

Economic factor	Environmental factor
Cost of generating electrical energy in terms of investment and development. In this factor also the quality of life for all the communities in excessive need of electricity has to be considered in terms of the Human Development Index used by the United Nations Development Program	Sometimes, incrementing renewable energies leads to the production of greenhouse emissions. Also, some visual damage and audible noise is added when some renewable energies are deployed such as wind energy
Efficient energy transformation leads to an extra cost	Land is needed to keep biodiversity and environmental conditions. Besides, the operation of the micro-grid could impact the environment if the disposal and recycling are not included as primary tasks
Heavily resource-constrained regarding technological limitations, mainly caused by intermittency and storage	Water consumption for operating the micro-grid. For instance, a significant amount of water is used to manufacture solar cells and wind turbines
Reduction of human risk during the manufacturing and operating process of micro-grids	Acceptance and adoption of communities

in terms of the worst sustainable technologies to generate electrical energy, and wind and hydro are the best technologies in terms of sustainability technology to generate electrical power. Hence, an investment to implement a micro-grid has to include a set of generation technologies in order to reduce the sustainable impact. Sometimes, additional sustainable indicators are included in power systems such as annual emissions of CO_2 (Mton/year), yearly emissions of NO_x (kton/year), yearly emissions of SO_x (kton/year) according to Prete et al. (2012), it is recommended to implement a sustainability evaluation framework to study different scenarios in which the micro-grid operates. Lastly, it is essential to mention that implementing micro-grids could promote economic growth, so rural and remote communities are impacted in a positive manner. However, the use of decentralised generation units is a technological challenge that requires to develop new technologies and economic regulations.

2 Micro-grids

2.1 Operation of Micro-grids

The operation of a micro-grid can be based on several features such as the connection scheme, environmental, technological and economic factors. This aspect defines the actions and participation of the micro-grid and stakeholders in activities such as the power exchange, energy security, economic, clean energy integration, pricing conditions of trading profit and ancillary services to mention some. The combination of the economic, environmental and technological aspects offer a solution to the optimal dispatch problem in the distributed generation (Hatziargyriou 2014).

The environmental aspects are determined by the emission quotas, and do not take under consideration the financial or technical aspects. Recently, there are new formulations related to the development of various policies, which are focused on increasing the promotion, development and implementation of renewable energy generation and distributed generation in order to reduce the dependency of electrical energy produced by fossil fuels resources. Nowadays, it is suggested the development of new policies, regulations, and incentives related to the micro-grid use, this with the main objective of increasing their penetration and implementation. The increment and utilisation of distributed energy will enable the reduction of the impact caused by the fossil fuel use.

The economic aspects are concentrated on minimising the total costs neither taking in consideration the performance and impact of the grid nor the environmental aspects. The infrastructure of micro-grids can provide a cost reduction because it is able to avoid the investment in the replacement and expansion of transmission lines, transformers and power plants. Moreover, the performance of micro-grid enables the increase of efficiency due to reduced congestion and line losses, distributing directly the power generated. The micro-grid can also provide ancillary services such as black start, reactive power and voltage control, power quality, frequency regulation and load following. The ability of micro-grids to emulate the inertia of conventional generation enables ancillary services and represent customer benefits.

The technical aspects are mainly concentrating on the losses, variations of voltage and device loading without considering environmental or/and economic aspects. Such features are related to the physical connection which is classified like the connected mode, transition-to-island mode, island mode and reconnection mode. During the operation under the aforementioned schemes, the solutions deal with the minimisation of losses, voltage stability, distribution system operation, control and protection in each mode in order to provide and offer a stable and high quality in the energy supply. The control system is designed to ensure the operation in the modes of connections.

2.1.1 Environmental Objectives

The power generated by the conventional power plants is transmitted along large distances in order to cover the electric demand. The transmission lines are commonly used to transmit over large distances high amounts of power. However, their installation generates visual inconveniences, communication interferences, and can represent a danger to low flying aircraft. In addition, there are health problems which might be provoked by the lines related to electromagnetic radiation.

The use of fossil fuels in the conventional process of electricity generation has an important participation in the production of greenhouse emissions to the environment. The environment is affected by several factors such as air pollution emissions, water use and discharge, waste generation and land use, which are derived by the conventional electricity generation. As a result, there are strong concerns in worldwide about the climate change and global warming.

The penetration and promotion of renewable energy technologies and installation have gained interest since they can help to reduce the production demand for electricity produced by the conventional processes. Micro-grids are characterized by the use of renewables to produce electrical energy. The adoption and use of micro-grids result in several benefits such as the increased efficiency, reduction of greenhouse emissions, minimization of health risks and conservation of the resources.

2.1.2 Economic Objectives

Energy markets operate according to several layers of complexity which are delimited from the completely regulated to completely liberalised models. Thereby, the generation and retail are considered as competitive activities, and the transmission and distribution as regulated activities. In particular, the wholesale market and the retail market are two major markets which deal with the trade and supply of energy. These markets can work with each other by way of group or/and via two-sided. An open transmission access to producers and energy importers has established a competitive wholesale market. On the other hand, the competition at the retail level is given by several options and offers in the supply and electricity cost.

There are different stakeholders involved in the energy market such as the consumers, distributed generation owners or operators, prosumers, market regulators, retail suppliers, energy service companies, distribution system operators and micro-grid operators. The consumers are persons or institutions that pay for the use of energy, the producers also called distributed generation owner or operator inject the energy produced to a network of distribution. The prosumer is a definition related to a customer that can deliver energy as well as consume energy. A market regulator is an authority to establish a correct and transparent operation of the market. The retail supplier/energy service company (ESCO) establish a contract to customers and can acquire energy from the wholesale market or spot market or local production. The distribution system operator (DSO) is the entity in charge of the operation, management, maintenance, regulation, and growth of the distribution network in a determinate area. In addition, DSO play an important role since providing a field neutral as market facilitators. Lastly, Micro-grid operator has in charge the same role of DSO in a local distribution network produced by the micro-grid.

The micro-grids are financed by facility owners as institutions and campus, which can use the distributed system infrastructure in order to reduce their installation cost. However, the relatively small size of a micro-grid limits their direct participation in the wholesale market or retail market. Hence, there are models that enable the micro-grids participation, which can be as part of a portfolio of a retail supplier or an energy service company, as well as the Direct control of DERs by DSOs. In this context, four scenarios have been proposed in order to generate a market decentralised structure to the micro-grid resources ownership such as ownership by the DSO, ownership by the end consumer or even consortium of prosumers, ownership by an independent power producer, and ownership by an energy supplier in a free market arrangement. In the same way, the participation of prosumer and integrate the energy prosumers under the next schemes peer-to-peer, prosumer to grid, and prosumer community.

The use and adoption of DSO, as well as the agreements between suppliers and DSOs, will enable major benefits to the customers by means of an adequate market, smooth process, local stability, reliability and security in the supply of energy.

2.1.3 Technical Objectives

The technical features are related to physical constraints such as the micro-grid capacity, energy balance, power loss, and reliability. In this sense, the levels which can be adopted by the micro-grid are divided into four and they are listed from zero to three. The zero is called inner control loops which adjusting the output voltage and control current while keeping the system stable. The first emulates the physical behaviours which produce a stable system and it is called primary control. The second or secondary control is in charge of supervising and guaranteeing the limits of the electrical values and it includes the management of the control loops to realize a seamlessly connection or disconnection of the micro-grid to or from distribution system. The third level involves the power flow control between the micro-grid and the main grid and it is also called tertiary control.

The micro-grid can operate by several modes, which are defined under certain ranges and operating points and it also provides active and reactive power to supply their loads or to be transferred to the main grid, this transfer is carried out without affecting the system stability. The micro-grid can operate as an island mode or grid-connected mode. The island mode is characterised by the stand-alone operation of the micrognids, auto-satisfy their loads. The island mode supplies the local demand since it is able to produce its own energy. In order to ensure an uninterrupted supply, the island mode prioritises the supply to the crucial, important and critical loads.

The grid-connected mode is described by the connection and exchanges between the micro-grid and the distribution system via PCC. In this mode, the distributed generators and storage system are synchronised according to the reference values of frequency and voltage provided the grid. Lastly, the transition mode is an important condition in order to reduce the power losses, since a smooth transition can reduce the aforementioned power losses which happen during this process.

2.2 Control of Micro-grids

There are several features from the literature that can describe and classify the objectives of control or functionalities. The droop control, voltage and frequency regulation, power sharing, energy management system (EMS), micro-grid optimisation and interaction between micro-grids are the main and important concerns related to micro-grid operation.

The droop controls simulate the process of energy demand in a conventional power system. During this process if the active power increases a frequency droop is provoked. Conversely, when the frequency increases then the active power falls, and, in the same manner, a similar effect occurs between the reactive power and the voltage's amplitude. A conventional power system is integrated through the use of huge synchronous machines with large inertia. The DERs are integrated into the grid by micro-grids and the micro-grid interface DER sources through inverters. The island mode in a micro-grid is represent by a scheme of multiple inverters connected in parallel.

- Centralised: The droop control has been designed to have a parallel operation of DERs inverters which work as in the island mode and grid-connected mode. During the island mode the controller works under voltage control mode and when it is connected to the grid it works in current control mode.
- Decentralised: In this scheme, the droop control is the most commonly implemented. The controller design takes into account the voltage-frequency control and power sharing using three loops which are nested. The first regulates the output voltage in the inner loop, the second is the loop of the output resistive impedance, and the third is the external loop to share active and reactive power

- Hierarchical: The proposals and use of droop controller are limited.
- Distributed: The coordination between the primary and secondary level in order to reach a proper power sharing and frequency synchronisation are the main recent proposals. The main concerns are the effect of communication delays and loads balance.

The objective of the voltage-frequency control is to reduce the effect generated by the small and large fluctuations in system frequency and voltage. The controller's objective is to hold the micro-grid within operation limits to the micro-grid in order to reduce the stability problems, distorted power quality and equipment failures.

2.2.1 Intelligent Local Controllers

Integration of control systems in micro-grids (MGs) is essential to guarantee reliability when MGs are working in connected and/or island mode. The control systems regulate voltages and frequency to maintain the operation of micro-grids within nominal values. Also, the power flow inside a micro-grid or between micro-grids, is under the care of the control system. The task of control systems operating in MGs are the following (Hirsch et al. 2018): to make the micro-grid a single self-controlled unit capable of providing frequency control; limiting the power flow within line ratings; to adjust frequency and voltage within admissible values, when the MG is working in island mode; to keep energy balance by means of the management of resources: and, to smoothly connect, disconnect, synchronise, and resynchronise, the MG with the electric grid.

2.3 Control Architectures

In order to accomplish the aforementioned tasks, the following control architectures have been developed (Sen and Kumar 2018):

- Centralised: it is composed of a central controller, which receives information from all MG sensors, and then the computation and execution of control actions are carried by the central controller, and the control law and set-points are sent to each unit;
- Decentralised: in this architecture, a local controller is integrated into each unit, which collects both local information and global information such as neighbourhood controller actions, while system-wide information is disregarded.
- Distributed: the distributed architecture is similar that decentralised, the main difference being that each local controller shares information with its neighbouring units, and then, a global management of the MG can be achieved while the autonomy of each unit is preserved.

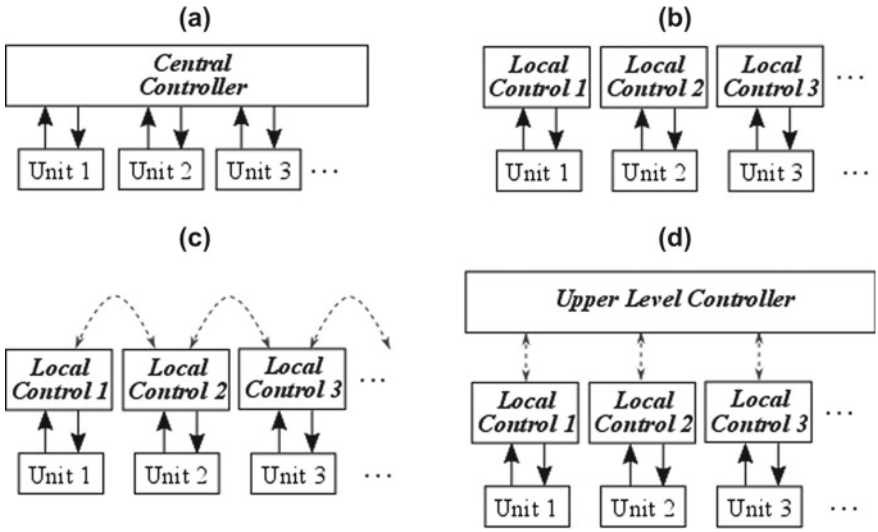

Fig. 1 Schematic diagrams of MG control architectures

- Hierarchical: this architecture defines a control structure divided into layers, usually three, segmented in accordance with time scales, which correspond to the time of execution and time of application of the control signals.

The schematic diagrams of each control architecture are presented in Fig. 1.

Considering MGs are conceived as the main element of smart grids, MGs have to work either in islanded, connected, or interacting mode. Thus, the combination of more than one control architectures is required, since hierarchical architecture has the advantage of integrating centralised, decentralised, and distributed control schemes to accomplish the MG targets of smart grid conception.

2.3.1 Hierarchical Control

Hierarchical architecture is composed of three control levels named primary, secondary and tertiary. The primary control interacts with the inner control of the distributed units, including the virtual inertia and regulating output impedances. The secondary control deals with frequency and voltage fluctuations caused by changes in the output impedances. The tertiary control is in charge of the power flows between the electricity grid and the MG at the PCC. A scheme of the hierarchical control is presented in Fig. 2, and more details about the control levels are given in the next subsections.

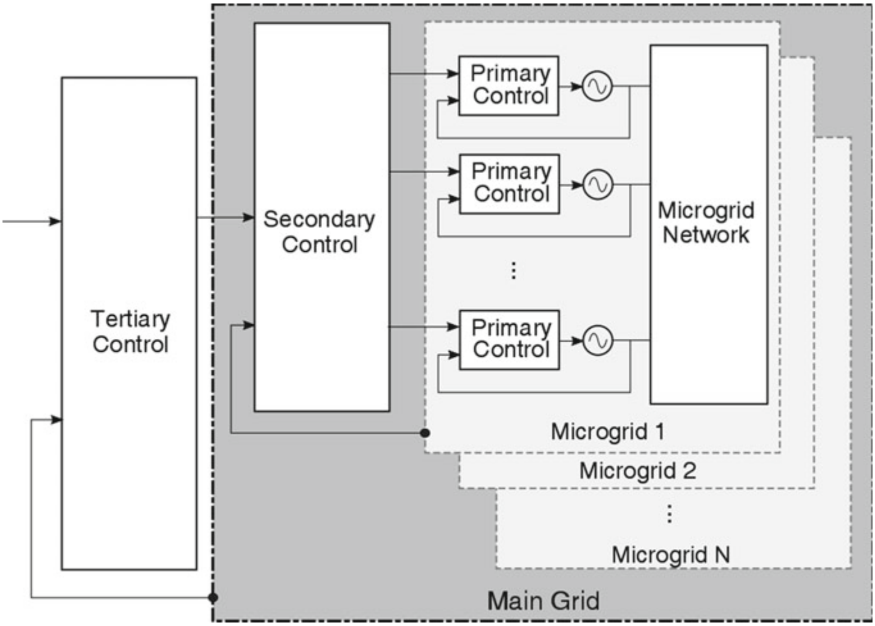

Fig. 2 Hierarchical control scheme

Primary Control

Primary control works with local measurements, has the fastest response in the hierarchical architecture, and is integrated locally inside each unit. The tasks of primary control include output control, power sharing control, and islanding detection.

The control actions are executed through intelligent power interfaces: voltage-source inverters (VSIs) and current-source inverters (CSIs). Output control consists in regulating current and voltages at the output of the power interface. Power sharing control deals with the regulation of reactive and active power by employing local measurements since voltage and frequency control are used to operate reactive and active power, respectively.

In this control level, the integration of virtual inertia is mandatory to emulate the behaviour of synchronous generators and compensate frequency deviations caused by lack of inertia in power interfaces.

Secondary Control

Secondary control is responsible for two tasks, to: drive to zero any frequency or voltage deviations produced by primary controls, or changes of load and generation in the MG; and guarantee a secure, reliable and economical operation of the MG. Due to the second task, the secondary control is also considered an energy management system (EMS) (Olivares et al. 2014).

When MGs are operating in island mode, the secondary control becomes the highest level in the hierarchical architecture, which is related directly with the EMS. Secondary control must manage the generation units to compensate for fluctuations in loads, the intermittency of generation, and the availability of energy in the storage systems.

Tertiary Control

Tertiary control is in charge of the organisation of multiple MGs when collaborating. Also, the power flow between the MG and the electricity grid is managed by tertiary control. Economic issues, such as economic optimisation by means of energy prices and electricity markets, are commonly considered to come under tertiary control.

When, the optimisation process is considered at this level, it refers to power flow optimisation and energy optimisation (Vandoorn et al. 2013). In power flow optimisation, the target is optimised by reactive power online. For energy optimisation, forecasting of generation and load is employ to optimize the energy with respect to energy cost.

3 Power Converters in the Micro-grid

The control actions required for any of the control levels presented in Sect. 3.2 come from a power interface, which is a power converter. Then, the power converters in the control of MGs are indispensable elements.

Power converters are capable of working as current-source inverters (CSIs) and/or voltage-source inverters (VSIs). CSIs are composed of an inner control loop plus a phase-lock loop to synchronize the CSI with the electricity grid. VSIs are the cascade of two control loops; the external one to regulate voltage and the internal one to regulate current. VSIs are employed in island mode whereas CSIs are used in grid-connected mode.

Power converters in MGs are classified as: grid-forming, grid-feeding, and grid-supporting (Rocabert et al. 2012; Schiffer et al. 2016), and are described in the following subsections.

3.1 Grid-Forming Inverter

Grid-forming works as a VSI composed of an inner loop to regulate the current and an outer loop to regulate voltage. The inner loop employs the current measured from

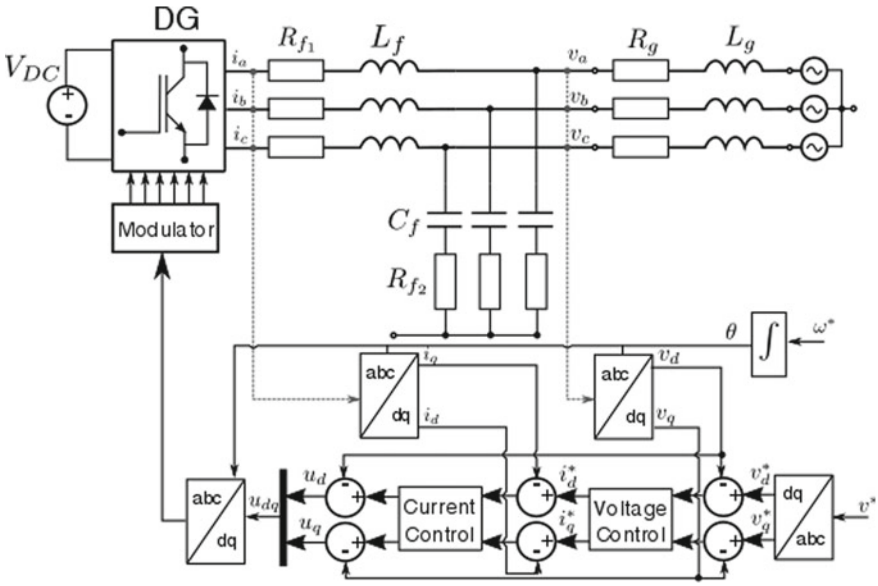

Fig. 3 Schematic of grid-forming

the filter inductance whereas the outer loop uses the voltage measured at the output of the inverter, see Fig. 3.

In primary control level, a grid-forming inverter is employed to regulate frequency and voltage when the MG is working in island mode. The secondary control level uses a grid-forming inverter when variations of voltage or frequency occur during the changeover between island and grid-connected mode. The objective is to resynchronise amplitude, frequency, and phase angle with respect to the electricity grid, before reconnection.

3.2 Grid-Feeding Inverter

The grid-feeding inverter regulates active and reactive power at predefined set-points received from energy management systems or higher control levels. This is also known as PQ control, or grid-following. Similar to grid-forming, grid-feeding is composed of a cascade of two control loops; the inner one is a current loop whereas the external one is a power loop, see Fig. 4.

In the hierarchical architecture, grid-feeding inverters are part of the primary, secondary, and tertiary controls. When generation units work under MPPT (maximum power point tracking) techniques, the grid-feeding inverter receives the references of power, P* and Q*, from the MPPT algorithm.

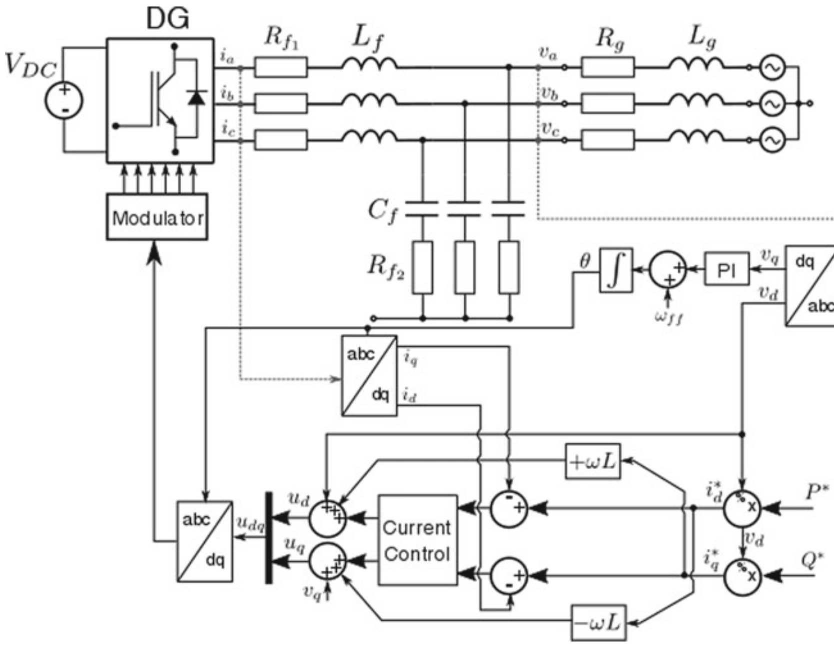

Fig. 4 Schematic of grid feeding

Under secondary control, the grid-feeding inverter takes the references of active and reactive power, P* and Q*, respectively, considering the capacity of the inverter, as well as the generation technology when the inverter is linked.

Since tertiary control deals with the optimal operation of the MG from an economical perspective, then, considering the cost of the energy generated by each type of generation technology, tertiary control provides the power references to the grid-feeding inverter.

3.3 *Grid-Supporting Inverter*

A grid-supporting inverter is capable of working either as a VSI or a CSI, following same target in both cases i.e. to regulate voltage amplitude and frequency via the reactive and active power injected into the grid. As presented in (Schiffer et al. 2016), the grid-supporting inverters are grid-forming with an external loop that includes droop controls to compute voltage set-points, see Fig. 5.

Grid-supporting inverters are integrated in primary and secondary control levels. For primary control, the grid-supporting inverter is used to regulate the phase angle, frequency, and amplitude of the voltage. On the other hand, when a grid-supporting

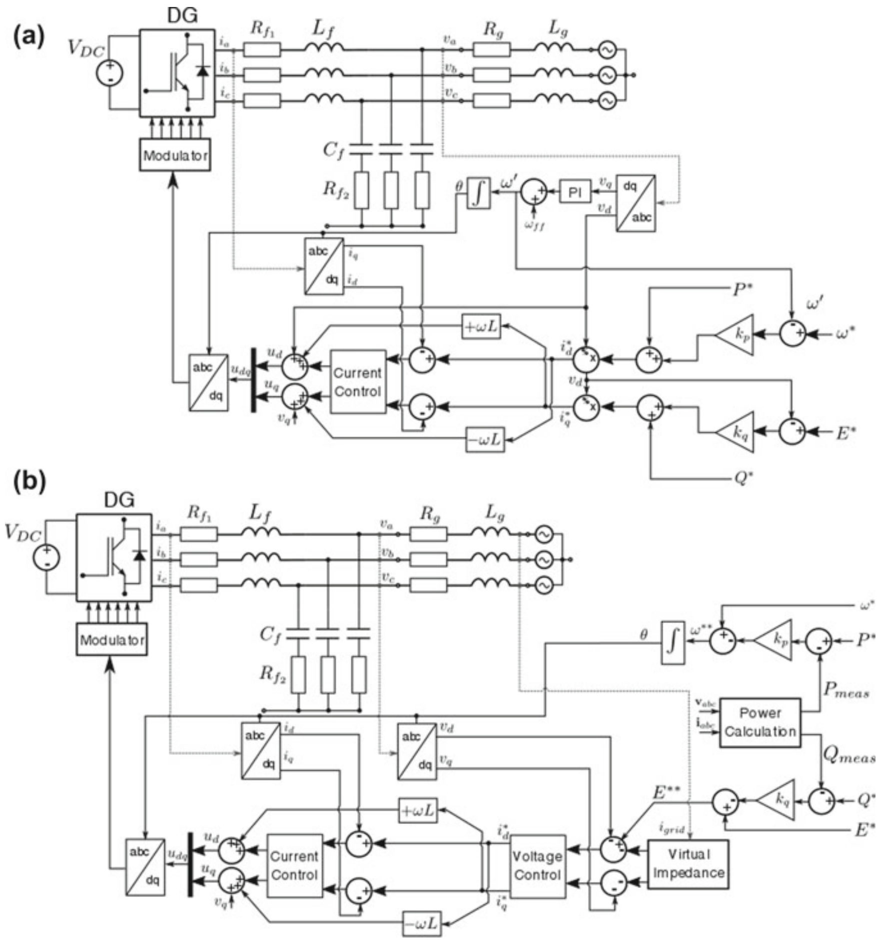

Fig. 5 Schematic of grid supporting as a: **a** CSI and **b** a VSI

inverter is employed in the secondary control, the frequency and voltage are adjusted by means of the references P* and Q*.

4 Protections

It is clear that MGs are different from the traditional electricity grid: their usage as distribution nuclei; the integration of Distributed Energy Resources (DERs); DERs can be inverters in micro-grids that also inject harmonic content into the MGs as well as the main grid; and, their constant monitoring set an obvious step towards a modern usage of electric power. However, such changes are normally discussed assuming ideal operation of the MG components, or from a superficial approach to power management, disregarding the challenges in protecting the MG. Among the differences between MGs and the traditional grid, electrical protection is perhaps the issue requiring most changes in order to enable safe and reliable operation (Kang et al. 2017).

There are several situations during the MG's operation that necessitate advanced protection capabilities; curiously enough, such added requirements are entirely related to the MG's expected benefits. This makes the protection systems not only necessary for the MG's conservation, but for its overall operation (Zamani et al. 2014). A MG is expected to be either connected or not to the main grid, to enable the "transparent" integration of DERs, and to isolate faults, etc. Such expectancy necessarily comes with added complexity, as is pointed out next (Hatziargyriou 2014):

- A grid-connected MG is susceptible to grid-side and MG-side faults
- Whenever a MG is connected to the main grid, the available fault current is larger than if disconnected
- The fault current's direction may change depending on the MG topology under fault
- Integrated DERs exhibit specific electrical dynamics which introduce uncertainty to magnitude and time thresholds
- The MG topology changes without prior notice when devices are added or removed
- The contribution of the DERs to the fault events depend on variable conditions such as sun irradiance, wind speed, and so forth
- MGs are supposed to cope with the grid codes during faults.

From a traditional point of view, protection systems rely on circuit breakers (CBs) associated with non-directional current-sensing devices. Taking into account the MG's distinctions, it is no longer possible to ensure adequate protection as one-time designed limits will seldom be useful in all the possible MG operating schemes (Kang et al. 2017; Zamani et al. 2014), and even less so for possible future scenarios. Indeed, the protection problem is not only related to non-tripping situations, but also to false-positives. Uncertainty precludes traditional design and, consequently, obliges novel proposals and enhanced protective devices (PDs).

Before describing the proposed solutions to MG protection, it is important to consider that any protection system is commonly assessed through the "3S" perspective (Hatziargyriou 2014): Sensitivity; Selectivity; and, Speed. Unlike instrumentation systems, sensitivity is related to the capacity of the protection system to identify a fault condition. On the other hand, selectivity involves near flawless disconnection of the faulty grid section. Lastly, an adequate speed is one which enables the protection system to react fast enough to avoid further damage to the protected grid.

For instance, the inclusion of DERs will directly cause a sensitivity problem for conventional protections, as shown in Fig. 6 This figure shows two short-circuit scenarios: the first one involving a direct grid-to-load short-circuit, causing the fuse (CB) to blow due to the current's magnitude; on the other hand, the addition of a generation parallel to the load would reduce the current's magnitude as seen by

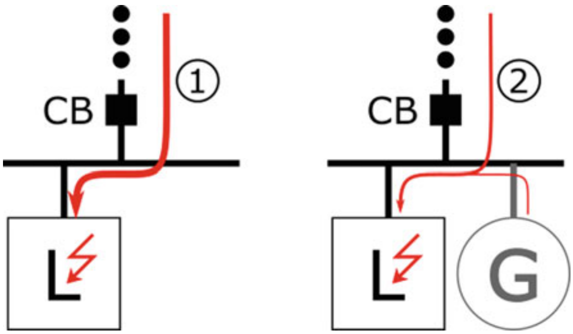

Fig. 6 The addition of a DER makes the traditional PD to fail in detecting a short-circuit

the CB, thus preventing protection. This sensitivity problem is also found when switching between connected and isolated modes, as the current availability will change depending on the presence of the main grid at the PPC.

Now, let Fig. 7 represent a radial network whose protection devices were originally designed to be unidirectional. Even if full switchboards (SB) are used at each branch, unlike the previous example, then a short-circuit may have very different implications whenever DERs are integrated. The fault shown in Fig. 7 should have tripped CB2, clearing the fault and permitting continued operation of the branch associated to CB1. However, as the added generator also contributes with current to the fault, CB1 or CB12 may trip. This clearly constitutes a selectivity issue.

Finally, the inclusion of high-power density devices, such as ultra-capacitors, commonly used in backup appliances, as well as in rotary machines, imply sudden current peaks during charging or starting, respectively. Those variations depend on the status of the MG, or at least on the power requirements of adjacent buses and branches. As changes in MG topology can come from user decisions, or unidentified CB or PCC connection/disconnections, the configuration of the related CBs may fail in considering transitory currents. This is a speed problem related to an incorrect or "naive" configuration of CBs in the presence of uncertainty.

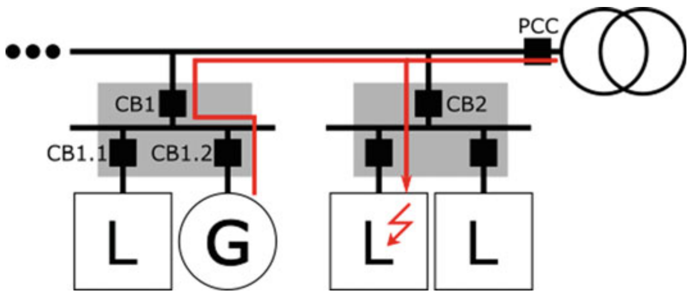

Fig. 7 Selectivity is also compromised if current direction is changed due to changes in the grid's topology

The above three examples are simple scenarios where the 3S approach to PDs is missed due to slight modifications to a traditional distribution grid. However, although MG protection implies added complexity and thorough planning, there are feasible alternatives for their effective operation. Such alternatives rely on non-conventional PDs, communication protocols, and infrastructure, and planning/management frameworks.

4.1 Protective Devices for Micro-grids

Protecting an MG is very similar to protecting a traditional but complex distribution network (Zamani et al. 2014). Actually, the devices used in MG protection are the same as those used in distribution protection tasks (overcurrent, distance, and differential (Brahma et al. 2014)), but including re-configuration and communication capabilities. If such high-level capacity is omitted and the electro-mechanical part is addressed on its own, their operation is very similar to the traditionally implemented PDs. Briefly, from a traditional point of view, an MG can be seen as a meshed distribution network.

All protective systems can be held to be comprised of an instrument, a processing unit, a decision-making engine, and a CB. The instrument is responsible for measuring the physical variable of interest, namely; voltage, current, frequency, etc., while the processing unit converts the acquired variables into meaningful inputs to the decision-making engine. The decision-making engine consists of one to several criteria, which can be time-dependent, and it normally works in an *if–then* fashion to determine the resultant state of the CB. Even old electro-mechanical PDs can be described in such terms, sometimes combining the aforesaid components into single mechanisms.

Mostly, faults are related to short-circuit conditions, thus making the current PDs the first line in MG protection. Non-directional current PDs, such as those meeting the ANSI 51 standard, can be incorporated at the load-only endpoints; or where a load-only radial distribution is followed inside a MG. Fuses and thermo-magnetic devices can be used safely when there is certainty about the current direction during a short-circuit; standard overcurrent CBs can be also used. Otherwise, directional overcurrent protections should be used, such as those conforming to the ANSI 67 standard.

Sometimes overcurrent PDs are not enough for effective protection as they depend on the source impedance, which is likely to change in MG operation (Kang et al. 2017). A schematic representation of this problem is shown in Fig. 8: changes in the supply side also change the fault current, independent of the distribution network and the load itself. The overcurrent PD can be directional or not, thus making no difference.

Distance protections sense both, voltage and directional current to compute an equivalent forward impedance. Tripping conditions are then established in terms of allowed impedances rather than current values. Usually, distance protections are used

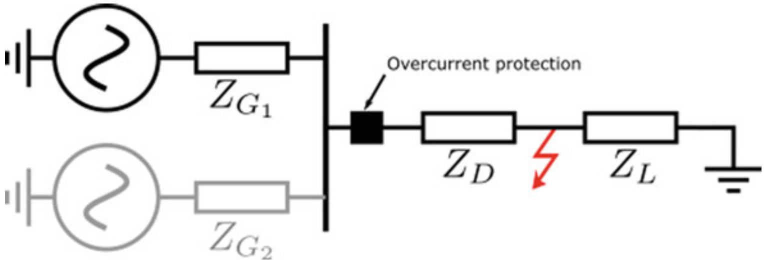

Fig. 8 Distance protection is required when source impedance may account for missing overcurrent protection missed or wrong tripping

in transmission lines whose impedance notably changes with respect to length; therefore, enabling this protection not only to detect a fault but to estimate the distance at which it occurred, hence the name. Independent from its habitual use, distance protection eliminates problems related to source impedance variations, thus enhancing sensitivity.

A distance protection (ANSI 21) will effectively account for faults in transmission lines because their impedance will seldom change and their power flow is determined from supply to loads. However, their application in MGs may also find difficulties as the foreseen impedances may change, and the integration of DERs preclude a clear identification of a "supply side," modifying the impedances of both sides of the PD. Nevertheless, distance protections extend the capabilities of the protection system beyond the effectiveness of sole overcurrent PDs.

Both of the revised PDs can identify faults *from* a given geographical point but cannot isolate their detection capabilities to a given area or grid section: a much-appreciated capability in MG operation. If ever local directional protection is not required, a differential PD must be used. These devices make two measurements, in respect of a given device or bus section, in order to detect input/output differences which can indicate a fault condition (Kang et al. 2017). Provided that the local conditions are known, the protection can be configured for known requirements and effectively trip if needed, ensuring selectivity. Differential PDs comprise the ANSI 87 standard.

A differential PD is normally distributed among different appliances, i.e., the instrumentation is not necessarily attached to the processor, nor the associated CBs. This configuration requires a reliable communication channel among its components to work properly. This link must be also fast to enable actual protection. This particular issue makes the use of supporting PDs mandatory, enabling the protection of specific devices, such as transformers and rotary machines, as their inputs and outputs are not distantly distributed.

None of the above protections is useful for MG protection in their conventional form. The aforementioned uncertainty regarding the MG topology is a major hindrance to the efficacy of protection systems. Thus, it is important for the incorporated PDs to be re-configurable and allow digital communication. Such characteristics are normally provided in microcontroller-based protection and automation systems. Ultimately, and as expected, these requirements come together in the MG's overall provision regarding sensing, communication, and automation capabilities.

4.2 MG Protection Techniques

It is now clear that a fixed, traditional, approach to MG protection would perform deplorably. Broadly speaking, its benefits come together with topology uncertainty and generation/load variability, as the MG changes stochastically. This inherent randomness means that any attempt to define a robust location and configuration of PDs is doomed to failure, while the developed alternatives involve the adaptability of the protection system.

This approach is commonly referred as "adaptive protection" (Kang et al. 2017), and involves the re-configuration of PDs settings, either continuously, or dependent on detected discrete states. Such re-configuration involves modification of protection thresholds and delay times, depending on the known/detected MG state. Due to the integration of DERs and storage devices, additional information is required, namely; weather, consumption patterns, market signals, etc., entirely contingent on the MG's added complexity.

Mainly, there are two ways in which the adaptive condition can be attained (Hatziargyriou 2014): by pre-calculated states or by real-time adaptability. Both paths require all the PDs to be communicated, and that their parameters are accessible and modifiable by such means. In this way, the communication protocols used in MG protection become paramount, and their reliability and safety issues must be minimised, e.g., cybersecurity, loss of information, latency, noise, etc. Such characteristics can be found in industrial communication systems, commonly involving a Modbus protocol over an RS-485 bus.

Although this section does not focus on the communication itself, it is noteworthy that both wired and wireless alternatives exist to handle the expected connection. Communication latency at this level imposes no real restriction on the adaptive protection operation as the data transmission is only intended to configure the PDs, not to perform the protection itself. Detecting the current state of the MG and configuring its associated PDs could take a short period of seconds, not compromising the protective capabilities. For instance, the aforesaid allowance was derived at from the implementation of master–slave topologies based on individual polling of PDs.

The adaptive approach to MGs protection can be clearly visualised from two perspectives: centralised; and, decentralised. A centralised MG controller gathers information from all PDs and returns configuration signals to establish the specifically required protection scheme, depending on the detected MG state. A decentralised MG controller moves the decision-making process to multiple decision cells, distributed among intelligent[1] PDs. Such distribution relies on modules formed to give protection adaptability, based on local information rather than on the overall MG state.

It is important to notice that the above MG controllers are not those normally referred to when describing a MG; these are management controllers (MC). The management of MGs can be divided into hierarchical stages, and protection adaptability should be the lowest stage. This distinction is important as the management and control of MGs work in parallel, but the decision-making process regarding protection systems is a management issue, not an automatic control concern.

In this spirit, MG management can be divided into three complementary levels, namely; configuration, management, and external. The configuration level includes the MCs referred to above. The management level comprises the traditional tools and interfaces for distribution systems, including an historic record of MG operation. Lastly, the external level deals with complex decision-making inputs, such as the weather status, energy market prices, and business strategies.

4.2.1 Centralised Approach to MG Protection

The centralised approach implies a master-multi-slave topology comprised of one central MC (master) and many PDs (slaves). The interaction is commonly performed by sensing and configuring the MG through the individual polling of each PD. It is clear that depending on the size and intricacy of the MG, the central controller will demand more complex computational capabilities in terms of processing and communication. There are two ways in which centralised controllers can attain adaptability; namely, precalculated states, and online state estimation.

Precalculated States

The easiest way of establishing a centralised adaptive controller is perhaps by the exhaustive testing of the MG operation. This, of course, implies the analysis of every possible configuration and all its associated potential faults. Such analysis, commonly performed by means of simulation, is later arranged in a knowledge-base: a list comprised of the discrete estimation of the MG state and the expected configuration of the PDs (the actions table). The centralised controller performs a periodical assessment of all the PDs, finds the matching precalculated state of the MG, and sends the corresponding configuration back to the PDs.

A major concern about the preceding approach is that all tests are performed with a fixed topology of the MG, prior to its actual operation. However, topology changes can be foreseen and tested, so the knowledge-base includes not certain but possible operating conditions. In addition, potential changes of the MG nodes can also be considered. For example, the inclusion of a DER at some node can be anticipated.

[1] The term ‘intelligent’ here implies the use of embedded devices for digital processing and communications. It is not related to artificial intelligence.

On the other hand, a new set of simulations can be run once the MG has sufficiently changed or new PDs have been incorporated, and the new knowledge-base can then be transferred to the central controller.

delay times; it may actually include particular settings for specific PDs, contingent upon need. It should also include priority scales depending on the MG connections and the existence of critical loads. Maintenance and sub-grid isolation can also be considered in the knowledge-base, and triggered at the operator's request.

Online State Estimation

The online state estimation approach takes the principal functionality of the previously presented "pre-calculated states" technique, but adds real-time feedback. Such feedback is useful to test and further detect the MG state, given a set of adaptation rules. Briefly, the central controller modifies the configuration of the PDs to acquire their related electrical variables, and analyse the knowledge-base to check matching operating states, estimating neighbouring fault currents. If the fault criteria, based on the interaction of the PDs, are met, a trip would be generated, otherwise, the PD's settings are kept as they correspond to the current MG status.

Actually, this approach relies on the interaction of two subsystems: online; and, offline. On the one hand, the online subsystem is continuously assessing the PDs and comparing their status to a known condition, i.e., the discovered grid state. On the other hand, there is an offline process running the adaptation routine to discover that grid's state: the PDs related variables; the current's direction and limits are computed; and, a matching state in the knowledge base is found. Three cases can arise from this: (1) the settings remain unchanged as energy flow and PDs limits are congruent with the preceding state; (2) a new state is found and the tripping settings are communicated to the online process; or, (3) no state matches the MG's current conditions, representing an unknown status which must be prohibited.

It is noteworthy that the tripping signals depend on the centralised controller as changes must be evaluated respect of the offline subsystem. There must be some sort of communication between both subsystems which must be fast and reliable. Indeed, the decision between a state change, and a fault, is centralised, so the normal operation of PDs may be delayed. The communication problem hinders the application of this approach from spreading, broad MGs and focuses on local.

4.3 Some Notes on Decentralised Protection

Changes in the MG cannot be avoided and are the main reason for adapting the protection system. Topology modifications and fast integration of new DERs make these systems prone to failure if the protection system cannot cope with fast modifications. Admittedly, it is clear that the aforementioned techniques, relying on a centralised controller, will throw up many difficulties for complex MGs.

The decentralised approach offers a way to provide locality to MG sections, i.e., separate MG complexity, potential faults, integrated DERs, and communication burdens in individual subnetworks. Such locality then involves focused management of the protection system for a particular section of the MG, not (or barely) considering the neighbouring sections. The previously presented alternatives for adaptive protection systems can now be applied individually to each section, resulting in a decentralised protection system.

The obvious implication of this approach is that there must exist a controller per section, dealing with the local processing of the MG's protection. Industrial devices, such as PLCs and multipurpose intelligent controllers, can be used for this purpose. In comparison, there is not a centralised controller, and if there is, its protection duties would include (if needed) communication with decentralised controllers, the update of databases, the acquisition of environmental variables, etc.

Although a module version of the protection system may look like a simplification of the overall protective tasks, it must be considered that a centralised controller would deal with one main uncertainty source: the PCC. Similarly, a sub-grid will need to consider topology changes coming from "outside", but in this case it will not be one but many. Moreover, one change in the MG would affect different sections of it, requiring an effective way to account for such operating variations overall. Hierarchical communications and controllers would then be needed to cope with subnetwork interactions.

4.4 MG Protection Trends

Nowadays the problems related with MG protection are well-known and many different schemes have been developed to tackle them. Such proposals normally rely on the presented PDs and their novelty relies in the way they are integrated. Other proposals deal with novel detection systems integrated into traditional PDs as presented by Mishra et al. (2016) where an intelligent approach to feature extraction and decision making is presented. Overall, MG protection requirements are (Brahma et al. 2014):

- Detection and isolation of internal/external faults
- PCC effective disconnection in external fault condition
- Avoiding unintentional islanding
- Avoiding out-of-phase reconnection at PCC
- Layered protection for fault isolation
- Meeting S3 conditions.

Some of the works cited by Kang et al. (2017) deal with the incorporation of voltage-based protection systems, able to detect and clear faults as with current-based PDs because short-circuit conditions commonly come along with voltage sags. Admittedly, a clear trend in MG protection has been established in the ordered integration of different PDs and their management, yielding hierarchical and coordinated protection systems. These distinctions make the different PDs and their controllers to be distributed in protection layers: a primary layer is comprised of PDs with expected immediate response; and, backup layers intended to intervene if the former fail.

Complex MG topologies normally require different, systematic tests to validate one fault condition among many other potential faults. This has led to installing PDs redundantly, e.g., overcurrent, distance, and differential protections for the same MG section. Such PDs can also be coordinated directly or through an hierarchically-higher controller, so the protection is also enhanced by layering.

5 Recommendation for Implementing MGs in Mexico as the Main Factors Guide

Implementing micro-grids in a developed country could be very attractive since they could be deployed under several economic, social, and environmental conditions, such as rural communities or cities that want to become smart cities. Mexico has the opportunity to increase the generation, distribution, and consumption of electrical energy based on micro-grids. Besides, Mexico could dramatically increment the number of renewable energy sources in the main grid. However, there are factors that must be considered when deploying a micro-grid. Thus, the main factors for implementing a micro-grid have to be taken into account. The fundamental factors referred to provide some directions for their implementation (Akinyele et al. 2018), but only the main factors are dealt with here.

5.1 Social Factors

These factors include the participation of planners, developers, financiers, investors, government, and the community. In general, these parties can become involved during the system planning and development stages, but also in the course of the maintenance of the system. Besides, it is essential to know how to efficiently use and conserve energy, as well as having an understanding of how to maintain the equipment, by researching previous studies on these topics. The communities for whom a system is installed, do not necessarily assume ownership, so they expect the operation and maintenance to be the responsibility of the benefactor. Interaction with the community is required to establish their real requirements, and it must be carried out to avoid design failure. The list below shows the most important topics when planning a micro-grid.

- Increment community engagement
- General education about micro-grids
- Solve the question about the ownership
- Installation by qualified practitioners

- Practical preliminary survey
- High-level of social awareness
- Security of Infrastructure.

5.2 Technical Factors

These factors refer to the design, maintenance, standardisation, monitoring, and supervision of the system. It is required to consider the what-if or worst-case scenarios that could lead to insufficient power generation in the future. Preventive/corrective procedures are standard in solar photovoltaic systems that could be affected by dust, wiring losses, etc. Involving local expertise leads to fewer foreign experts who are not familiar with the local conditions. Adhering to international security standards avoids system failure within a few years after installation. The use of sub-standard materials to make the installation cheaper, lowers the lifespan of the system is not the correct way to design a micro-grid. Monitoring and maintaining rural micro-grid systems assiduously, obviates the number of system failures due to a lack of proper preventative measures. Some of the fundamental factors to consider are presented below.

- Appropriate complete design
- Follow standard maintenance procedures
- Local skilled practitioners
- Conformity to international standard codes
- Use standard materials
- Adequate knowledge of renewable energy
- Complete monitoring systems
- Constant project supervision.

5.3 Economic Factors

Any financial partner of the project has a fiscal responsibility, subject to a failure factor. Governments may support and promote renewable energy systems, however, communities do not usually assume ownership of donated systems, so the financial responsibility for the systems fails. Replacing micro-grid components represents a high cost that, in a financially unhealthy community, could lead to failure. The list below illustrates the primary factors that have to be integrated as economic factors to deploy micro-grids.

- Financial support by the government
- The question of who takes the financial responsibility has to be addressed at the beginning of the Micro-grid project
- Entire financial framework
- Plan revenue generation

- Consider the high cost of component replacements.

5.4 Environmental Factors

The environmental aspect is a vital part of a sustainability ecosystem: A comprehensive analysis of the location's energy resources is fundamental when planning a micro-grid; Environmental impact assessment for evaluating the implications about the environment for the proposed energy source; Renewable energy mistakenly taken to be impact-free environmental technologies; and, characteristics such as life cycle, correct disposal, and so on, should be considered. The following list includes the main environmental factors that have to be addressed.

- Comprehensive energy resources assessment
- Planned environmental assessment
- Environmental Awareness.

5.4.1 Policy Factors

Policies that work with social, technical, and economic factors are integrated into this section. Some examples of existing policies are feed-in tariffs (FiTs), feed-in premiums (FiPs), net metering/net billing, tax credits/incentives, etc. Governments are the dominant player in the promotion and application of micro-grids; therefore, their political will, stability, and certainty is an essential factor. Ineffective regulatory frameworks for the renewable energy market are a significant obstacle to the growth of micro-grids. Thus, a list of policy factors that have to be considered when a micro-grid is installed is presented below.

- Effective Policy Initiatives
- Political will for widespread application
- Effective frameworks that encourage the private Sector
- Accurate communication channels with society.

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Chapter 8
Current Trends and Challenges in Sustainable Generation, Transmission and Distribution of Electricity

Jonathan Carlos Mayo-Maldonado, Jesús Elías Resendiz-Valdez, and Julio César Rosas-Caro

Abstract This chapter addresses the technical aspects of electricity in the whole overview of energy sustainability treated in this book. Whereas in other chapters the reader can find general aspects regarding market dynamics, energy harvesting, alternative sources of energy and policy aspects; here the Authors concentrate on discussing the new technological challenges associated with modern electrical systems. We discuss the technical challenges involved in the development of a new generation of power grids, also known as smart grids. We summarise some of the main emerging issues derived from the integration of renewable energy from the electrical engineering point of view. We also elaborate on the technical challenges in decentralised energy generation; the new scenarios in the transmission of electricity that foster developments such as high-voltage direct current systems; and issues in distribution networks with a high penetration of renewable energy.

Abbreviations

AC	Alternating Current
DC	Direct Current
DG	Distributed Generation
FACT	Flexible Alternating Current Technologies
HVDC	High Voltage Direct Current
ICE	Internal Combustion Engine

J. C. Mayo-Maldonado (✉) · J. E. Resendiz-Valdez
Tecnologico de Monterrey, Campus Monterrey. Av. Eugenio Garza Sada Sur No. 2501, Colonia Tecnológico en Monterrey, C.P. 64849 Monterrey, Nuevo León, Mexico
e-mail: jcmayo@tec.mx

J. E. Resendiz-Valdez
e-mail: jesuvaldez@tec.mx

J. C. Rosas-Caro
Universidad Panamericana, Campus Guadalajara, Álvaro del Portillo 49, Granja, 45010 Zapopan, Jalisco, Mexico
e-mail: crosas@up.edu.mx

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IGBT	Insulated-Gate Bipolar Transistor
LED	Light Emitting Diode
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor
MPPT	Maximum Power Point Tracking
PLL	Phase-Locked Loops
PMU	Phasor Measurement Units
PV	Photovoltaic

1 Introduction

Over the last decades, the development of a new paradigm for energy generation, transmission and the distribution of electricity has become a pressing research question, and a policy issue, related also with technological and commercial themes. Issues such as the urge to reduce CO_2 emissions, the development of lower cost semiconductor and photovoltaic devices, the compelling advantages of renewable energy generation and the undesirable power losses in complex transmission lines, is increasingly motivating the development of distributed energy generation systems based on renewables. However, the intermittent nature of renewable energies is reflected in the characteristics of the voltages/currents (e.g. amplitude and frequency) provided by transducers, prompting regulation of such variables to satisfy the nominal requirements of the loads and the grid (Ali 2013).

Moreover, a decentralised, sustainable and reliable electrical system is an issue that is prompting technological development in all voltage levels, e.g. low voltage at residential photovoltaic generation, medium voltage at medium in distributed generation in the form e.g. of solar plants and high-voltage, e.g. in the form of largescale windfarms and high voltage direct current (HVDC) converters for transmission lines (Ali 2013). In this chapter we discuss the current shortcomings and opportunities in generation, transmission and distribution from the electrical engineering point of view. We examine the current ways as well as their limitation and promising technologies that, when mature, can overcome the current scenarios of increasing demand of sustainable energy.

2 Generation

Electrical energy has been generated for more than a century by means of rotational machines. Traditionally, the generation process involves energy conversion from a primary energy source such as gas, coal or wind; to a mechanical force that is finally used to rotate the shaft of an electricity generator. The electrical energy generation process is the first stage of the electrical energy supply chain and is usually carried out in power plants by commercial energy companies (Murty 2017; Von-Meier 2006).

Nowadays alternating current (AC) electricity is mostly produced using three-phase generators known as alternators or synchronous machines (Murty 2017; Stein 1979). An alternator has a three-phase winding fixed in the stator while the electromagnetic field is produced in the rotor by a direct current (DC) coil that is feed through a set of rings and brushes. When the rotor is spinning, a rotating electromagnetic field is produced, the coils in the stator cut the magnetic flux, producing an induced voltage is induced across its terminals. The induced voltage mainly depends on the magnetic field strength of the rotor windings, the number of turns of the stator coils, and the speed of the rotor.

A power plant can have several generators connected in parallel, operating simultaneously. Also, several power plants can be connected to the same power system. To make this happen, the generators must have exhibited the same voltage, frequency and phase sequence. The process to connect a generator to the electrical grid is known as synchronisation. One of the benefits of using synchronous generators in power plants is that once the generator is synchronised, it remains tied to the grid frequency and voltage since in steady state its angular electrical and mechanical velocities are equal (Murty 2017; Stein 1979).

The electric power by a power plant is generated at large scale in the order of Megawatts (MW). This type of facilities is usually located at the border of cities due to land requirements, the required resources and the contaminant emissions and waste. There are different types of power plants and their classification mainly depends on the kind of fuel that they use to produce electricity (Nasar and Trutt 1998). In the following we discuss a simplified classification.

2.1 Thermoelectric Power Plant

This type of power plants is the most common. In cogeneration plants, thermal energy that remains after an underlying process, can be used for other productive processes, which allows taking advantage of the energetic resources. There exist three main classification for thermic power plants (Murty 2017; Von-Meier 2006):

- By primary energy source.
  - Fossil fuel: coal, gas.
  - Nuclear: Uranium 235, plutonium 239.
  - Biomass: sugar cane bagasse.
- By primary machine.
  - Steam turbine.
  - Gas turbine.
  - Internal combustion engine (ICE).
- By utilization purpose.
  - Base demand.

– Peak demand.
– Load tracking.

2.2 Hydroelectric Power Plant

This type of plants takes advantage of the potential energy of the. The water flow is used to move turbines coupled to electric generators. These power plants have much lower energy production capacity than thermoelectric plants (Ali 2013; Barton and Infield 2004).

2.3 Wind Power Plants

Wind power plants, usually known as wind parks or wind farms, are large land spaces in which wind turbines are installed. The turbines are based on electric machines coupled with a mechanical transmission and a set of blades, which are moved by wind. In these parks, energy is directly generated without using combustion. The location of wind parks is one of the most important issue, consequently, places with high wind resource potential offer better conditions for electricity generation (Boyle 2012; Nelson and Starcher 2015; Wengenmayr and Bührke 2012).

2.4 Photovoltaic Power Plant

In a photovoltaic (PV) park, sun light is converted into electric energy (direct current) by means of semiconductor devices that are clustered and interconnected in which is known as a photovoltaic panel. In a PV park, hundreds and even thousands of PV panels are connected forming different series–parallel arrays. Additional power electronics converters are required to inject the power generated by the PV arrays to the grid. As in the case of wind farms, for a good amount of electricity generation, it is required to locate the park in a good solar potential region (Boyle 2012; Wengenmayr and Bührke 2012).

2.5 Current Trends

Most of the electricity generated around the world is produced using thermic processes. It can be considered, that the most efficient option in this case is the combined cycle plant. In Mexico most of the electric energy is produced by combined cycle plants. This plant uses a gas turbine combined with a steam turbine, both coupled to an electric generator to produce electricity. The use of gas and steam turbines allows to increase the overall efficiency of the power plant compared to traditional thermoelectric plants. Solar and wind installations produce a significant amount of electricity without burning fuels, however these technologies are not completely mature and still require research efforts (Boyle 2012; Nelson and Starcher 2015).

As the electric energy demand increases, new technologies for electricity generation and challenges arise. Recent policies related to the environmental impact caused by burning fuels have also re-shaped the way in which part of electricity around the world is generated. That is also the case of México, where new policies have established the required increase of electric energy production by means of renewable resources.

The new trends in electricity generation includes the use of solid-state power converters to connect electric energy sources to the grid. That is the case of most of the renewable sources like photovoltaic (PV) and wind energy. In the case of PV installations, power converters accomplish two important tasks. First, they are required to exploit the maximum power capability of the solar panels; this allows operating the system with overall increased efficiency. Second, power converters are required to change the parameters of the electricity coming from the solar panels, this is because PV panels generate DC current, which requires conversion to AC to be compatible with the grid (Blaabjerg et al. 2004, 2006).

The two mentioned tasks can be implemented in two power conversion stages. The first one known as DC-DC converter is the responsible of integrating the maximum power point tracking (MPPT) capability. The second stage is known as DC to AC converter (i.e. inverter) which transforms DC to AC, and is responsible of the synchronization process and injection of electric power into the grid. In some cases, all these tasks are performed by a single DC–AC stage, this allows to reduce the operating cost and increase the efficiency of the system (Blaabjerg et al. 2004; Katiraei and Iravani 2006).

In this type of converters, the synchronisation process is carried out by algorithms, usually called phase-locked loops (PLLs). These algorithms must run continuously in order to guarantee the synchronisation between the grid and the power converter (Lawder et al. 2014). This is the reason why this type of generation, based on power converters, is called non-synchronous generation. Indeed, the development of PLLs is one of the current challenges involved in the design of grid tied power converters. The reason is that in order to be able to synchronise the generated AC voltage, the PLL is required to sample the AC grid voltage, which in some cases is polluted with harmonics or is affected by unbalances and other perturbations, which complicates the synchronisation process.

Another relevant trend is distributed generation (DG). This is the term used to designate the injection of electric power into the distribution grid, close to the consumers or load centers location. Most of the times the DG energy comes from intermittent renewable energy sources like PV installations or wind turbines, although DG also includes the energy generated by means of thermic cycles like internal combustion engines (ICE) (Blaabjerg et al. 2004, 2006; Katiraei and Iravani 2006).

In the last years, the DG has had a considerable proliferation into the distribution grids and it is expected that this tendency will keep for the next 30 years. This propagation of distributed generators obeys several factors, some of them are listed here:

- The development of new technologies related to renewable sources and power converters.
- The advent of policies related to the use of clean sources to generate electricity and the deregulation of the markets.
- The restriction to build new transmission lines or to increase the power capability of lines already built.
- The increase in the power demand and energy consumption.

There are several advantages in distributed generation. In some circumstances, the distributed generation can help to overcome some problems related to power quality and voltage profile in a distribution feeder. Furthermore, depending on the control algorithm of the power converters, DG can provide some ancillary services like reactive power support. The use of distributed generation can decrease technical loses related to transmission and distribution lines up to 30% due that the generation of electricity is near to the consumption. From the utility point of view, distributed generation could replace the investment in transmission and distribution infrastructure (towers, lines, rights of way, etc.). In this sense, the installation of distributed generation systems becomes an attractive option to decrease losses in the electrical grid. A distributed generator with optimal location could contribute to reduce loses in a range of 10–15% (Kim et al. 2013; Lawder et al. 2014; Vazquez et al. 2010).

Furthermore, DG can provide auxiliary services, helping to keep a stable and continuous operation of the grid, e.g. DG can be used to stabilise variations in the grid frequency caused by the reduction in generation capacity or increase in the power demand. However, there are also some shortcoming in DG.

In the case of México and other developing countries, the DG have not been widely spread, although new grid codes contemplate the propagation of this type of electricity generation

One of the biggest challenges that DG has, is the high cost per installed kW, compared with a traditional large power plant. The price of the fuel used by some DG technologies (diesel machines, fuel cells, turbines, etc.) is also high compared to power plants. The reliability of the grid is also a concern, due that some type of distributed generators cannot be controlled from the same site that controls the rest of the grid. This can produce variability in the power delivery and additional reserve power could be necessary.

2.6 Energy Storage

Energy storage installations have been recently proposed to overcome the disadvantages of distributed generation based on renewable sources like PV and wind DG.

The most commonly used energy source is the electrochemical battery which has a relatively high energy density. Battery technologies like lithium-ion have become popular for grid applications mainly due to its low failure rate, high energy density and high number of charge–discharge cycles (Barton and Infield 2004; Lawder et al. 2014; Vazquez et al. 2010).

Energy storage installations are not only able to inject active power into the grid, but also can provide reactive support in case of perturbations or failures of the grid. An in most of the DG, energy storage installations require static power converters, in this case, the converter must be able to allow bidirectional power flow to charge and discharge the batteries (Barton and Infield 2004; Byrne et al. 2018; Roberts and Sandberg 2011). Power converters control the charge of the battery bank, first transforming the AC current into DC current (rectification) and second, regulating the charging current. When the power needs to be transferred from the battery bank to the grid, a DC-AC conversion process needs to be performed by the power converter. In this scenario, the converter needs to control the active and reactive power injection into the grid accordingly with the control requirements (Barton and Infield 2004; Byrne et al. 2018; Roberts and Sandberg 2011).

3 Transmission

The large-scale development of a transmission network has adopted high-voltage alternate-current as the predominant mechanism for long-distance transmission of electricity. This is not a sheer coincidence, since in such large-scale projects their efficiency, practicality and costs play the main role in the selected technology (Grainger et al. 2003). Taking this into account, the most robust generation scheme involves AC synchronous generators, which besides the issue that they can be easily synchronised with the grid, they are also naturally endowed with inertia, due to the commonly large mass associated to the rotor of the machine. The latter characteristic permits to store kinetic energy that can be eventually used to account for the unbalance between generation and consumption. This inertia provides additional time for the generator to maintain a set-point of delivered power. Then its coupled turbine, commonly moved by a fossil fuel-based process, increases or decreases the mechanical torque injected to the generator compensating velocity deviations. Moreover, the AC profile of the generator permits the use of transformers, which are able to achieve high voltage levels that permit to minimize the value of RMS (Root-Mean-Squared) currents through transmission lines. This is highly desirable, since losses associated to the Joule effect are a square function of the effective (RMS) current. Consequently, losses are also minimised (Grainger et al. 2003).

Looking at their counterpart, a DC generator is also a matured technology. Moreover, DC synchronisation is not an issue as in AC, and the losses by Joule effect can be equally mitigated by using high voltages. However, DC generators are not as efficient as synchronous generators. Unfortunately, they involve extraction of power from their rotor, which requires brushes that are eventually degraded, prompting a continuous maintenance. Moreover, although even nowadays we count with several ways to boost DC voltage via power electronics converters, they are simply not as cheap, efficient and reliable as an AC transformer (Grainger et al. 2003).

Consequently, their AC profile, inertia and the natural synchronisation of synchronous generators made them a compelling option for the development of a tailored transmission network, which took place in the twentieth century. This is considered as a major achievement in technology which permitted the development of industry and residential energy supply in every country around the world. The world-wide adopted configuration of the transmission network has been so successful that it is easy to fall into the delusion that there are no new challenges in electricity, rather than changing fossil fuel-based generation by renewables, using the same robust infrastructure. However, this is not the case at all. The challenges associated to the transmission of electricity are a major pressing issue nowadays.

For instance, in most of the countries, the electrical infrastructure installed during the twentieth century requires a major upgrade, maintenance and even replacement. This is a major issue considering that the demand of electricity is much greater than the one anticipated when firstly developed, which also results in congestion and increases the technical losses. Moreover, the location of certain energy resources prompt countries to adopt very long distance or submarine transmission lines that have a very low efficiency in AC (Grainger et al. 2003).

We can notice not only glimpses of limitations in AC transmission, but significant alerts that prompt us to look for short- and mid-term solutions. The limitations are now discussed.

3.1 Impedance

Impedance is a frequency domain quantity represented by a complex number. Consequently, it is only present in AC, accounting for a more general definition of opposition to electric current than resistance—involving also inductances and capacitances. In the case of a transmission line, its equivalent electrical representation involves series inductances, due to the inherent ability of conductors to generate magnetic fields when electrical currents flow through them; while capacitances appear in shunt connection due to the potential difference between the ground and the line itself, which implies the presence of an electric field. The higher the impedance, the higher the RMS current through the cable, which increases the Joule effect losses as well. Consequently, at very long distances, the impedance increases significantly, which has a major impact in the efficiency of the line, yielding high technical losses (Grainger et al. 2003).

Another case where the impedance plays a major role is in submarine lines. These types of links are very compelling in the case of e.g. offshore wind farms or due to other geographical reasons as in some peninsular areas. Notice for instance the case of the states of Baja California and Baja California Sur, where a submarine line would enable a suitable interconnection of those states to the Mexican electric system via

Sinaloa. However, though compelling, in the case of an AC link, a submarine cable involves a much higher capacitance than in conventional aerial lines.

3.2 Stability

Another important issue and limitation in AC transmission systems is the amount of power that can be transmitted between two nodes, which is strongly associated to stability. In power systems, the point-to-point transmission in watts, from a node 1 to a node 2, is given by the well-known equation (Grainger et al. 2003):

$$P_{1\to 2} := \frac{V_1 V_2 \sin\delta}{X},$$

where V_1 and V_2 are the voltage magnitude at nodes 1 and 2, respectively; X is the reactance of the transmission line, i.e. the imaginary part of the impedance; and δ is the phase difference between the voltages of nodes 1 and 2.

This equation has a stability regime that is surpassed when the angle difference between the emitter and receiver points reaches 90°. In words, an unstable regime implies a change of sign in the formula which leads to an equivalent positive feedback for the receiver, then deviations, e.g. in frequency, are amplified instead of being mitigated. For this reason, the transmission of power is usually operated in a much more conservative point, e.g. 60°. This issue undermines the possibility to satisfy the increasing power demand in certain areas where the transmission lines are "congested", i.e. operating close to the 60° limit.

3.3 Asynchronous Interconnection

As previously discussed, an AC power system requires synchronisation, i.e. a uniform frequency for all the interconnected generators. However, in many cases it might be of interest to interconnect systems with different frequencies. For example, interconnection among countries. However, it is simply unfeasible to require synchronisation of the whole electric system of different countries to be able to share electricity, since now the dependence when taking decisions and risk of stability issues, will be completely shared.

This situation does not permit to develop a wholesale electricity market that could take advantage e.g. of time differences. For instance, notice that in the case of Mexico and USA, the peak hours of the major cities do not coincide, since their time is shifted due to geographical reasons. Consequently, the price of electricity varies considerably, which may permit a more competitive price at peak hours that could benefit both countries.

3.4 Asynchronous Generation

A paradigm shift from fossil-fuel to renewable energy generation is not an easy task. As previously discussed, renewable energy generation is in general asynchronous and requires power converters as an interface with the grid. Moreover, renewables are not endowed with the natural inertia of synchronous generators, which prompts the operation of the utility to act in a much faster way to deal with generation and consumption imbalances.

3.5 Solution Scenarios

A plausible solution to the limitations of AC lines in modern scenarios of increasing demand and pressing need of integration of renewable energy, is the combination of AC and DC systems. For instance, while AC presents several shortcomings, it is undeniable that the best way to step-up voltages for transmission purposes is via transformers. At this point it does not matter that this is a passive component that in the future could be replaced by an electronic counterpart, but nowadays, it is the most mature, cheap and efficient way to yield and interface between generation and transmission systems. On the other hand, power converters in the form of rectifiers and inverters could serve as yet another interface to transmit power in DC at long distances. This is the case of LCC (line commutated converters), which are based on mercury-arc valves of thyristors. Other modern power electronics interfaces between AC and DC at high voltage levels (HVDC) involve back-to-back IGBT-based (Insulated-gate bipolar transistor) converters, which permit to achieve an AC to DC conversion, then transmit electricity through a long-distance DC-line and transform back from DC to AC at the other end of the line. There are some operating interconnections of this type of HVDC converters in the world, though the most predominant is still the LCC configuration, due to the costs and reliability of IGBT-based stations. The latter are promising technologies since they permit major flexibility and control on the grid, e.g. voltage regulation and they permit to revert the power flow at any time. Installation of HVDC lines also conjugates well with renewables, since they are usually located in remote places and require rapid evacuation due to their intermittency.

4 Distribution

By the end of nineteenth century the first power plant installations appeared. Before that, electricity was generated in situ where it was needed to avoid the complex infrastructure required to take the electric energy from one place to another. Power systems have been there for more than a century and their use increased rapidly. Today these systems are vital for the development of economies in which new electricity applications have raised additional requirements in the production, transportation and distribution of electric energy (Murty 2017; Stein 1979; Von-Meier 2006).

Distribution systems are the last part of the electrical system chain and are concerned with delivering the electricity from the distribution substation to the final users. Usually, responsibility for these grids lies with the utilities; electricity companies that must guarantee the electricity supply to all the grid users.

In México, the electricity distribution is usually carried out in two stages: medium voltage (voltages from 6 to 35 kV) and low voltage (voltages from 220 to 440 V). The medium-voltage stage takes place from the output of the substation to the pole transformers or to medium-voltage users who require high power (Nasar and Trutt 1998; Stein 1979; Wengenmayr and Bührke 2012). This circuit is often known as a distribution feeder or primary feeder. The distribution substation is the link between the transmission power system and the distribution system. The low voltage distribution stage is the circuit that is connected to the pole transformer's secondary winding. Most of the residential users are connected to the secondary distribution feeder. This electricity power supply could be in one phase (127 V) or two phases (220 V).

In general, the electricity distribution system can be divided into six parts: Subtransmission circuits; distribution substation; primary feeders; distribution transformers; secondary feeders, and, consumers services (Murty 2017; Nasar and Trutt 1998; Stein 1979; Von-Meier 2006).

Distribution substations usually service a load area, which is a subdivision of the total distribution network. In the distribution substation the main equipment are the power transformers, on-load tap changers, switch gears, and connection buses (Murty 2017; Nasar and Trutt 1998; Von-Meier 2006).

The effectiveness of distribution systems is measured in terms of the following criteria:

- Voltage regulation to avoid unwanted voltage variations, which are usually known as swells (voltage increase for several cycles), sags (voltage decrease for several cycles) and flickers (sudden voltage variation).
- Continuity of service, which implies a minimum number of interruptions in the electric supply.
- Flexibility to allow the expansion or modification of the electricity system caused by an increase in users or demand.

For a distribution system, it is important to keep the capacity close to the real load requirements, this permit having a more affective investment use. The cost of the electricity distribution is an important factor in the total electrical energy supply cost and in many cases; it is more than the 50% of the total investment cost (Nasar and Trutt 1998; Wengenmayr and Bührke 2012). One of the main challenges of electricity distribution is related to design, build, and the operation of the distribution system to provide an adequate electricity service to a load center at the minimum cost (Nasar and Trutt 1998; Wengenmayr and Bührke 2012). Due that, load centers present different topographies, load densities and users, thus for each distribution circuit a custom design is required.

The voltage level of a primary feeder is the most important parameter because it has a direct impact in the design of the distribution circuit, its cost, and operation. Some of the factors to be considered when selecting the voltage level are:

- Length of the feeder.
- Load of the feeder.
- The number of substations.
- The capacity of substations.
- Maintenance cycles that will be required.
- The physical infrastructure required (poles, wires, etc.)
- Electrical protections.
- Type of isolators.
- Energy losses.
- Policies and grid code.
- Voltage drop in the lines.

Usually, primary feeders located in low-load density areas are limited by the length and load due to the permissible voltage drop. On the other hand, in high load density areas, like industrial and commercial zones, the length of the feeder is limited by thermic restrictions. In general, for a given permissible voltage drop, the length and load are functions of the voltage level of the feeder. Distribution circuits can be classified by the type of load they serve. The load can be defined as the characteristics of energy consumption. There exist three types of loads which are discussed following.

4.1 Residential Loads

They are basically for apartment buildings and houses in urban areas. These loads are low voltage-low power and in most of the cases are supplied as single or two phases. Residential loads are predominantly resistive with a very low reactive power component.

4.2 Commercial Loads

Most of the times, they are located close to the centre of the cities. They are normally three phase and consume medium power. In this case, the power density is bigger than in residential loads, but it is still mostly a resistive load.

4.3 Industrial Loads

These loads have the biggest demand and they are usually supplied at medium voltage (or even high voltage). They have an important component of reactive power due to the large number of motors and other inductive-type loads (Nasar and Trutt 1998; Stein 1979; Von-Meier 2006). Usually, these loads have reactive compensation systems and load management due to their hourly-based tariff.

4.4 Location and Reliability

Distribution networks may also be classified by their geographic location.

The most common are the urban networks which have the following characteristics:

- Ease of connection to the electricity grid.
- High load density.
- Three phase distribution transformers are usually used.
- There exist single, two and three phase loads.
- There is small distance between the primary and secondary circuits.
- Necessity to coordinate the electrification networks with, phone, and water services.

Rural networks are not always economically feasible; however, they are needed for agriculture and cattle raising. Another common justification for rural electrification is the social benefit and the increase in quality of life for poor communities. The main characteristics of rural networks are:

- Low load density due to disperse users.
- Mostly single-phase loads.
- Higher cost per kW and kWh compared to urban installations.
- Wooden poles can be used.
- Additional requirements such as “right of way” need to be considered.

The last classification for distribution networks has to do with reliability. There exist three levels of reliability considering the suspension of electrical service. First level loads; any interruption of the electricity supply to these loads can have a severe impact on the health of people, industrial equipment or national security, and hospitals are at the top of the list. In the case of severe failure of the electrical network, sensitive loads need to keep energised. In second place could be the institutions related to government and the military facilities (Von-Meier 2006). Second level loads. In this group are industrial installations that can be damaged in the case of an outage. Some examples would be the textile industry or chemicals production factories. Third level loads can withstand more than half an hour without electricity without having serious consequences. This is the case for residential and commercial loads. When a contingency in the electricity network occurs and loads need to be disconnected, the first option is to disconnect the third level loads. Decisions about the substation location needs to be based on the reliability of the system and economic issues. The reliability of the distribution system is an important quality indicator and careful plans need to be made in order to ensure the availability of electrical energy (Nasar and Trutt 1998; Stein 1979; Von-Meier 2006; Wengenmayr and Bührke 2012). As the technology related to the production and consumption of electrical energy has increased, important challenges related to the analysis, planning and operation of distribution networks have arisen. We can separate the challenges related to the distribution grid into two main categories.

- The first one has to do with new ways of electricity generation on a small scale.
- The second one is related to new types of loads that are connected in distribution circuits.

4.5 Distributed Generation and Its Impact in the Grid

Distributed generation is referred to as the introduction of electrical power into the distribution network. In this type of electricity generation, the energy is introduced by the users, in locations close to the load centres (Boyle 2012; Nelson and Starcher 2015). Most of the time, this energy comes from renewable resources, such as photovoltaic energy and wind energy, although diesel generators can be also considered among others. Additionally, it is also possible to insert power from energy storage systems, such as battery banks. In recent years, the installation of small rooftop PV sources has increased as an alternative way of obtaining an electricity supply (Blaabjerg et al. 2004, 2006; Nelson and Starcher 2015). Here we list some of the issues related to distributed generation. **Bidirectional power flow**.

As mentioned before, traditional distribution grids were designed thinking of power delivery from the substation to different type of loads. On one hand, power demand varies throughout the day having some peak hours, usually early in the morning, or at the night. On the other hand, distributed power generation based on renewable sources such as PV panels, have peak generation hours close to noon (Blaabjerg et al. 2006; Nelson and Starcher 2015). As can be seen, the peak hours of generation do not match up with the demand peak hours, and this can cause a reverse power flow back to the primary feeder and to the distribution substation if the quantity of PV installed capacity is larger than the minimum consumption of the feeder. There are two main problems related with bidirectional power flow:

Distribution power protection is not prepared for bidirectional power flow; this can cause false trips and problems with the protection coordination and short circuit current computation (Blaabjerg et al. 2004, 2006; Boyle 2012; Nelson and Starcher 2015). Feeder voltage profile could be affected and maximum voltage level can be exceeded. This can damage sensitive loads connected to the grid. One plausible solution to avoid bidirectional power flow is the use of energy storage systems. This could allow storing energy in peak solar hours and release that energy in peak consumption hours. Indeed, this technique has been named as peak shaping due to its capability to re-shape the peak demand over a day (Katiraei and Iravani 2006; Kim et al. 2013).

Most of the distributed electrical energy is introduced into the grid by means of a solid-state power electronics converter. Due that, power converters are based on high frequency switching. If the current that is injected into the distribution network has some harmonic pollution it contributes to the distortion of the voltage waveform. Some new switching modulation techniques, converter topologies and filter designs have been proposed in order to reduce the harmonic content of the output current and it is expected that this will become and insignificant issue (Lawder et al. 2014).

Anti-island.

Low power distributed generators are not dispatchable; this means that they are not controlled by the utility. Instead, they inject as much power as they can, but this operation mode can come with some problems for the distribution network (Barton and Infield 2004; Byrne et al. 2018). For example, in the case of a fault in some part of the grid, protection will be triggered interrupting the energy supply to several parts of the circuit in order to isolate the failure. A grid island can be formed if distributed generators continue injecting power into the sectioned grid; in some cases, (high impedance faults) the distributed generators can even continue injecting current into the faulted section. This scenario is dangerous for grid operators that are fixing the fault, due to the isolated sections becoming energized, initiating a potential risk of electric shocks. Nowadays by norm, grid-tied power inverters are normally provided with an anti-islanding structure in order to avoid these hazardous situations (Barton and Infield 2004).

4.6 Low Inertia

Rotating generators, such as those that are traditionally used in large power plants have a relatively high moment of inertia due to the rotating mass of the rotor. This inertia can be considered as an energy buffer that is able to respond quickly to load changing, thereby helping to keep the power system in a stable condition (Byrne et al. 2018; Roberts and Sandberg 2011). The increased use of non-rotating generators, such as those based on solid-state power converters, can have a low inertia effect on grids. This low inertia can cause stability problems that may lead to massive outages.

In order to avoid these problems, new control systems implemented in power converters could be able to emulate what is called a "virtual inertia" (Dehghani et al. 2019; Roberts and Sandberg 2011; Zhu et al. 2018). These new control techniques are even capable of emulating the behaviour of synchronous machines. This approach solves not only the inertia problem, but also the one related to synchronisation (Roberts and Sandberg 2011; Yi et al. 2019).

Another plausible solution is the use of energy storage systems to provide virtual inertia to the grid. As the real inertia (rotor) acts as a small high-power/low-energy source, in this case batteries or ultra-capacitors can be used as quick response energy buffers (Dehghani et al. 2019; Zhu et al. 2018).

4.7 New Loads in Distribution Systems

New technologies have come with new challenges for the grid. Users expect to have a continuous supply of energy whenever they connect to the power outlet. As the types of load have changed with time, new considerations are needed to be taken into account by the utility companies.

4.8 Non-linear Loads

One of those challenges is related to the increase in non-linear loads connected to distribution circuits. As a counterpart of linear loads, which are those formed by passive elements (resistive and reactive), the non-linear loads are based on electronic devices like diodes or transistors. Due to the increase of electronic type loads, which usually require DC current to work, the use of rectification circuits, whether diode or transistor-based circuits, are often required as a front-end component of several appliances.

The problem with rectifiers is that most of them demand pulsating current from the grid. This produces distorted waveforms that can be considered as a harmonic pollution for the grid. As the non-linear loads increases the pollution becomes more severe. Specific cases of this change of paradigm are light bulbs. Years ago, most of the light bulbs were of the incandescent type (predominantly a resistive load). Today, the fluorescent and LED lamps are the most common type of lighting in use. These types of lamps use rectifiers as a front-end circuit, which makes them a non-linear load. Nowadays, high power non-linear loads, such as inverter-based air conditioners, are required to incorporate what is called a power factor corrector (PFC) circuit. Such circuit regulates the current demand in order to avoid the harmonic distortion (Singh 2012).

4.9 Electric Vehicles

Although vehicle electrification could be a good option for reducing air pollution, the electric vehicle proliferation represents a challenging problem for electricity grids. Each electric vehicle (sedan type) consumes an average of 10 kWh daily (Clement-Nyns et al. 2010; Liu et al. 2013; Rezaee et al. 2013). This energy needs to be taken from the grid to charge the vehicle's battery. If a considerable number of vehicles were connected to the same distribution feeder, additional energy supply would be needed in order to satisfy the additional energy required (Clement-Nyns et al. 2010; Lopes et al. 2011; Pieltain-Fernandez et al. 2011; Rezaee et al. 2013). Furthermore, it would also be also necessary to considerable increase the capacity (power) of the distribution feeder. For example, if the 10 kWh needed to be supplied, in an 8-h changing period, an additional capacity of 1.3 kW per car would be needed. Faster charging will require additional installed capacity.

Most of the distribution feeders are not equipped to allocate electric vehicle chargers due to their limited capacity. The massive connection of electric vehicles to the distribution grids could cause overheating in electrical equipment such as distribution transformers and AC lines (Rezaee et al. 2013, Pieltain-Fernandez et al. 2011). Energy storage systems can be also beneficial in the case of electric car proliferation. Energy can be slowly stored into the battery bank and then released as needed to charge the vehicles (Clement-Nyns et al. 2010; Liu et al. 2013; Rezaee et al. 2013).

5 Power Electronics

Power electronics is an enabling technology, which was followed by the fast development of other technologies, such as renewable energy generation, and transmission and distribution improvements. This chapter covers some of the main aspects of all three main parts of the power system, generation, transmission and distribution.

5.1 Power Electronics in Generation Systems

The first part of a power system is the generation sub-system, in which electrical energy is obtained from different sources, traditional and well stablished power sources such as hydro-electric generation, nuclear plants, and fossil fuel-based energy generation (based on coal, gas, or other petroleum based fuels), have new competitors based on renewable energy sources, such as wind farms, and solar power in the form of photovoltaic panels and sunlight concentrators, ocean wave energy generators and tide generators. Most of those energy sources have challenges that have been overcome thanks to power electronics converters.

5.2 Photovoltaic Solar Panels

Photovoltaic PV Solar panels (after decades of research) have reached a competitive cost against the traditional electrical energy generation (Romero-Cadaval et al. 2013; Yang et al. 2017), one of the two main aspects which gave solar panels this edge was the development of more efficient solar panels by itself. The second reason is related to the power electronics field, the interconnection of the panel systems to the grid permitted by improvements in the efficiency of power electronics converters enables the development of what we now call maximum power point tracking MPPT. This principle is now used in all renewable energy systems, not only for PV panels systems.

Once the energy can be introduced into the grid, the system doesn't need to bind its energy production to their load requirements, or to their battery's state of charge. Any additional energy can be injected into the grid and used somewhere else, and this maximises the profitability of the investment. All this is driven by power electronics-based converters. Another rising renewable energy generation system is solar concentrators, but in this specific field, power electronics does not play an important role.

5.3 Wind Turbines

The electrical energy generated from the wind was a big surprise for its fast cost reduction compared to that of PV panels. The variable nature of the wind was a major challenge for their use in energy generation (Muller et al. 2002; Pao and Johnson 2011; Pieltain-Fernandez et al. 2011; Thresher et al. 2007), while traditional sources of energy (hydro-electric, nuclear and fossil-based) rely on synchronous machines to perform energy conversion from mechanical to electrical form.

On one side, the frequency of the voltage produced with a synchronous generator, depends on the rotor speed. And the voltage-frequency of the power system must be kept constant, at 50 or 60 Hz, depending on the regional standard. The well stablished synchronous generation technology could not be applied to the new wind-turbine energy generation systems, but after several years of research, a new standard emerged which is now the doubly feed induction generator. This generator allows a decoupling between the speed of the rotor and the frequency of the generated voltage. The speed of the wind turbine can then be chosen in order to maximise the generated power, while the frequency of the generated voltage can be adjusted to allow connection to the power grid (Muller et al. 2002; Pao and Johnson 2011; Thresher et al. 2007).

The power converter used for this purpose is composed of two three-phase inverters connected through their dc-link, which is called back to back connection. Converters operate at different frequency which allows the connection of the induction generator to the power grid.

5.4 Ocean Wave-Based Generators

Ocean wave can be used to generate electricity, it is a promising (non-mature) technology, and many systems are under development for this purpose (Ringwood et al. 2014), power electronics is used in the development of all propositions, but the mayor challenges of wave energy generation systems are in the mechanical engineering system, to change the kinetic movement of waves into a rotating movement to be used in electrical generators.

5.5 Stability Challenge Due to Renewable Energy

The power system faces a stability challenge due the increment in renewable energy generation systems (Ackermann et al. 2015). This is caused by the fact that electrical energy cannot be stored in large quantities. Consequently, simultaneous production and consumption is difficult, since the load is unpredictable. However, energy consumption profiles change only slightly from one day to another. Hence, unpredictable loads are a small percentage of total energy consumption.

Once the consumption profile is predicted statistically, there are two kinds of traditional generators (from the dispatch point of view): (i) The first type receives a fixed generation profile for the next day, called 'dispatch'; (ii) the second kind is designated for frequency regulation, they will be ready to produce power, but they can actually produce nothing. The operation of this small percentage of the generation system designated to compensate for the small unpredictable deviations, is called frequency regulation.

Generators in charge of frequency regulation represent a small percentage of the total power capability of the system, they represent a cost, the cost of the uncertainty in the load profile, but they are required to maintain the system operation.

Renewable energies add another uncertainty to the system, they have an unpredictable generated energy, cloud can reduce the energy produced in solar panels, a reduction of the wind speed, would produce a reduction of the energy generated at wind mill farms, so now an additional uncertainty appear, not at the consumption side, but at the generation side. This unpredictable behaviour requires a backup, which can be from traditional generators, or energy stored, for example in batteries. It is important to point out that systems with a small percentage of traditional generation don't have a problem, because the uncertainty can be handled by the frequency regulation, but as long as renewable energy generation systems become more popular, this challenge may become a severe limitation (Ackermann et al. 2015).

5.6 The Google's Little Box Challenge

Distributed generation is another option for the generation of electrical energy, in which final users can produce the energy on site, for example with solar panels in the case of residential users. In 2014, Google launched the little box challenge LBC (Halsted and Manjrekar 2018; Sniderman 2016; White 2016), with the intention of contributing to distributed renewable energy generation development. The challenge was to increase the power density of power electronics-based inverters (which would reduce the size of converters for a specific power rating).

The challenge was to design and build a 2-kVA inverter with a power density of at least 50 W per cubic inch having an efficiency of at least 95% (Halsted and Manjrekar 2018; Sniderman 2016; White 2016). The input voltage was defined as 450 V DC. Other specification details can be found at (Halsted and Manjrekar 2018). The winner's award was 1 million dollars. This competition reflects the humanity interest in the distributed generation based on renewable energy.

5.7 Power Electronics in Transmission Systems

In a transmission sub-system, power electronics is the key technology for the high voltage direct current HVDC transmission (Litzenberger and Lips 2007; Marquardt 2018). Traditional alternating current transmission has its limits over long distances, due the parasitic inductance and capacitance of the lines, as the transmission line approaches 1,000 kms length. The DC approach overcomes these AC transmission limitations.

The main drawback of the DC transmission is the cost of the converters, an AC to DC converter is required at each extreme of the line. From this point of view the HVDC transmission field can be classified in two main ways: (i) the well-established and mature technology based on thyristors (Litzenberger and Lips 2007), on which almost all DC links and transmission lines are based, and, the emerging transistor-based technology, in this field. Development of the modular multilevel converter technology, allowed the construction of very high voltage converters (Marquardt 2018), and the topology improvement along with the development of high voltage transistors based on silicon carbide promises to bring high voltage converters not only for medium voltage or distribution systems but also for HVDC systems (Marquardt 2018).

Another important development of power electronics for the transmission system was the development of the Flexible AC Transmission Systems FACTS (Gemmell and Korytowski 2016; Reed et al. 2003), in which several topologies where proposed to control grid parameters such as the voltage in certain nodes, the impedance or the power flow in certain lines, as well as for the HVDC. Most FACTS devices are still based on the well established thyristor technology waiting for the enabling of topology improvements or the a new age of transistors.

5.8 Power Electronics in Distribution Systems

The main trend for the power electronics field in the distribution system is the development of the electronic transformer (Briz et al. 2016). This aims to eliminate the grid frequency transformer and replace it with an electronic-based alternative.

Grid frequency transformers are of relatively large size and weight, but electronic transformers utilise a medium frequency transformer along with switching converters. The development of modern battery chargers for mobile phones, gives a good idea of how this principle can reduce the size and weight and also provide advanced functions such as voltage regulation and power factor correction.

Several electronic transformers have been tested; their main limitations are two.

(i) Their cost is higher than for conventional electrical transformers; and, (ii) pure electrical transformers have strict regulations to ensure their operation under contingencies; the tests electrical transformers pass include atmospheric discharges and inrush currents. Electrical transformers are able to operate at, for example, more than 10 times their voltage rating during an atmospheric discharge (for a relatively short time), or more than 10 times their current rating during an inrush current (also for a relatively short time). Those are extremes which cellphone battery chargers did not need to face, and they represent a big challenge which solid state transformers have not yet overcome. Electronic components cannot sustain this kind of stress, and the relatively short time periods for electrical transformers, represent very long time periods for transistors.

Even when an electronic transformer can be designed with a rating much larger than its nominal operation, that would increases the price to prohibitive levels. Again, the fast development of silicon carbide and gallium nitride transistors promise to overcome those challenges, in the near future.

The distribution system is experiencing a fast evolution, since distributed generation is being connected at the low voltage side of the distribution system then has generation and transmission functions. Another important challenge for the distribution system is the high penetration of electric vehicle chargers. These chargers have a high-power rating, and their installation requires the distribution system to be reinforced to ensure the system operates safely.

5.9 Wide-Bandgap Semiconductors

As mentioned in a former section, the development of new transistors is a promising news for power electronics at all levels (Bindra 2015; Kaplar et al. 2017). These new transistors switch faster, can sustain a larger voltage and drain a larger amount of electrical current. For medium and high voltage rated applications, silicon carbide devices are expected to be substituted for the currently used silicon IGBTs, and for the low voltage applications, gallium nitride transistors are expected to replace of silicon based MOSFETs (Bindra 2015; Kaplar et al. 2017).

6 Conclusions and Recommendations

We examined the background to the development of the current means of generating, transmitting and distributing electricity. The current challenges as well as the trends that arise from the increasing demand of clean energy were also discussed. In particular, the role of power electronics in the development of solutions was argued for. We emphasised that the development of mature and low-cost technologies in power electronics will permit the transition to a sustainable way to consume electricity. It was noticed that the development of technology is a crucial step to achieving energy sustainability.

Nowadays, the electrical power systems around the world are moving towards more efficient and modern solutions that including High Voltage Direct Current (HVDC) systems, Flexible Alternating Current Technologies (FACTs), Phasor Measurement Units (PMUs), renewable energy sources, distributed generation, microgrids, and smart grids.

All these new technologies have promoted an increase in the overall efficiency of the electric energy supply chain.

In Mexico some of these technologies have started to be implemented, and some other are planned to be developed in the next years.

For instance, there already exist a regulatory framework for the distributed generation that considers the maximum allowed installed capacity. There is also a recently deployed grid code, which takes into consideration several of the new technologies that will be deployed in the future.

Mexico, now has the opportunity to become a user of several excellent technologies for generation, transmission and distribution of the electricity this will allow Mexico to have cheaper and cleaner electrical energy for its industrial, transportation and residential sectors.

Some recommendations are given as follows, Mexico should:

- Include the implementation of new generation technologies in the national development program for the electricity sector.
- Institute tax incentives schemes to promote the implementation of more efficient technologies for the electricity generation.
- Continue with the development and expansion of the national electricity system, to increase its transmission capacity in order to allow the installation of new technology generation plants.
- Start with the development of HVDC transmission lines to make feasible the transportation of huge amounts of energy over long distances. This will allow the development of more wind and solar farms in the south and north of the country, respectively.
- Promote the implementation of microgrids in buildings, commercial environments, factories and other urban centres.
- Implement information technologies related to the monitoring, control and fault detection in the electrical power system.

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Chapter 9
Residual Biomass Use for Energy Generation

Francisco J. Lozano, Diego Fabián Lozano-García, Alejandro Montesinos Castellanos, and Antonio Flores-Tlacuahuac

Abstract Residual biomass from agricultural produce can be used to generate energy in various forms, as well as chemicals. Availability for residual biomass across Mexico from various crops is presented in this chapter using a Geographic Information System (GIS) that allows to pinpoint this availability at the municipal level, as well as considering several restrictions to be imposed to adequately select sites to install processing facilities. Agave, barley, maize, pecan nut, rice, sugar cane, sorghum, and wheat were the crops selected due to its large producing volume in Mexico. Base processing technology is biomass gasification, with sub-stoichiometric air or with steam, to render a synthesis gas to be further processed. Secondary processing technologies assessed are: direct combustion to generate electricity and refrigeration (through combustion turbine and steam turbines), producing Fischer-Tropsch liquids, or producing ammonia or urea or methanol. Proposing the specific processing sites throughout Mexico and concluding that producing in some facilities electricity and Fischer-Tropsch liquids is a combination that has adequate profit.

Abbreviations

BTL Biomass to Liquids

F. J. Lozano (✉)
Tecnologico de Monterrey, Campus Toluca, Avenida Eduardo Monroy, Cárdenas 2000 San Antonio Buenavista, 50110 Toluca de Lerdo, Mexico
e-mail: fjlozano@tec.mx

D. F. Lozano-García · A. M. Castellanos · A. Flores-Tlacuahuac
Tecnologico de Monterrey, Colonia Tecnológico en Monterrey, Nuevo León. C.P. 64849, Campus Monterrey. Av. Eugenio Garza Sada Sur No. 2501, Monterrey, Mexico
e-mail: dflozano@tec.mx

A. M. Castellanos
e-mail: alejandro_montesinos@tec.mx

A. Flores-Tlacuahuac
e-mail: antonio.flores.t@tec.mx

F. J. Lozano et al. (eds.), *Energy Issues and Transition to a Low Carbon Economy*, Strategies for Sustainability, https://doi.org/10.1007/978-3-030-75661-1_9

FTL	Fischer-Tropsch Liquids
GIS	Geographic Information Systems
GTL	Gas to Liquids
MILP	Mixed-Integer Linear Programming
NPP	Net Primary Productivity
ROCE	Return on Capital Employed
USA	United States of America

1 Introduction

Plant domestication started several millennia ago, when humans began to cultivate plants from the wild as food. Achieving the latter was a success story of human ingenuity and adaptability. This early cultivation was the beginning of agriculture, as we know it today, and the production of plant derived biomass at scale.

Historically, biomass has been used as an energy source, wood specifically, but also agricultural residues, besides its use as a feedstock for humans and livestock. A more ample discussion has been done in Chap. 1.

Waste biomass is a secondary product of the primary use of biomass, for instance, sawdust from wood harvesting or residual biomass from crops and cattle manure. Municipal solid waste is also a part of waste biomass and useful for energy production (metals and plastic are not biomass). Another source of waste biomass is the sewage produced from water treatments plants, However, here only waste biomass from agricultural and forestry activities are considered.

Residual biomass from agricultural production is a potential raw material for energy generation, either electrical or thermal, besides being a possible source of chemicals. Biomass production is subject to uncertainty due to climate, market, economic and technological factors. Hence, when choosing a facility location, these factors need to be considered so as to optimise economic feasibility, as well as the adequate production flexibility. The optimal blend of electrical and thermal energy, coupled with the chemical production technologies needed will be addressed in this chapter.

2 Residual Biomass Availability[1]

Planet energetics, along with a discussion of photosynthesis by (Smil 2008) regarding the growth rate for different biomes and their Net Primary Productivity (NPP) is relevant to assessing annual carbon capture. The latter estimates are in the range of

[1] The term biomass in the present chapter refers to phytomass that proceeds from agricultural or forestry activities.

40–70 Gt C/year (equivalent to 40–70 Pg carbon/year in SI units) this needs to be compared with an estimate of 10 Gt C/year of annual carbon emissions from human activities.

Historically, biomass has been used as an energy source, wood specifically but also agricultural residues, besides its use as a feedstock for humans and livestock. A more ample discussion has been done in Chap. 1.

Forestry residues are generated when cutting logs, producing a certain amount in situ. Also, when logs are transported to processing sites, such as sawmills, there is further residues generation.

Agricultural residues normally are generated in situ and can be used as animal feed, specifically ruminants, or a portion is left in the fields for conservation tillage.

In some countries there has been a tendency to use grain, specifically corn, to produce ethanol as fuel, but this generates an ethical conundrum, because grain is supposed to be used for human or animal consumption, and there is the economic dilemma that a higher demand for grain will generate a price increase.

Agricultural products generate a certain amount of residue for each specific plant species. Our discussion will be centred in plants producing straws, stover, bagasse, nutshell, and agave residue.

The residue to product ratio varies according to plant type, Table 1, shows the values for the abovementioned crops, noting that for the grain type crops, the smallest residue to crop ratio corresponds to corn (maize).

Residual biomass availability depends on the country assessed. Crops vary and a comparison between Mexico and the USA is shown in Table 2. There is a larger production of barley, sugarcane, corn, rice and wheat have a large production in the USA, while sorghum is produced at the same order of magnitude in both countries, but for pecan nut, Mexico has a larger production. There is no production of agave in the USA, for example.

Using data from Table 1, estimations were calculated for residual biomass availability in Mexico and the USA. The results are presented in Table 2; total residues mass for USA is almost an order of magnitude higher than Mexico. Not surprisingly,

Table 1 Residue to crop ratio

Main crop	Agricultural residue	Residue amount per crop	
		$kg_{residue}/kg_{crop}$	References
Agave	Agave bagasse	0.111	Iñiguez-Covarrubias et al. (2001)
Rice	Rice straw	1.625	Girard et al. (2002)
Sugar cane	Sugar cane bagasse	0.135	Chen (1991)
Barley	Barley straw	1.660	Lal (2005)
Maize	Corn stover	0.825	Girard et al. (2002)
Pecan nut	Pecan nut shell	0.550	Girard et al. (2002)
Sorghum	Sorghum straw	1.425	Girard et al. (2002)
Wheat	Wheat straw	1.835	Girard et al. (2002)

Table 2 Crop production, value and estimated residues generated for Mexico and the USA

Year: 2014						
	Mexico			USA		
Crop or wood	Production (Mg)	Value (10^6 US Dls)	Residue (Mg)	Production (Mg)	Value (10^6 US Dls)	Residue (Mg)
Agave	2,408,884	778	602,221			
Rice	232,159	71	377,258	2,595,546	3,076	4,217,763
Sugar cane	56,672,829	2,013	7,650,832	201,638,201	1,002	27,221,157
Barley (grain)	845,707	226	1,403,874	3,952,591	915	6,561,300
Maize or corn	23,133,599	5,533	19,085,219	361,134,003	52,958	297,935,552
Pecan nut	122,536	469	224,853	66,549	82	36,602
Sorghum grain	8,394,057	1,534	11,961,531	10,987,855	1,721	15,657,693
Wheat	3,971,536	971	7,287,768	55,146,837	11,915	101,194,446
Wood	2,928,805	540	380,745			
Grand total	**98,710,111**	**12,134**	**48,974,301**	**635,521,581**	**71,670**	**452,824,514**

Sources SAGARPA (2014a)
(USDA—National agricultural statistics service—Data and statistics, no date)

since the area cultivated by the USA is around 103. Million ha, while the area in Mexico is 16.7 million ha (FAO 2018).

China's potential to use forest residues for energy on an industrial scale is given by (Anttila et al. 2015) stating that availability is adequate, and there is a need to establish a proper supply chain structure. Presently supply costs are high, hence they could be lowered by a proper selection of raw material acquisition regions, and selecting appropriate processing technologies.

Assessing biomass availability in Europe has been done by (Nikolaou et al. 2003) classifying according to sources such as straws, corn stover and cobs, pruning, grasses, oil, sugar and starch crops, along with wood fuel and forest residues. Industrial residues were considered, such as black liquor from paper and pulp production. Municipal solid waste, either used in incineration plants or producing landfill gas or sewage sludge gas., was also considered. Agricultural residues have an energy potential of 1,370 PJ/year, and 646 PJ/year for livestock waste. Furthermore, biomass delivery cost is discussed; consisting of production cost, transport costs, and storage and handling; since these have an impact on the overall energy manufacturing cost.

A specific case of residual biomass potential for Italy, to meet EU targets on renewable energy and climate, is presented by (Paiano and Lagioia 2016) where for 2013 a total of 403 PJ electricity was produced from renewable energy. The authors conclude that there is a total potential availability of 391 PJ/year from crops, herbaceous, and arboreal residues for Italy, but the supply chain for residual biomass needs to be incorporated in a bioenergy policy.

Hence in the discussion, besides residues distribution in country regions, their postharvest processing, as well as transportation to processing sites needs to be taken into account. Pordesimo et al. (2004) discuss the corn stover potential for bioenergy or for industrial applications, as well as the biomass dry conditions impact on assessment. Handling, use and market possibilities for corn stover and straws are also presented by Reyes Muro et al. (2013) for central and southern Mexico, concluding that conservation agriculture (CA) has to be taken into account on decision making, present uses for soil cover for humidity regulation, diminish water erosion, weed control and the provision of organic matter and nutrients to the soil, also as feedstock, forage specifically for ruminants.

3 Gasification as Initial Processing Technology

Transforming biomass in its various forms is presented in Fig. 1 where the possibilities are ample.

For instance, residual biomass can be hydrolysed, producing five and six carbon sugars, along with the possibility of producing furfural.

Another option is gasification, either with sub-stoichiometric air or steam. The former renders a gas containing hydrogen, carbon monoxide, some methane and nitrogen; the latter generates a synthesis gas (syngas) with mainly hydrogen and carbon monoxide, but a certain amount of the residual biomass has to be used as fuel providing the higher temperature needed for the process.

The advantage of gasification is that can be used in a cogeneration system producing electricity in a combustion turbine, and then generate superheated steam with further electricity generation in expansion turbines. Remaining thermal energy

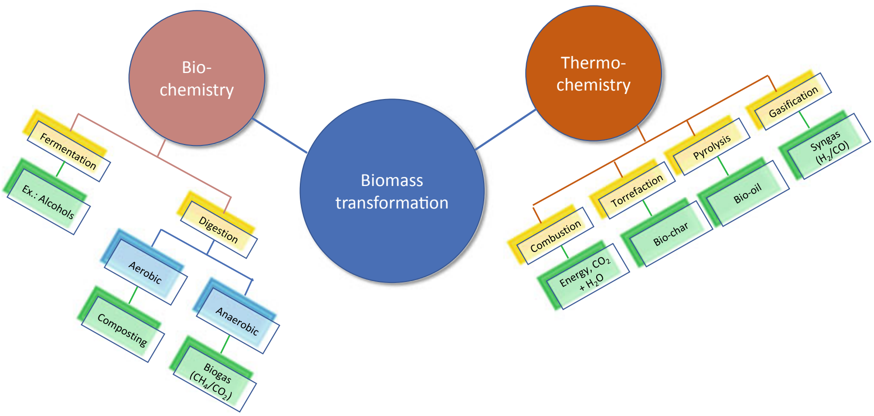

Fig. 1 Biomass general processing paths

can be used for process heating or through an absorption refrigeration system, generating a cold process utility. Direct combustion of residual biomass does not allow using a combustion turbine to increase energy efficiency.

The present discussion will be centred on gasification technology where a preliminary assessment for the production of chemicals, and electricity generation is presented by (Lozano and Lozano 2018). This paper compares chemicals production, as well as electricity generation. On an annual sales basis urea and ammonia had the highest sales value, also the production of Fischer-Tropsch liquids was done (through steam gasification technology) these having the lowest sales value. It is worth noting that prices for chemicals and energy tend to fluctuate over time and that this uncertainty ought to be taken into consideration on assessing the technology selection. Further refining is achieved by incorporating hydrogen or methanol fuel cells to generate electricity from both gasification processes.

Gasification is carried out with various equipment types, Downdraft gasifiers (Reed and Das 1988), upward draft, bubbling fluidised beds (Rauch no date; Corella et al. 1998; Hofbauer et al. 2002; Pröll et al. 2006; Corella et al. 2007, 2008); and circulating fluidised beds (Shadle et al. 2002; Spath and Dayton 2003; Li et al. 2004; Corella and Sanz 2005; Milbrandt 2005; Spath et al. 2005).

A comparison between combustion and gasification economics to generate energy, and the logistics variables was carried out by (Caputo et al. 2005). The comparison was made between combustion and high pressure superheated steam generation to further generate electricity in expansion turbines; and, fluidised bed gasification to produce a syngas that is combusted in a gas turbine, where hot combustion gases are used to generate high pressure superheated steam, producing electricity in expansion turbines. From a thermodynamic point of view the latter technology is more energy efficient than the former. A maximum efficiency 45% for gasification-steam technology is achieved, while the combustion-steam reaches 30%. Also, the biomass consumed for a certain power level output is less than for gasification-steam. Finally, net present value for gasification-steam technology was less than for combustion in the plant power range studied. Relevance of this research lies in the economic analysis that takes into account plant capital investment and operating costs.

The relevance of gasification technologies is presented in (Wang et al. 2008) stressing the various routes for energy production, such as combined heat and power for electricity; hydrogen production; Fischer-Tropsch liquids (FTL), methanol and dimethyl ether; and bio-based products obtained through fermentation using syngas. But an economic analysis regarding capital investment and operating costs is lacking, as well as energy efficient calculations for the presented technologies.

Liquids fuels are relevant for the market, due to their high energy content per unit volume, and ease of transporting and storage. Table 3 presents higher heating values for various fuels on a volume basis, where liquid petroleum products have the highest values, while natural gas and hydrogen the lowest.

Integrating gasification with Fischer-Tropsch liquids permits assessment of the adequacy of the technology configuration, and its economic feasibility using biomass as raw material, (Tijmensen et al. 2002). From this study, it was found that the operating pressure conditions indicate a higher energy efficiency, and that operating costs,

Table 3 Heat content for various fuels (HHV), volume base

	Heat content (HHV)
	MJ/m^3
Diesel	41,724
Residual oil	41,699
Fuel oil no. 6	40,651
Kerosene	39,339
Distillate no. 2	38,270
Wax paraffin	36,724
Gasoline	34,635
1-Butene	28,692
Propylene	25,442
Propane	24,822
LPG	23,605
Ethylene	20,441
Ethane	20,441
Natural gas	38.4
Hydrogen	13

though high (order of 16 US dollar/GJ), can benefit from large scale production and catalyst improvement, when selectivity inclines towards higher carbon compounds.

Comparing gas to liquids (GTL) and biomass to liquids (BTL) conversion, when producing Fischer–Tropsch (FTL) fuels (Boerrigter 2006) analysed capital investment and production costs as a function of plant capacity. Using a 15% ROCE (Return on Capital Employed) there is a plant capacity with an FTL price that is equal to a diesel price of 3.207 US dollar/gal (EIA for 20-August 2018). As discussed by (Tijmensen et al. 2002) plant capacity can make BTL economically profitable.

4 Energy and Chemicals Processing Technologies Based on Syngas Obtained Through Gasification

Starting with syngas generated through gasification, as stated in Sect. 2, a similar discussion can be had for a set of technologies that use residual biomass for chemicals production, for generating liquids fuels, or simply by combusting syngas in a cogeneration plant, producing electricity.

In the present chapter two main reaction paths are considered for processing residual biomass:

(a) Using air in sub-stoichiometric ratio to generate a gas stream containing hydrogen, carbon monoxide, methane, carbon dioxide and nitrogen as their main components (avoiding total combustion)

(b) Using steam at high temperatures (800–900°C) generating a gas stream with mainly hydrogen, carbon monoxide, and lesser amount of methane, carbon dioxide; practically no nitrogen present.

The first path is energy self-sustained due to the exothermic reaction; while the second path is endothermic and it needs heat to sustain the process, this is provided for example by using two fluidised beds. The endothermic section renders a fluidised solid with char (typical composition of 74.7%C, 6.55%H, 18.7%O, plus minor amount of nitrogen and sulphur) that is sent to a second fluidised bed where the char is combusted in air, providing the heat needed and recycling the solid to the first fluidised bed (Spath et al. 2005).

The syngas with nitrogen, generated in the first path can yield ammonia, then urea or it can be combusted in a gas turbine producing electricity; the exhaust gases are used to produced high pressure superheated steam, which is then sent to an expansion turbine producing further electricity.

The syngas with high carbon monoxide and hydrogen content, from the second path can yield methanol, formaldehyde or Fischer-Tropsch liquids. Using the water gas shift reaction, converting carbon monoxide to hydrogen and carbon dioxide, the process generates high purity hydrogen that can be used as fuel, in fuel cells, or for the production of chemicals.

Each technology has a specific functionality regarding capital investment and production costs vis-a-vis plant capacity. This is important when selecting locations to install processing facilities and choosing what can be produced on the site. Normally capital investment per unit production capacity, as well as production costs per unit production capacity decrease as plant capacity increases.

5 Geographic Information Systems (GIS) and Residual Biomass

A Geographic Information System (GIS) is an integrated geographic data collection system with various functionalities, coupled with software to manage the information, as well as displaying it graphically. Using the data options, it can be used either to select specific data or to calculate numerical information for decision-making.

Agricultural biomass in any country is distributed in many regions and has specific geographic locations. For instance, not everywhere corn is produced, either in Mexico or the USA. For the other crops considered in this chapter a similar argument can apply.

Using GIS to assess residual biomass availability for processing, first through gasification and second to produce energy or liquid fuels or chemicals, allows the plant location to be determined through mathematical methods.

For example, potential biomass supply in the US for energy crop (switchgrass) using a GIS model, considering costs and environmental impacts, is presented by (Graham et al. 2000), taking into account yield and transportation costs. The delivered feedstock price is in the range of 33 to 55 US dollar/dry Mg in a facility processing 100,000 Mg/year. Prices are calculated using a net present value approach for energy productions costs, also land and management; and energy crop yield per hectare. Calculations were done for 11 states in the US.

An assessment of potential biomass resources available in Central America was analysed by Cutz et al. (2016). Their work covered the Belize, Guatemala, Honduras, El Salvador, Costa Rica, Nicaragua, and Panamá areas. They considered six factors relating to biomass conversion: Resource availability; Technology state; Flexibility; Costs; Product-market; and Policies. They concluded that the crucial factors to be considered in the design of an energy system are (based on their order of importance) resource availability; personnel competence; engineering companies; market availability; policies; and manufacturing equipment. Additionally, owing to the limited availability of fossil fuels, Central American countries feature ligno-cellulose based biomass as having resource potential.

In a similar way biomass availability and supply logistics for an optimal biorefinery site location can use GIS, as in the case of Georgia in the USA, where cotton stalks as residual biomass (Sahoo et al. 2016) produce pellets as fuel in a sustainable way in the state of Georgia, USA. They take into account crop residues and energy crops, but with restriction in order to provide a sustainable long-term soil health, using a soil conditioning index to minimise soil erosion. The two caveats can be applied to specific sites, that are susceptible to use GIS. Authors coupled GIS data with artificial neural networks, suitable sites and optimised to minimise transport distance and delivered cost, thereby pinpointing seven optimal processing plant locations in Georgia with a total plant capacity of 200,000 dry Mg.

For European regions, sustainable potential crop residues are assessed, besides considering the residue to crop or product ratio. Additional considerations, as stated above, are alternate uses for residues such as animal feedstock, soil cover to maintain a humus balance and diminished soil erosion (Haase et al. 2016). As already mentioned, GIS modelling allows to manage high resolution spatial data, along with attached ecological restrictions, such as soil carbon content, erodibility and protected areas. With other limitations, such as the location of cities, towns, villages location. The assessment calculated residual biomass availability for Germany of 8–13 10^6 Mg/year. Four European regions were analysed: West Midlands, Île de France, Wallonia, North Rhine-Westphalia, and South Netherlands.

Also, Haase et al. (2016) and Ketzer et al. (2017) analysed the variability of various residue sources (cereals, root crops, oil plants, cattle, pigs, sheep, and other animal residues) for bioenergy generation in five regions of the continent: West Midlands (UK), North Rhine-Westphalia, Wallonia (Germany), South Netherlands, and Ile-de-France. They found that the "maximum sustainable residue potential" varies greatly between regions and residue type.

The case of bioenergy in India from agricultural and cattle residues is analysed by (Brahma et al. 2016), they proposed using biomethanation technology where residues are anaerobically fermented to produce biogas (65% volume methane, 35% volume carbon dioxide). GIS model is used for power plant location, stipulating several electric power capacities in the assessment (0.5 to 2.5 MW).

Another GIS-based analysis for biorefineries or storage depots in the US is discussed by (Gonzales and Searcy 2017), taking into account herbaceous biomass, underlining transportation costs, and reflecting the residual biomass's low density, which implies moving larger volumes per unit mass. Emphasis is put on residue pre-processing in situ to lower transport costs. Specific US state data suggest the possibility of having stranded biomass in certain regions.

This previous information was incorporated into the GIS model so as to maximise access to biomass within a certain radius, along with a specified minimum biomass amount for supply to the processing facility. Topographical details are also incorporated so as to exclude wetlands, open water, forests, and developed areas, along with location proximity to road and rail links. Three scenarios were analysed giving results for biorefinery biomass processing ranging from 754×10^3 dry Mg/year to $1{,}795 \times 10^3$ dry Mg/year; and depots capable to handle from 126×10^3 dry Mg/year to 209×10^3 dry Mg/year.

GIS modelling coupled with optimisation procedures and applied for using residual biomass in energy or chemicals production schemes can provide a powerful tool for decision-making. A supply chain platform is discussed by (Lin et al. 2015) correlating farm data with transport costs, pre-processing of the biomass, and then transport to a biorefinery site with its appropriate costs, when producing ethanol. Where objective function for optimisation is minimising the sum of biomass purchase and transport costs (to pre-processing facility and to biorefinery), and finally the associated processing facility costs; the latter implies maximising profitability. This platform allows selecting location for pre-processing and processing facilities from the biomass in several counties in USA.

Another contribution using a GIS model coupled to optimisation, using biomass residues from forestry and agriculture is presented by (Zhang et al. 2016) where the intent is to replace some of the fossil fuels consumption in transportation with biofuel (ethanol).

Considering biomass harvesting areas, transportation cost, and biofuel facility location, biomass inventory is taken into account on a time used basis for supplying the processing facility adequately, with associated cost. The optimisation procedure is a Mixed-Integer Linear Programming (MILP) where the objective function minimises delivered biomass cost, inventory cost, energy cost and emissions cost. A study was done for Michigan State in the US where, for producing from 114 to 1,135 10^6 L biofuel per year, the results give optimal counties for supplying the processing facilities, along with locations for the latter.

Considering electricity cogeneration, biofuels production, thermal power plants and district heating for Ivanjica municipality in Serbia (Vukašinović and Gordić 2016) the authors used a GIS model for cost-effective investments using biomass. Biomass availability was related to an optimisation procedure where the net present value quotient (NPVQ) is maximised. The NPVQ relates the Net Present Value (NPV) to Capital investment, and NPV is calculated with annual profit and capital investment. Hence the connection between biomass potential (through GIS) and economic criteria for decision making is proposed by the authors.

Continuing processing sites locations based on GIS using a sequential approach coupling GIS location with optimal planning for energy and chemicals production Santibañez et al. (2019).

In the case of Mexico Santibañez et al. (2018) have developed a system to locate processing sites for residual biomass using GIS that includes various criteria that put restrictions, as well as considering biomass availability, linked to various crops produced in municipalities throughout the country, taking into account uncertainty due to crop yield variation through time.

6 Case Study of Mexico and Residual Biomass Use for Energy and Chemicals

The above-mentioned GIS studies and assessments postulated a certain end use for the collected residual biomass. Though valid, they lack the systemic outlook needed to address the task. From a biorefinery point of view, besides residual biomass availability, there is a need to select the most profitable processing technologies, either for energy production, liquids fuels, or chemicals, required for the market. That needs a coupled approach using GIS modelling with an optimisation procedure for maximising profit for the overall processing plants in the optimal locations, as well as considering uncertainty in residual biomass due to time variations in crop production.

Variability through time in crop production is a source of uncertainty that has an impact on residues; estimated residual biomass in Mexico for the selected crops from 2009 to 2014 is presented in Table 4. The average value for total residues is close to 55×10^6 Mg with a standard deviation of 9.7% on average value. Hence biomass must be taken as a stochastic variable, which is relevant to the selection of a processing plants location, as well as to plant design for the appropriate processing technologies. The largest biomass contributions comes from corn stover, sorghum, wheat, and sugar cane.

For example, corn stover variability through time and for each state is shown in Table 5, where standard deviation varies from 7 to 78% of average. Furthermore, in Figs. 2 and 3 corn stover variation for two municipalities in different states, show clearly the fluctuations for different years. For Sinaloa state standard deviation fluctuates from 19 to 38%, while for Hidalgo state it goes from 63 to 79%. This exemplifies variability which occurs in all municipalities with harvesting sites.

For Mexico as a country standard deviation for Corn stover is 15%. See Fig. 4 The above discussion underlines residual biomass variability, and that needs to be considered when locating processing facilities to maximise profit.

Besides residual biomass availability at selected locations to be able to process it, variables such as water bodies, wetland zones, natural protected areas, and archaeological sites need to be avoided. A GIS model adequately incorporates all the other

Table 4 Residual biomass variability for selected crops and total mass in Mexico

Crop	Residue (Mg)							
	2009	2010	2011	2012	2013	2014	Average	StdDev
Agave	141,375	145,705	197,547	192,761	212,881	267,385	192,942	42,527
Rice	427,420	352,830	282,049	290,529	292,258	377,258	337,057	53,585
Sugar cane	6,717,342	6,956,894	6,907,064	7,188,451	8,595,191	7,650,832	7,335,962	634,678
Barley	1,387,206	1,627,510	1,265,665	2,585,050	1,711,828	1,403,874	1,663,522	438,730
Corn	22,604,249	26,923,916	20,512,497	27,136,951	29,354,484	19,085,219	24,269,553	3,761,431
Pecan nut	57,236	39,088	48,045	55,443	57,879	224,853	80,424	64,919
Sorghum	14,155,329	14,796,008	12,843,928	15,433,596	15,846,271	11,961,531	14,172,777	1,380,484
Wheat	7,624,118	6,847,358	6,770,353	6,616,765	6,331,540	7,287,768	6,912,984	427,522
Total	53,114,275	57,689,309	48,827,147	59,499,547	62,402,331	48,258,720	54,965,222	5,313,042

Table 5 Estimated corn stover mass variability (in thousands Mg) for each state in Mexico

State (10^3 Mg)	Area (km^2)	Residue (10^3 Mg)							
		2009	2010	2011	2012	2013	2014	Average	Std Dev
Aguascalientes	5,559	794	942	816	960	1,181	53	791	353
Campeche	57,277	230	317	377	284	363	335	318	50
Chiapas	73,612	1,005	1,150	1,282	1,159	1,262	971	1,138	117
Chihuahua	246,973	1,382	1,635	1,173	1,853	1,857	1,126	1,504	298
Coahuila	150,671	70	73	101	88	592	36	160	194
Durango	122,131	931	809	569	1,302	1,594	341	924	423
Guanajuato	30,340	838	1,195	1,034	1,199	1,475	1,172	1,152	192
Guerrero	63,565	947	1,178	1,094	1,089	828	1,096	1,039	116
Hidalgo	20,655	465	617	491	627	613	537	558	64
Jalisco	77,966	3,083	4,481	3,341	4,824	5,005	2,864	3,933	862
México	22,227	1,964	2,130	1,781	2,083	2,766	1,480	2,034	392
Michoacán	58,296	976	1,259	1,144	1,487	1,441	1,594	1,317	212
Nayarit	27,817	204	212	231	348	362	139	249	80
Nuevo León	63,559	376	726	77	274	195	68	286	224
Oaxaca	93,960	510	555	595	624	540	534	560	39
Puebla	34,152	714	1056	648	1033	961	779	865	159
Querétaro	11,589	721	840	737	793	878	235	701	215
San Luis Potosí	60,500	101	150	102	131	152	155	132	23
Sinaloa	56,803	4,320	4,313	2,417	3,010	2,995	3,041	3,349	716
Sonora	180,841	87	202	78	153	108	112	123	42

(continued)

Table 5 (continued)

State (10^3 Mg)	Area (km^2)	Residue (10^3 Mg)							
		2009	2010	2011	2012	2013	2014	Average	Std Dev
Tabasco	24,695	97	86	109	150	128	107	113	21
Tamaulipas	79,426	353	447	404	430	334	435	401	43
Tlaxcala	3974	487	543	217	498	488	301	422	120
Veracruz	71,461	965	817	880	1,067	1,000	1,044	962	89
Yucatán	39,533	37	101	123	100	87	87	89	26
Zacatecas	74,480	574	621	298	1,111	1,655	277	756	487
Mexico (country)	**1,956,239**	**22,418**	**26,696**	**20,340**	**26,917**	**29,102**	**19,074**	**24,091**	**3,695**

Time series from 2009 to 2014

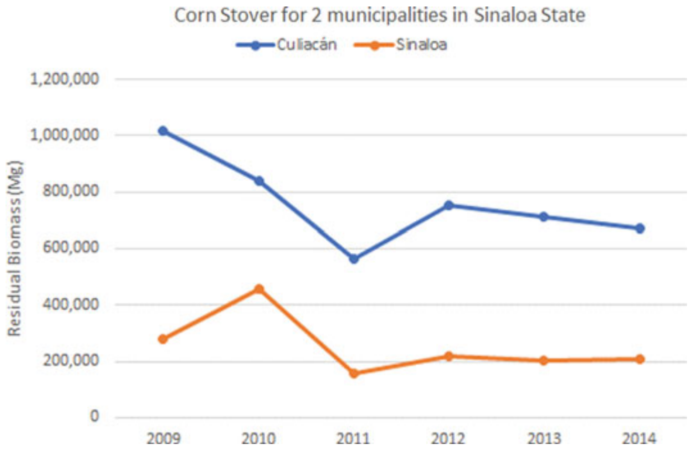

Fig. 2 Corn stover variability for two municipalities in Sinaloa state

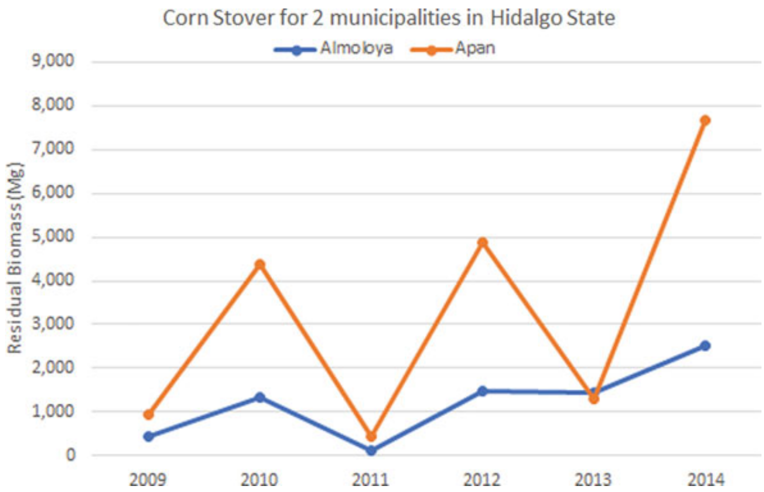

Fig. 3 Corn stover variability for two municipalities in Hidalgo state

salient topographical features such as proximity of towns, cities; roads and highways network, power grid networks; oil and gas pipelines, and the terrain's gradient. Climate issues such as frequency of drought; hailstorms; and, hurricanes, are also considered.

When planning to locate processing plants in regions with high biomass availability, including yearly uncertainty in supply, only those regions having high biomass availability identified using GIS spatial data are deemed as viable. But this first approach needs to be complemented using the constraints from other GIS layers such as:

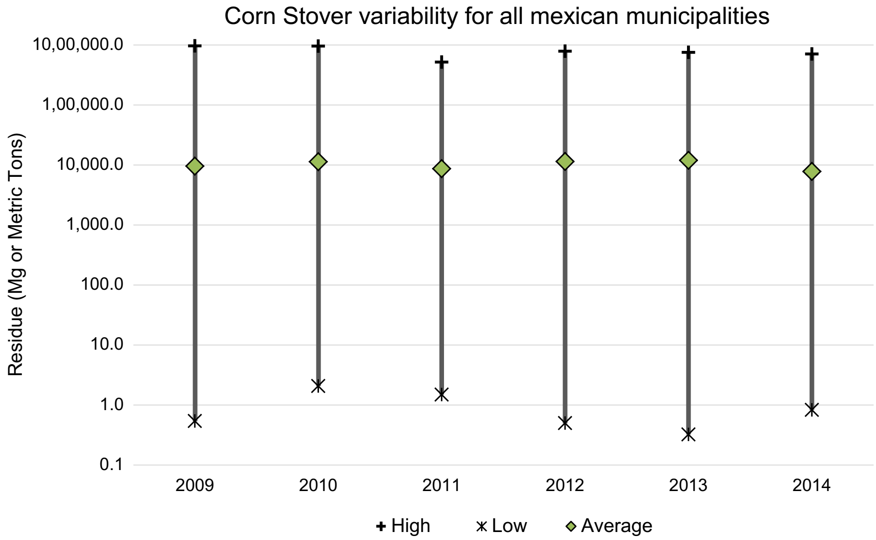

Fig. 4 Corn Stover variability for all Mexican municipalities

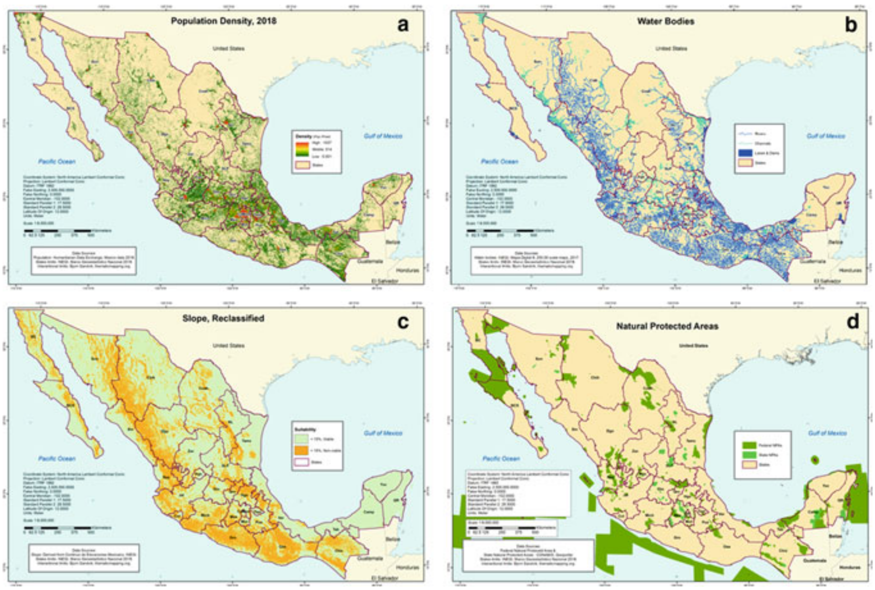

Fig. 5 Population Density (**a**), Water Bodies (**b**), Slope (**c**) and Natural Protected Areas (**d**)

(a) Population level and Population density Fig. 5a, related to towns and cities, distance greater than:

1. 500 m for 500–1,000 inhabitants
2. 1 km for 1,000–2,000 inhabitants
3. 2 km for more than 2,000 inhabitants
4. 2 km for large urban communities.

(b) Water bodies (Fig. 5b), wetland zones, the distance location in an 800 m radius for permanent bodies, and 100 m radius for intermittent bodies.
(c) Terrain slope lower than 15% for high viability Fig. 5c.
(d) Natural protected areas are excluded (Fig. 5d), and locations should have a buffer zone of 800 m radius from such areas.
(e) Regions with primary vegetation are excluded (Fig. 6a).
(f) Infrastructure related such as:

1. Power grids, buffer distance of at least 100 m for locations (Fig. 6b).
2. Roads and highways 30 m < distance > 24 km; airports and heliports, distance > 800 m (Fig. 6c).

(g) Historic and archaeological sites excluded (Fig. 6d).

Using GIS, the average agriculture produce data in each municipality was associated to its corresponding municipal polygon, and then it was possible to display the estimated crop residue by municipality.

Maps for the corn crop are presented in Figs. 7 and 8.

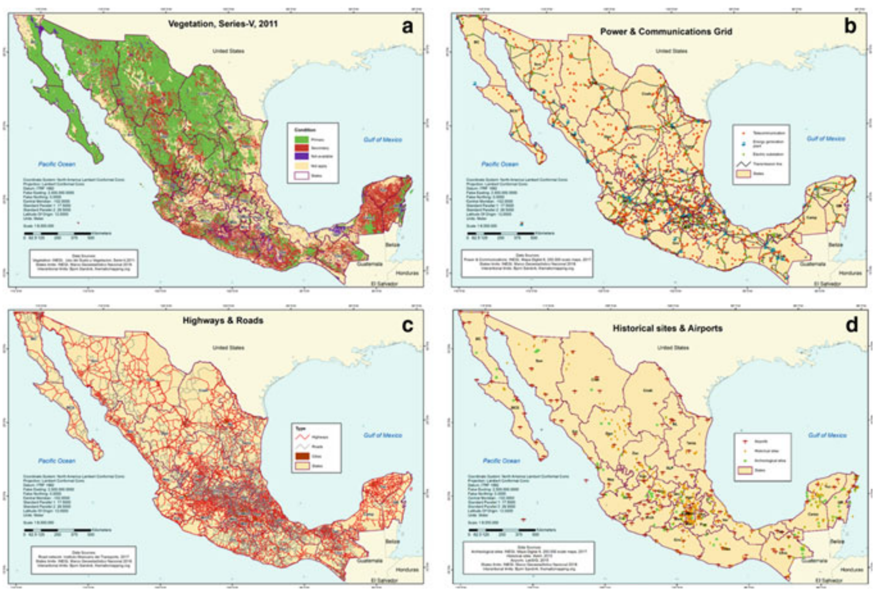

Fig. 6 Vegetation (**a**), Power & Communications Grids (**b**), Highways & Roads (**c**), and Historical Sites, Airports (**d**)

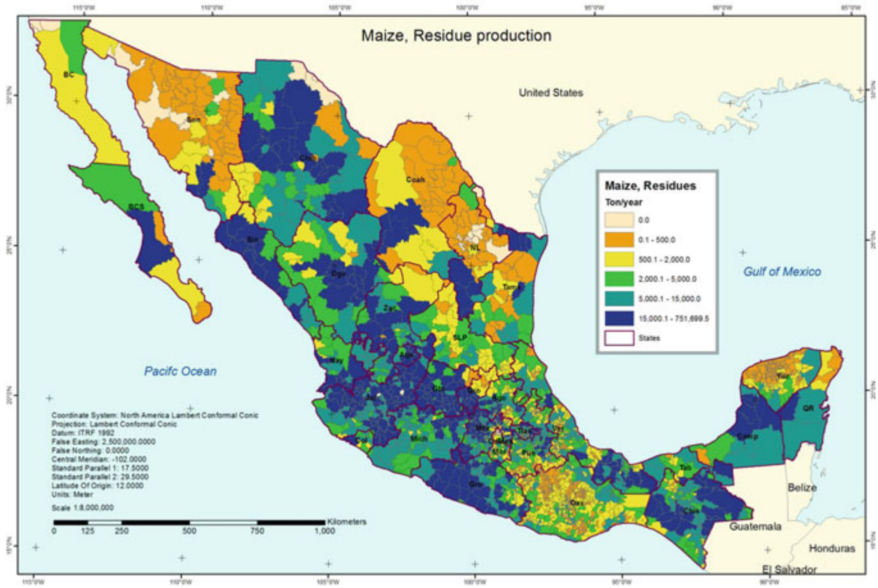

Fig. 7 Estimated available mass of maize corn stover residue (Metric Ton/year or Mg/year), data for the years 2009 to 2014. SAGARPA (2014b)

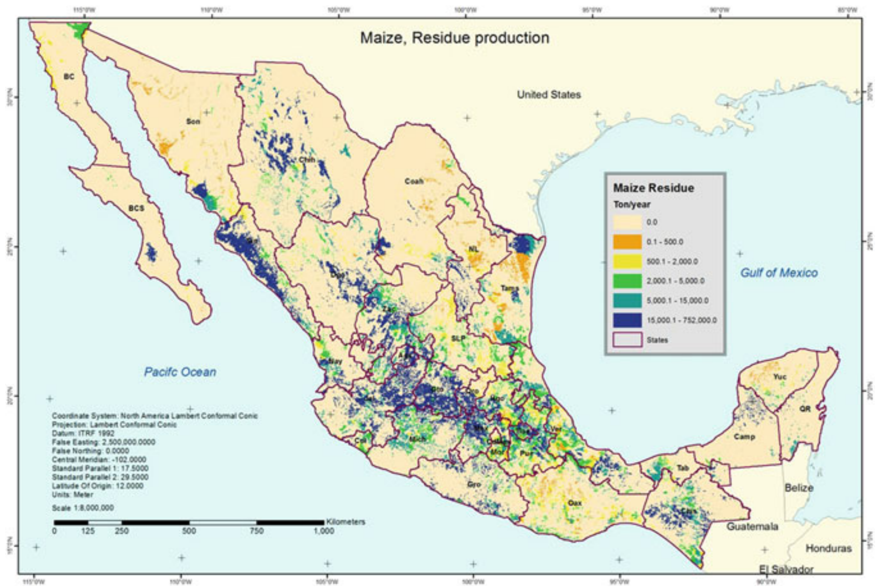

Fig. 8 Average estimated production of Maize residue (Metric Ton/year or Mg/year) assigned to agricultural areas within each municipality for the years 2009–2014

However, this approach created bias since the entire municipality area is not dedicated to agricultural activities; Comber et al. (2015) indicated that this is an important issue regarding the use of Multi-Criteri Evaluation models, since these approaches "identify suitable areas, they do not identify discrete locations". Thus, we used the Land cover/Land use map from INEGI (2017) to identify the agricultural areas within each municipality and then assigned the resulting values for crop residue to those polygons classified as "agriculture" in the municipality. This was relevant in those municipalities that have a very large area, as well as those where there were several separated agricultural areas, mostly in Mexico's northern and south-eastern parts.

Residual biomass availability data for each municipality in Mexico (SAGARPA e), can be estimated from the selected harvests, e.g. using the information for maize and calculating the corresponding corn stover. Municipal agricultural data was associated with its corresponding municipal polygon to make it possible to display the estimated crop residue regarding the municipality. However, because the entire municipality area is not dedicated to agricultural activities, this approach created bias; Comber et al. (2015) identified this as an important issue facing the use of multi-criteria evaluation models because though these approaches "identify suitable areas, they do not identify discrete locations". Thus, we used the Land cover/Land Use map from INEGI to identify the agricultural areas within each municipality and, then, assigned the resulting values of crop residue to the polygons which are classified as "agriculture" in the municipality. This was relevant in municipalities that have a very large area as well as those that have several separated agricultural areas, mostly in Mexico's northern and southeaster regions. Figure 7 shows the map of corn stover availability in Mexico from 2009 to 2014 (Colour is related to Mg/year or tonnes/year), associated with the municipality polygons, while Fig. 8 shows the same data associated with the agricultural areas within each municipality. Similar maps were produced for all the other seven crops analysed in this study.

7 Processing Facilities Location

Using irrigation district data for each municipality (SAGARPA), containing information on crops cultivated with irrigation and rainfed; the estimated available residual biomass was calculated.

GIS permits selection of suitable locations for processing facilities; Table 6 lists the sites with the available biomass, based on the above-mentioned agricultural areas for the residual biomass.

Total available residual biomass for those sites is 27,186 Gg/year, but as has been stated previously only a fraction should be used for processing. The fraction chosen is 0.60 of total available.

As stated in Sect. 3 there are two reaction paths considered for energy and chemical production.

Table 6 Selected sites for processing facilities with residual biomass availability

Plant	Biomass (Mg/y)	Site	State	Residue
1	2,132,909	Guasave-Los Mochis-Guamúchil-La Cruz	Sinaloa	1
2	705,378	Culiacán	Sinaloa	1
3	937,961	Jamay (La Barca 70)	Jalisco	1
4	458,053	Lagos de Moreno	Jalisco	1
5	587,549	Teuchitlán (Ameca 67)	Jalisco	1
6	351,973	Ciudad Guzmán (71)	Jalisco	1
7	58,292	Tomatlán (68)	Jalisco	1
8	148,127	El Grullo (69)	Jalisco	1
9	317,896	Zapopan (65)	Jalisco	1
10	139,139	Apatzingán-Uruapan-Pátzcuaro (85,86,90)	Michoacán	1
11	846,621	Zamora-Sahuayo-La Piedad (87,88,89)	Michoacán	1
12	469,659	Morelia-Zitácuaro (92,93)	Michoacán	1
13	67,999	Huetamo (92)	Michoacán	1
14	97,938	Dolores Hidalgo, San Luis de la Paz (48,49)	Guanajuato	1
15	186,689	León (50)	Guanajuato	1
16	886,897	Celaya, Cortazar (51, 52)	Guanajuato	1
17	1,375,078	Huayacocotla, Martínez de la Torre, Tuxpan (172)	Veracruz	1
18	16,926	Veracruz (173)	Veracruz	1
19	34,044	Ciudad Alemán (174)	Veracruz	1
20	187,655	San Andrés Tuxtla (175)	Veracruz	1
21	123,384	Jaltipán, San Andrés Tuxtla (176)	Veracruz	1
22	119,585	Choapas (177)	Veracruz	1
23	70,357	Pánuco (178)	Veracruz	1
24	492,296	Tuxtla Gutiérrez, San Cristobal, Villa Flores (18, 19, 21)	Chiapas	1
25	66,292	Pichucalco (22)	Chiapas	1
26	90,250	Martínez de la Torre, Coatepec (169,170)	Veracruz	5
27	862,127	Fortín (171)	Veracruz	5
28	294,632	La Antigua (172)	Veracruz	5
29	129,459	Veracruz (173)	Veracruz	5
30	793,018	Ciudad Alemán, San Andrés Tuxtla (174,175)	Veracruz	5
31	308,839	Pánuco (178)	Veracruz	5
32	2,786,146	Díaz Ordaz, Control (156,157)	Tamaulipas	4
33	1,496,707	San Fernando (158)	Tamaulipas	4
34	249,355	Abasolo, Victoria (159,160)	Tamaulipas	4

(continued)

Table 6 (continued)

Plant	Biomass (Mg/y)	Site	State	Residue
35	186,929	Mante, González (162,163)	Tamaulipas	4
36	2,164,409	León, Celaya, Cortazar (50,51,52)	Guanajuato	4
37	1,139,609	Río Colorado (BC), San Luis Río Colorado (Sonora) [2, 193]	BC & Sonora	6
38	83,689	Hermosillo (144)	Sonora	6
39	3,036,775	Cajeme, Navojoa (148,149)	Sonora	6
40	511,154	Los Mochis, Guasave, Guamúchil (133,134,135)	Sinaloa	6
41	118,143	Casas Grandes, Buenaventura, El Carmen (28, 29, 30)	Chihuahua	6
42	241,041	Delicias (40)	Chihuahua	6
43	243,557	Zamora, Sahuayo, La Piedad (87,88,89)	Michoacán	6
44	32,965	Morelia (91)	Michoacán	6
45	30,643	Apodaca (101)	Nuevo León	6
46	295,577	Dolores Hidalgo, Cortazar (48,52)	Guanajuato	6
47	550,840	Dolores Hidalgo, León, Cortazar (48,50,52)	Guanajuato	7
48	139,090	Cappellano, Huamantla (165,166)	Tlaxcala	7
49	58,521	Libres (114)	Puebla	7
50	113,820	Lagos de Moreno (66)	Jalisco	3
51	53,495	Ameca (67)	Jalisco	3
52	17,822	Delicias (40)	Chihuahua	8
53	72,030	Santiago Ixcuintla, Tepic (95,99)	Nayarit	2
54	63,643	Apatzingán (85)	Michoacán	2
55	48,835	Champotón, Escárcega (10,11)	Campeche	2
56	48,349	Veracruz, Ciudad Alemán (173,174)	Veracruz	2
57	26,251	Colima, Tecomán (16,17)	Colima	2
58	20,011	Zacatepec (94)	Morelos	2

Note 1 Residue type 1 corn stover, 2 rice straw, 3 agave bagasse, 4 sorghum straw, 5 sugar cane bagasse, 6 wheat straw, 7 barley straw, 8 pecan nut shell
Note 2 Number in sites refer to irrigation districts

So, a combination of electrical energy, fuels and chemicals can be assessed economically.

The mass or electrical energy produced per residual biomass is presented in Table 7. These data have been obtained through process design simulation with Aspen Plus Chemical Process Simulator (*Aspen Plus*, no date), using the gasification process as start-up.

Table 7 Mass or electrical energy produced per Residual Biomass

Product		Units
Ammonia	291	kg/Mg biomass
HCHO 37% wt	572	kg/Mg biomass
Electricity, steam, and refrigeration	1,315	kWh/Mg biomass
Fischer-Tropsch liquids	341	kg/Mg biomass
Urea	514	kg/Mg biomass
Methanol	365	kg/Mg biomass

Table 8 Prices for products in US dollars

Product	Units	Price
Ammonia	US $/Mg	571.8
HCHO 37% wt in water	US $/Mg	463.0
Electricity, steam, and refrigeration	US $/MWh	56.9
Fischer-Tropsch liquids	US $/Mg	822.0
Urea	US $/Mg	335.0
Methanol	US $/Mg	313.0

Sources ICIS (2006), Makan (2013), IntraTec (2016, 2017), CENACE (2018), Farm-Futures (2018)

Economic viability depends on product generated in each processing facility. For selecting products or products the objective function chosen is overall profit for all facilities.

For a profitability assessment the information needed are product prices to calculate revenue, manufacturing cost, raw material cost, and transport cost for residual biomass from harvesting site to processing facilities and from processing facilities to distribution centres.

Regarding product prices these are shown in Table 8 and although prices fluctuate over time depending on market conditions, those in the Table have been used for evaluation. Similarly, raw material prices are shown in Table 9 for residual biomass types selected.

For evaluating manufacturing costs, a function (specific manufacturing cost) was defined that represented the manufacturing cost as a function of production capacity divided by the production capacity. The equation used is shown in Fig. 9.

The processing technologies selected, and their corresponding manufacturing cost parameters are shown in Table 10; this data will be needed for profitability assessment. It also shows lower and upper capacity bounds, as well as a reference capacity, which have been obtained from the literature.

Economically each technology has a break-even production capacity, below which there is loss, above there is profit. As an example, for ammonia and Fischer-Tropsch liquids Fig. 10 shows behaviour as a function of residual biomass flow. Ammonia has a higher break-even value for residual biomass, than Fischer-Tropsch liquids.

Table 9 Residual biomass prices in US dollars

Residue	US \$/Mg	References
Corn stover	34.86	Reyes Muro et al. (2013)
Rice straw	30.00	Perlack and Stokes (Leads) (2011)
Agave bagasse	33.32	**
Sorghum straw	31.85	Reyes Muro et al. (2013)
Sugarcane bagasse	53.89	Chang (2015)
Wheat straw	20.13	Reyes Muro et al. (2013)
Barley straw	29.15	Reyes Muro, et al. (2013)
Pecan nut shell	33.32	**

**Average value for rice, sorghum, wheat straw, sugar cane bagasse and corn stover

$$\text{ManufCost} = \text{ManufCost}_{\text{Ref}}\left(\frac{\text{CapProd}}{\text{CapProd}_{\text{Ref}}}\right)^{m}$$

ManufCost = Manufacturing Cost, Operating labor, Supervision, Maintenance, Operating charges, Overhead, Property taxes, Depreciation, Administration costs, etc.

CapProd = Plant Production Capacity

Subindex Ref =Reference Manufacturing Cost or Reference Production Capacity

m = exponent, normally negative and <1

Fig. 9 Function to calculate manufacturing cost for processing technologies

Table 10 Manufacturing cost parameters for processing technologies

Processing technology	$\text{CapProd}_{\text{ref}}$	Units	$\text{ManufCost}_{\text{ref}}$	Exponent	Units
Ammonia	459,353	Mg/y	358.3	−0.2153	\$US/Mg
Formaldehyde	68,100	Mg/y	250.0	−0.1390	\$US/Mg
Electricity, steam, and refrigeration	44,112	MWh/y	23.35	−0.1770	\$US/MWh
Fischer-Tropsch liquids	1,549,900	Mg/y	409.7	−0.16457	\$US/Mg
Urea	1,187,200	Mg/y	299.42	−0.0757	\$US/Mg
Methanol	913,242	Mg/y	214.25	−0.3063	\$US/Mg

For each processing facility, as listed in Table 11, and with the available residual biomass for each site, profit for each technology was calculated, and the one with the highest value chosen as the one to be installed in the site. No restrictions were attached to this procedure and the cumulative profit for all sites had a value of 1,014 million US dollar/year, with revenue of 4,098 million US dollar/year. The former represents

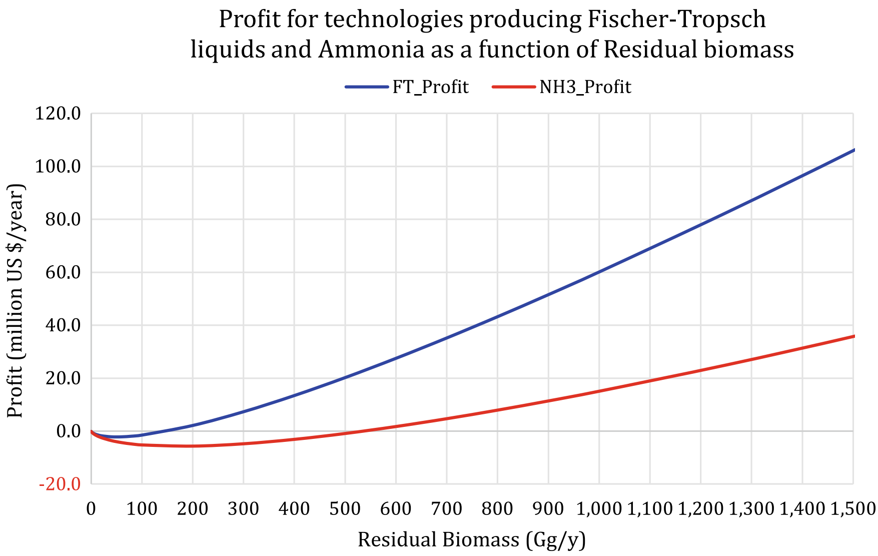

Fig. 10 Break-even behaviour for ammonia and Fischer-Tropsch Liquids behaviour as a function of residual biomass used

24.7% profit over revenue. The main products were (a) 3,262 Gg/year of Fischer-Tropsch liquids and 3,060 Gg/year of Formaldehyde (37% wt. in water); no electricity was produced, and showing specific details for processing sites in Table 12.

Restricting the profitability assessment with no Formaldehyde production, this resulted in cumulative profit for all sites with a value of 749 million US dollar/year, and revenue of 3,921 million US dollar/year. The former represents a 19% profit over revenue. The main products were (a) 4,545 Gg/year of Fischer-Tropsch liquids; and 3,259 GWh/year of electricity, process heat and refrigeration, as listed in Table11, and showing specific details for processing sites in Table 13.

Several municipalities in various Mexican states, with smaller residual biomass production, were not considered in the previous analysis. Complementing energy production technology for electricity generation, ranging from 10 to 150 kW, is available in the market through small scale gasifiers. Municipalities from the states of Chiapas, Guerrero, Michoacán, Nuevo León, Oaxaca, Puebla, Veracruz, and Yucatán were considered, and 1,752 GWh/year of electricity can be generated.

Table 14 presents the number of gasifiers and the electricity production for each power type, supplying electricity to local communities, where otherwise there is no supply from a the public power company, and this impacts 811 communities in the aforementioned states. The states of Chiapas, Guerrero and Oaxaca have the lowest Human Development Index in Mexico, as well as having a high marginalisation index (CONEVAL 2011; National Council for the Evaluation of Social Development Policy 2012; Programa de las Naciones Unidas para el Desarrollo 2015).

Table 11 Summary for sales, profit, products and Residual biomass used in both options

Residual biomass available	Gg/year	27,186	
Processing facilities		58	
Mexican states	Sinaloa, Jalisco, Michoacán, Guanajuato, Veracruz, Chiapas, Tamaulipas, Sonora, Chihuahua, Nuevo León, Tlaxcala, Puebla, Nayarit, Campeche, Colima, Morelos		
Types of residues used	Corn stover, Sugar cane bagasse; Sorghum, Wheat, Barley and Rice Straws; Agave bagasse, Pecan nut shell		
First option (producing for the largest profit)			
Annual sales	Million US $/year	**4,098**	
Profit	Million US $/year	**1,014**	
% Profit/sales		**24.7%**	
Fischer-Tropsch liquids	Gg/year	3,262	
Fischer-Tropsch liquids	Barrels/year	24,661,658	
Formaldehyde	Gg/year	3,060	
Residual biomassused (first option)			**Biomass Cost (10^6US $/y)**
Corn stover	7,086,419	Mg/year	247.03
Sugar cane bagasse	1,518,394	Mg/year	81.83
Sorghum straw	4,018,558	Mg/year	127.99
Wheat straw	3,692,334	Mg/year	74.33
Barley straw	558,250	Mg/year	16.27
Agave bagasse	157,125	Mg/year	5.24
Pecan nut shell	16,737	Mg/year	0.56
Rice straw	262,121	Mg/year	7.86
Total	17,309,938	Mg/year	561.11
Second option (no Formaldehyde production)			
Annual sales	Million US $/year	**3,921**	
Profit	Million US $/year	**749**	
% Profit/sales		**19.1%**	
Fischer-tropsch liquids	Gg/year	4,545	
Fischer-tropsch liquids	Barrels/year	34,362,647	
Electricity production, process heat and refrigeration	GWh/year	3,259	
Electric power	MW	372	
Residual Biomassused (Second option)			**Biomass Cost (10^6US $/y)**
Corn stover	9,268,818	Mg/year	323.11

(continued)

Table 11 (continued)

Residual biomass available	Gg/year	27,186	
Sugar cane bagasse	926,464	Mg/year	49.93
Sorghum straw	4,551,417	Mg/year	144.96
Wheat straw	4,882,849	Mg/year	98.29
Barley straw	735,264	Mg/year	21.43
Agave bagasse	361,476	Mg/year	12.04
Pecan nut shell	38,505	Mg/year	1.28
Rice straw	603,025	Mg/year	18.09
Total	21,367,818	Mg/year	669.14

8 Conclusions and Recommendations

For several regions in Mexico there is adequate residual biomass availability for energy generation, first through gasification processes, and then either by direct electricity generation or through chemical conversion as Fischer-Tropsch liquids. However, there is also the possibility for generating as well chemicals for the market. There are two production levels that can be attained: large scale biomass availability (with more than 30,000 Mg/year); and small-scale biomass availability (less than 30,000 Mg/year), that allows the installation of processing facilities in several municipalities.

For the large-scale option a total of 58 processing facilities were identified using eight types of residual biomass, based on the GIS analysis for optimal location, close to municipalities producing the residual biomass.

In this case, two options have been presented in this chapter: The production of Fischer-Tropsch liquids and Formaldehyde where a profit of 1,014 million US $/year can be achieved; or, the production of 24.6 million barrels/year of Fischer-Tropsch liquids, and 3,060 Gg/year of formaldehyde, using 17.31 Tg/year of residual biomass. The second option produces Fischer-Tropsch liquids and Electricity with an estimated profit of 749 million US $/year from producing 34.4 million barrels/year of Fischer-Tropsch liquids and electricity at 3,259 GWh/year, using 21.37 Tg/year of residual biomass, needing 372 MW installed electricity generation plants.

Though Formaldehyde has specific uses in the market a further in-depth assessment needs to be carried out to ascertain an optimal production to avoid flooding the market, and the possibility of lowering the price. For that reason, the second evaluation was carried out with no Formaldehyde produced, and then Fischer-Tropsch liquids and Electricity were the products that generated a larger profit overall.

- For large scale facilities, it is necessary that an in-depth appraisal be carried out to determine the storage facilities and capacities needed to be done to feed these large processing facilities, on the different sites selected. Throughout the country

Table 12 Example for results with no restrictions selecting processing path. Profit and Revenue for a partial sample of processing facilities

	Profit	Production capacity	Residual biomass			Revenue
	10^6 US $/yr	Mg/y or MWh/yr	Mg/yr	Product type	Residual biomass type	10^6 US $/yr
Guasave-Los Mochis-Guamúchil-La Cruz	79.08	436,009	1,279,745	Fischer–tropsch	Corn stover	358.40
Culiacán	20.09	136,100	423,227	Formaldehyde	Corn stover	63.01
Jamay (La Barca 70)	22.95	191,738	562,776	Fischer–tropsch	Corn stover	157.61
Lagos de Moreno	20.09	136,100	274,832	Formaldehyde	Corn stover	63.01
Teuchitlán (Ameca 67)	20.09	136,100	352,530	Formaldehyde	Corn stover	63.01
Ciudad Guzmán (71)	17.43	120,713	211,184	Formaldehyde	Corn stover	55.89
Tomatlán (68)	1.78	19,992	34,975	Formaldehyde	Corn stover	9.26
El Grullo (69)	6.07	50,802	88,876	Formaldehyde	Corn stover	23.52
Zapopan (65)	15.44	109,026	190,738	Formaldehyde	Corn stover	50.48
Apatzingán-Uruapan-Pátzcuaro (85,86,90)	5.61	47,719	83,483	Formaldehyde	Corn stover	22.09
Zamora-Sahuayo-La Piedad (87,88,89)	20.09	136,100	507,972	Formaldehyde	Corn stover	63.01
Morelia-Zitácuaro (92,93)	20.09	136,100	281,796	Formaldehyde	Corn stover	63.01
Huetamo (92)	2.20	23,321	40,799	Formaldehyde	Corn stover	10.80
Dolores Hidalgo, San Luis de la Paz (48,49)	3.58	33,589	58,763	Formaldehyde	Corn stover	15.55
León (50)	8.10	64,027	112,013	Formaldehyde	Corn stover	29.64
Celaya, Cortazar (51, 52)	20.88	181,300	532,138	Fischer–tropsch	Corn stover	149.03
Huayacocotla, Martínez de la Torre, Tuxpan (172)	42.01	281,093	825,047	Fischer–tropsch	Corn stover	231.06

(continued)

Table 12 (continued)

	Profit	Production capacity	Residual biomass			Revenue
	10^6 US $/yr	Mg/y or MWh/yr	Mg/yr	Product type	Residual biomass type	10^6 US $/yr
Veracruz (173)	0.24	5,805	10,156	Formaldehyde	Corn stover	2.69
Ciudad Alemán (174)	0.81	11,676	20,426	Formaldehyde	Corn stover	5.41
San Andrés Tuxtla (175)	8.15	64,358	112,593	Formaldehyde	Corn stover	29.80
Jaltipán, San Andrés Tuxtla (176)	4.82	42,316	74,030	Formaldehyde	Corn stover	19.59
Choapas (177)	4.63	41,013	71,751	Formaldehyde	Corn stover	18.99
Pánuco (178)	2.31	24,130	42,214	Formaldehyde	Corn stover	11.17
Tuxtla Gutiérrez, San Cristobal, Villa Flores (18, 19, 21)	20.09	136,100	295,378	Formaldehyde	Corn stover	63.01
Pichucalco (22)	2.13	22,735	39,775	Formaldehyde	Corn stover	10.53
Martínez de la Torre, Coatepec (169,170)	2.34	30,952	54,150	Formaldehyde	Sugarcane bagasse	14.33
Fortín (171)	16.27	136,100	517,276	Formaldehyde	Sugarcane bagasse	63.01
La Antigua (172)	11.26	101,047	176,779	Formaldehyde	Sugarcane bagasse	46.78

Table 13 Example for results with no Formaldehyde productin

	Profit	Production capacity	Residual Biomass			Revenue
	10^6 US $/yr	Mg/y or MWh/yr	Mg/yr	Product type	Residual biomass type	10^6 US $/yr
Guasave-Los Mochis-Guamúchil-La Cruz	79.08	436,009	1,279,745	Fischer–tropsch	Corn stover	358.40
Culiacán	13.88	144,193	423,227	Fischer–tropsch	Corn stover	118.53
Jamay (La Barca 70)	22.95	191,738	562,776	Fischer–tropsch	Corn stover	157.61
Lagos de Moreno	5.49	93,635	274,832	Fischer–tropsch	Corn stover	76.97
Teuchitlán (Ameca 67)	9.69	120,107	352,530	Fischer–tropsch	Corn stover	98.73
Ciudad Guzmán (71)	3.17	277,707	211,184	Electricity	Corn stover	15.80
Tomatlán (68)	0.28	45,992	34,975	Electricity	Corn stover	2.62
El Grullo (69)	1.06	116,872	88,876	Electricity	Corn stover	6.65
Zapopan (65)	2.80	250,820	190,738	Electricity	Corn stover	14.27
Apatzingán-Uruapan-Pátzcuaro (85,86,90)	0.97	109,781	83,483	Electricity	Corn stover	6.25
Zamora-Sahuayo-La Piedad (87,88,89)	19.28	173,066	507,972	Fischer–tropsch	Corn stover	142.26
Morelia-Zitácuaro (92,93)	5.85	96,008	281,796	Fischer–Tropsch	Corn stover	78.92
Huetamo (92)	0.35	53,651	40,799	Electricity	Corn stover	3.05
Dolores Hidalgo, San Luis de la Paz (48,49)	0.60	77,273	58,763	Electricity	Corn stover	4.40
León (50)	1.43	147,297	112,013	Electricity	Corn stover	8.38
Celaya, Cortazar (51, 52)	20.88	181,300	532,138	Fischer–Tropsch	Corn stover	149.03
Huayacocotla, Martínez de la Torre, Tuxpan (172)	42.01	281,093	825,047	Fischer–Tropsch	Corn stover	231.06

(continued)

Table 13 (continued)

	Profit	Production capacity	Residual Biomass			Revenue
	10^6 US $/yr	Mg/y or MWh/yr	Mg/yr	Product type	Residual biomass type	10^6 US $/yr
Veracruz (173)	0.02	13,355	10,156	Electricity	Corn stover	0.76
Ciudad Alemán (174)	0.11	26,860	20,426	Electricity	Corn stover	1.53
San Andrés Tuxtla (175)	1.44	148,060	112,593	Electricity	Corn stover	8.42
Jaltipán, San Andrés Tuxtla (176)	0.83	97,350	74,030	Electricity	Corn stover	5.54
Choapas (177)	0.79	94,353	71,751	Electricity	Corn stover	5.37
Pánuco (178)	0.37	55,512	42,214	Electricity	Corn stover	3.16
Tuxtla Gutiérrez, San Cristobal, Villa Flores (18, 19, 21)	6.55	100,635	295,378	Fischer–tropsch	Corn stover	82.72
Pichucalco (22)	0.34	52,304	39,775	Electricity	Corn stover	2.98
Martínez de la Torre, Coatepec (169,170)	0.00	0	54,150	Electricity	Sugarcane bagasse	0.00
Fortín (171)	11.58	176,236	517,276	Fischer–tropsch	Sugarcane bagasse	144.87
La Antigua (172)	0.00	0	176,779	Fischer–tropsch	Sugarcane bagasse	0.00

Profit and revenue for a partial sample of processing facilities, where only Fischer-tropsch liquids and electricity are produced

Table 14 Small communities' gasifiers that produce electricity locally

Gasifier power (kW)	Number of gasifiers	Electricity produced (GWh/year)
150	4556	1737.0
100	48	7.2
20	163	8.2
10	12	0.2

there are two main crop seasons: spring–summer and autumn–winter that need to be considered to provide adequate raw material inventory for the plants, and these would need to be considered with more detail.

- For small scale facilities the recommendation is to assess those communities with no access to the main power grid, as well as to adequate roads, in order to determine the location and in situ electricity generation. For this option, the social impact on the communities, where the gasifiers will be used to generate electricity, needs to be evaluated to enhance communities' wellbeing, and public policy can also help to foster this option.
- Adequate sustainability indexes need to be applied when generating further value for residual biomass, from the presented crops, as that will provide additional cash flow for the regions and further sustainability by using a renewable resource without negatively impacting the crops that have to be available for human and livestock consumption.
- Processing sites and residual biomass location can also be addressed by using modern Machine Learning strategies such as statistical Clustering and Classification methods, Deep Learning techniques and Support Vector Machines. This will allow us to make use of extensive data bases. In some cases, the Machine Learning tool can be merged with first principles models to exploit the advantages of both traditional modelling techniques and recently developed Artificial Intelligence tools.

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Chapter 10
Collaborative Decision-Making Centres for Sustainable Energy

José Martín Molina Espinosa, Sergio Ruiz Loza, Julieta Noguez, Rafael Lozano Espinosa, and Manuel Álvarez-Madrigal

Abstract When building country-wide electricity sector models the number of variables to consider, as well as careful design to consider sustainable energy issues restrictions, poses a considerable technological execution and visualisation challenge, even more so when such models must be executed in real-time to support evidence-based decision-making process in the form of configurable scenarios. This chapter presents methodological and technological tools designed for a Collaborative Decision-Making Centre (CDMC), a facility that aims to support a group of decision-makers with real-time computed indicators for such scenarios, allowing the group to find the best alternative for problems in the field of management of energy sustainability.

Abbreviations

CDMC	Collaborative Decision-Making Centre
CEL	Clean Energy Certificates (Mexico)
CFE	Comisión Federal de Electricidad or National Utility Company
DSL	Domain Specific Language
EV-platform	Execution-Visualization software platform
KPI	Key Performance Indicators

J. M. Molina Espinosa (✉) · S. Ruiz Loza · J. Noguez · R. Lozano Espinosa ·
M. Álvarez-Madrigal (Deceased)
Tecnologico de Monterrey, Campus Ciudad de Mexico, Calle Puente 222, Ejidos de Huipulco, 14380 Tlalpan, Ciudad de México, Mexico
e-mail: jose.molina@tec.mx

S. Ruiz Loza
e-mail: sergio.ruiz.loza@tec.mx

J. Noguez
e-mail: jnoguez@tec.mx

R. Lozano Espinosa
e-mail: ralozano@tec.mx

F. J. Lozano et al. (eds.), *Energy Issues and Transition to a Low Carbon Economy*, Strategies for Sustainability, https://doi.org/10.1007/978-3-030-75661-1_10

NGO	Non-governmental Organisation
SOA	Service-Oriented Architecture
SQL	Structured Query Language

1 Introduction

Sustainable development has to be approached from a systemic perspective. Connections between various sustainability dimensions such as environment, social, economic, future generations, ethics, education, etc. resonate among them. The first three listed are among the most relevant, while the fourth signals our transit through time.

The various chapters in this book, have addressed different issues pertinent to a sustainable energy future.

Hence this systemic outlook with its inherent complexity, needs some methodological approach for decision making in a collaborative way, wherein stakeholders can participate in this decision process.

The complexity of modern problems related to production, supply, and distribution of energy, add complexity to the decision-making process itself. Global phenomena such as climate change (IPCC 2019), over-exploitation of sea resources (Alvarez-Madrigal 2018) and the fast reduction of biodiversity (WWF 2018) are inter-related with practically every anthropogenic system that ensure human survival and lifestyle. When engaging Energy Sector problems, their solutions will surely impact more than one of these relevant global systems. Given these relations, there will probably not exist a perfect fit, or entirely good or entirely deficient solution.

In the energy sector, decisions about production, distribution and consumption of energy affect so diverse areas that there does not exist a common metric to compare the relevant effects for each, because they depend on the particular goals of each affected area. For instance, through the characteristics of the economic, environmental, and social areas are considered, each area manifests its own objectives and goals, as well as its own metrics of evaluation, which in turn are not inter-comparable. Given this difference, decisions may not be optimal in every measurable aspect.

The utility of the actions taken to approach a problem depends on the interests of the actors evaluating it, for instance, an environmentalist, an entrepreneur, a politician, or a social leader. For each professional the selection of the best alternatives will vary. A way to reduce this variation is by means of the involvement of various stakeholders in the decision-making. However, a formal and special structure is required for group decision-making to reflect the participation of all those involved. We call that support "ecosystem" a Collaborative Decision-Making Centre (CDMC) where several coordinated elements coincide, from an adequate physical space for the decision-making group, to a technological infrastructure to design digital models used to evaluate scenarios, and the visualisation of information for the group. These elements are articulated by means of a robust procedure sequence, allowing the group to reach a decision that represents the interests and goals of the everyone. These elements conform with the CDMC aims, which we consider to be adequate for evaluating complex decisions related to the Sustainable Development in the Energy Sector.

A CDMC is a technological facility to support groups that require an agreement, based on big data and complex models. Tecnologico de Monterrey, Mexico City Campus, hosts a CDMC that is employed for internal and external decision-making projects:

- Internal. Students from different disciplines can explore models and data visualisation for diverse applications.
- External. The CDMC promotes inter-institutional bonding, providing a space for consulting and training in decision-making for enterprises, such as government agencies and NGOs.

At the internal level, a CDMC is a powerful technological tool for both teaching and learning purposes. For instructors in classic sessions, it allows the convergence of a set of unique content transference tools:

- Its seven large format screens allow the learning sessions to display key contents permanently, without the need to switch presentation slides. In this fashion, instructors focus more time on the topics they share, without interrupting their own train of thought.
- The display format of the system, along with its easy-to-use execution platform, allows instructors from different disciplines, including health, international relations, architecture, software engineering, business processes and finances to use the CDMC after a four-hour training course. Stakeholders participating in decision-making sessions do not require previous training.
- For advanced users, the CDMC has a powerful built-in hardware execution platform, allowing them to execute specialised software to run even complex models on site, combined with the ability to display large data sets with ease.

For active learners, the CDMC is a team skill-training arena, that gives them the opportunity to experience many roles:

- **Content designer**. The large-format display offers new and interesting options to explore in terms of User Experience (UX).
- **Moderator/presenter**. A decision-making session requires a moderator, and a business pitch requires skilful negotiators.
- **Technology expert**. The use of back-end specialized software requires experts to program and use it for the presentation.
- **Modeler**. For the ability to produce a mathematical representation of a given phenomenon, in order to conduct an evidence-based, decision-making session.

1.1 Evidence-Based Decision-Making

Evidence is knowledge that appears intuitively to us in such a way that we can affirm the validity of its content, as true, with certainty, without a shadow of a doubt. In a narrower sense, evidence is any knowledge or proof that corroborates the truth of a proposition (Sackett et al. 2000).

For a complex management decision process, evidence needs to be added or integrated as part of the process. The evidence can be either quantitative, qualitative, theoretical or a mix of all three. Evidence is about known to be facts, organised sets of information or observations, that is used as support to justify beliefs or inferences. Two main characteristics of evidence itself are to be rigorousness and relevance, in which case both have to be relevant to the context they belong in.

Regarding an organisation, evidence-based decision-making is better known as evidence-based management (Baba and HakemZadeh 2012), in which to make informed decisions, the proposal of a model is made. This model proposal follows three main principles. The first one states that the process of decision-making is not seen from one rational viewpoint, instead, the second principle suggests adopting a multi-level perspective to consider the integration of different and contextual factors, during the process. The third one suggests total transparency of decisions.

An evidence-based decision-making model seeks to provide evidence along with the context needed to interpret it in the best way. Although quantitative information is objective and clear, the qualitative information provided needs an appropriate interpretation that is related to the preferences and values of stakeholders. The model must be accompanied with a proper methodology to gather the best evidence by selecting the right questions and looking to the best approach to answer them. As the decision-making process itself, the evidence-based decision-making process is dynamic, focusing on the transformation of the discovered evidence into management decisions.

As proposed by (Baba and HakemZadeh 2012) a model should follow a multi-level structure with a well-defined and structured individual level, following a cross-level configuration between individual, organisational and institutional levels individually and in a collaborative way. Figure 1 shows the evidence-based model proposed by Baba. Individually, managers use the evidence to support their training, education, experience and judgement, although the process is influenced by the manager's preferences and values. Other influences come from the stakeholders, whose preferences are defined by a mix of institutional, organizational and individual levels. An important role is played by the context in which the decision-making is made, but taking in consideration structural, environmental, cultural and political constraints, which are directly related to the context. Also, the ethical constraints should be taken into consideration.

Wright et al. (2016) propose an evidence-based decision process, as shown in Fig. 2.

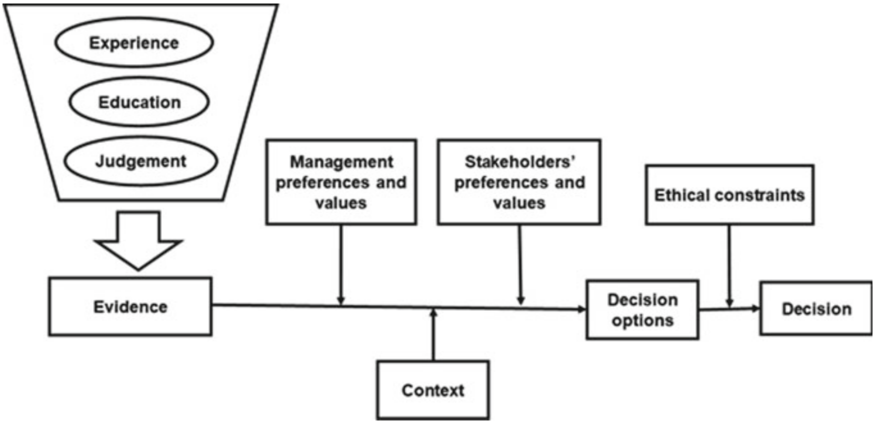

Fig. 1 Evidence-based decision-making model proposed by Baba, V. V

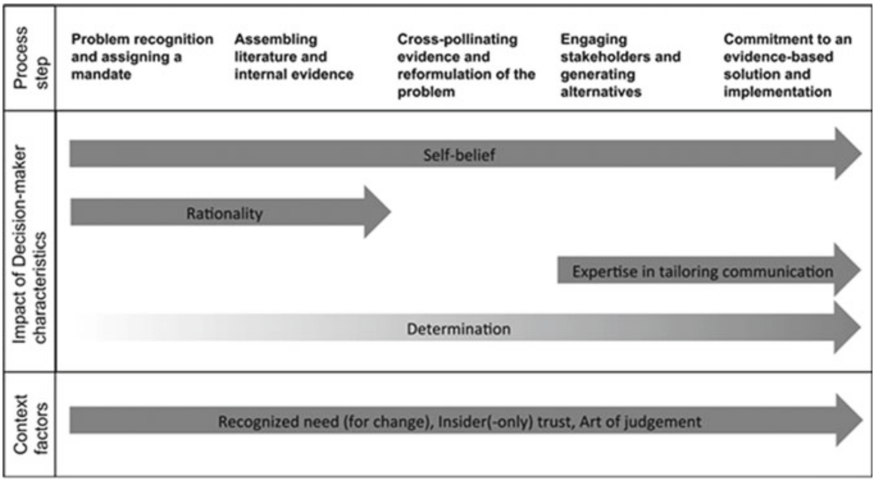

Fig. 2 Decision-maker and context factors within the EBM process (Wright et al. 2016)

The process consists of five main phases: problem recognition and assigning a mandate; assembling literature and internal evidence; crossing evidence and reformulation of the problem; engaging stakeholders and generating evidence-based alternatives; and, committing to an evidence-based solution and implementation. The process also considers context factors, and the impact of the decision-maker, such as self-belief, rationality and expertise.

Some studies reveal important insights into an evidence-based decision-making processes and the role of the right person-context to engage with the evidence and stakeholders to achieve an implementable and effective decision. These ideas have potential benefits for application in public administration and effective management in the private sector.

Evidence-based management incorporates many factors through using a model, or process, as part of a more systematic process within the organisation in a scientific format. However, it should be understood that evidence itself must be seen as the input within the information process that will transform it into making better judgements, in order to make better decisions (Rousseau and Olivas-Luján 2015). It is important to keep four main activities in mind, which are; using the best scientific findings, gathering organisation facts, reflective judgement to reduce bias and improve decision quality, without forgetting ethical issues that may impact the decisions of stakeholders.

2 Collaborative Decision-Making Centre Technological Platform

The CDMC is a meeting room with high-performance computing resources and several large-format displays distributed in a semicircle. In this immersive environment, data is presented in a graphic format that facilitates its analysis. The CDMC is useful when the following elements are present:

- A data visualisation centre for collaborative decision-making is required.
- Large data sets are involved.
- High uncertainty and complex models are involved, but must be executed in real-time to support the decision-making process.
- Multiple stakeholders will collaborate towards consensus.

The data is presented to decision-making groups, where every stakeholder is able to experience the requirements of other stakeholders, as well as the update of the model to weigh their proposed course of action, so they can decide based on reliable evidence obtained by real-time model processing and data visualisation. The CDMC is also an open space for the academic community, in which teachers and students may visualise, discuss and learn using cutting edge execution and visualisation technologies.

2.1 Hardware and Software Components

The general layout of the CDMC is as follows.

- Room for 16–20 stakeholders with flexible seat layout:
  - U shape
  - Auditorium

  - Classroom
  - Boardroom
  - Hollow square
  - Group pods.
- Execution hardware
  - A workstation equipped with a powerful CPU to support real-time model execution.
  - Double graphics card setup to output data for the visualisation hardware, and possibly support parallel execution of the models.
  - Ethernet, wireless and Bluetooth connectivity to support remote data collection and local peripherals.
- Visualisation hardware
  - 7 screens (or an odd number to situate a central screen) to present data covering 120° of vision as shown in Fig. 3.
  - An additional screen, camera, and audio system to support remote participants' interaction.
- Software components:
  - A commercially available (Windows, Mac) or open source (Linux) Operating System.
  - Commercially available or open source office tools focused on flexibility, so that users will adopt this innovation with ease.

Fig. 3 CDMC general layout

– Powerful simulation and execution software tools for advanced users (Vensim®, PowerSim®, programming language compilers such as R, Python, C++).
– For Tecnologico de Monterrey's implementation, the mathematical model was embedded in an online (Web-based), open source office tool, coupled with a controller developed in Python, extending the concept proposed by Kolditz et al. (2014) regarding accessible data visualisation.

2.2 Integration

The hardware and software components described in Sect. 2.1, are integrated in a flexible platform capable of executing and visualising models in real time, supporting the process described in Fig. 4.

The CDMC team at Tecnologico de Monterrey has developed an execution-visualisation software platform (EV-platform) to support the decision-making session design and facilitation in the CDMC hardware platform. The EV-platform aids the teams in:

- **Execution**. To run the models designed by the Modeling team, in real-time, receiving parameters from stakeholders and sending the required data to the visualisation equipment.

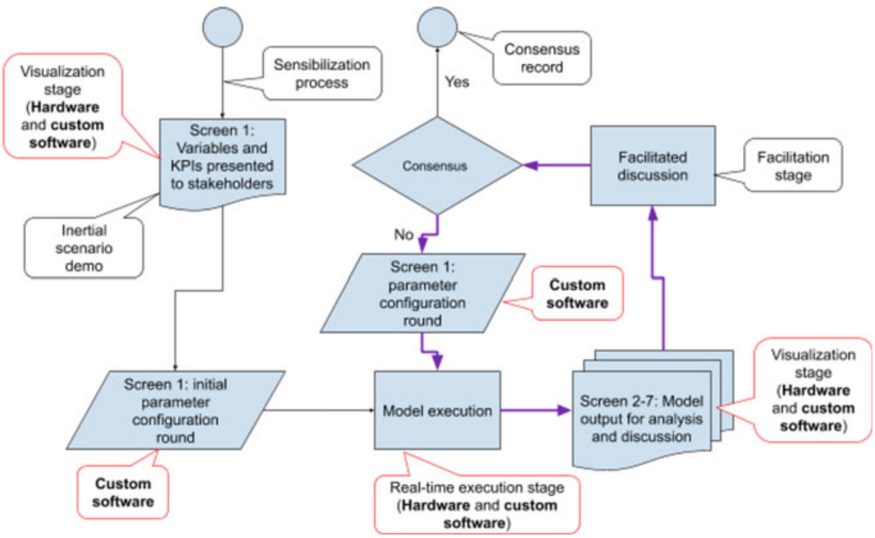

Fig. 4 Decision-making session process, supported by hardware and software integration

- **Visualisation**. To display the selected KPIs (Key Performance Indicators) at the pre-selected displays, in a format designed by the Modeling team, along with the requirements of the stakeholders.
- **Facilitation**. To provide an input mechanism for the stakeholders to enter values for specific variables when the decision-making session occurs.

3 Collaborative Decision-Making Centre Lifecycle

3.1 Execution

Once a model is created and tested in a mathematical way, it is necessary to code in a language or framework that processes input data into output data in accordance to the model. A model in this context, is something static that must be executed by a person, in order to produce a result. The idea of the execution phase is that a computer machine processes the input to produce an output.

Figure 5 shows the context for the execution phase. The model (previous phase) is a sort of input to this phase. In the case of Fig. 5, a Google spreadsheet has been used as the core of the execution phase. A Google spreadsheet has the same characteristics as an Excel spreadsheet, but with the advantage that it "lives" in Google's cloud. Klimberg and Ratick (2018) consider that.

> ... By far, the most widely used tool used by decision-makers is the spreadsheet. Spreadsheet software, and in recent years with the dominance of Microsoft, Excel in particular, has radically changed the function and analytical capabilities of a decision-maker.

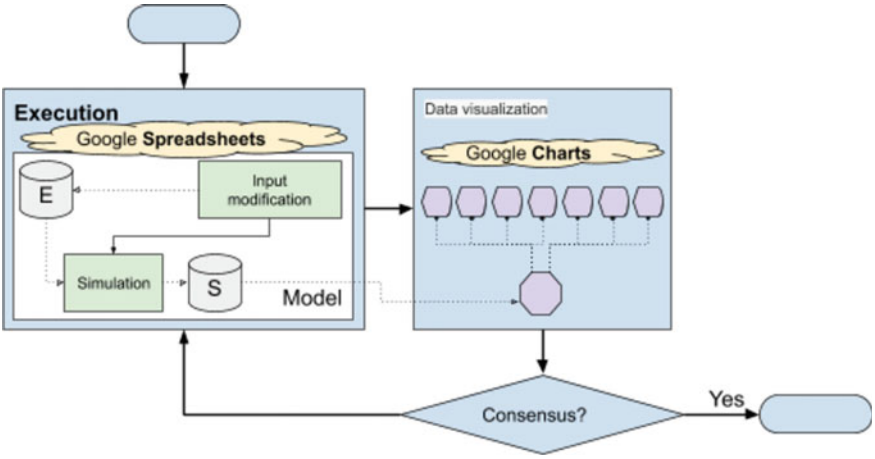

Fig. 5 Execution phase context

Therefore, the choice of a spreadsheet to house the model to be executed it is not a bad idea, mainly for all the functionalities that it provides but also the expertise that many users have in using spreadsheets.

In general, an execution platform must fulfil the following characteristics:

1. **Expressivity**. This means that all the features expressed in a model, must be mapped to one or more characteristics on the execution platform.
2. **Usage facility**. Coders that must translate the model to the language of the execution platform, can do their work in an easy and straightforward way.

There are two main kinds of languages for mapping a model onto an execution platform: textual and visual.

Visual languages are based on visual elements, where each element has a specific meaning or semantic associated. In the programming field, LabVIEW is a good example of visual coding. National Instruments describes LabVIEW (National Instruments. s.f.) as:

> ...a graphical programming approach that helps you visualise every aspect of your application, including hardware configuration, measurement data, and debugging. This visualisation makes it simple to integrate measurement hardware from any vendor, represent complex logic on the diagram, develop data analysis algorithms, and design custom engineering user interfaces.

The main advantage of a visual language is that it offers a dataflow metaphor that is very natural for many users, because users can see, step by step, how data is transformed from input to output. For the CDMC case, stakeholders could see how a potential scenario output or response was obtained, therefore, it offers a kind of white box where users can see the way that an output is achieved. A drawback of visual languages is the expressivity. To cope with this situation, many visual languages offer a script node where it is possible to write code using textual languages. LabVIEW, for example, offers MathScript and Formula nodes.

Textual languages have traditionally been used for human communication and code programming. There is a vast experience in language processing systems. In the context of model execution for decision making, a full or Turing complete language is not necessary; a Domain Specific Language (DSL) is more appropriate in this case. A DSL or domain specific language is a computer language but it is specialized in a particular application domain. In this case, the domain is the execution of a model for decision making, but also the facilitation of meetings, i.e., the space and time where the decision-making for the stakeholders is taking place.

DSLs are languages designed for the adequate manipulation (create, read, update, delete) of objects of a specific domain. The idea behind a DSL is to create an ad hoc language for these objects, in such a way that tasks involving objects of the specific domain are very easy to do.

There are many examples of DSLs, but SQL is, probably, the most widely known. SQL allows us to manipulate relations in a very easy way. With SQL we can create a relation, insert data into a table, delete data, update data, plus other operations. There are many factors behind the success of the relational databases but SQL must be one of the key factors (Curé and Blin 2015).

3. **Interactive capability**. During the visualisation and facilitation phases, we expect that the stakeholders will test some scenarios in order to see the results that the model predicts on the visualisation media. Each scenario in this context is a set of possible input data that can be interesting for the stakeholders. Scenarios can be prebuilt or can be generated on the fly during the facilitation phase.
4. **Local or cloud execution**. In many cases it is necessary to choose between a local execution (in-situ), and a cloud execution. Local execution has the advantage in that it does not depend on an Internet connection, meaning that there is not a latency due to data communication. An inconvenience of this kind of execution is that the execution code is owned by the computer that executes it.

On the other hand, cloud execution has the advantage that the model can be executed by any visualisation computer that controls the visualisation displays, therefore, scalability can be achieved using cloud computing techniques such as microservices. Microservices are a software development technique which follows the design principles of SOA (Service-oriented architecture). SOA is the successor of the client–server architecture, where services are provided by a well-defined application programming interface or API by 'lending' application components to other software components (Erl 2016).

A drawback of this kind of solution is that it depends on the Internet and therefore it inherits the same issues of security and latency, for example.

We said that interactive capability is one of the most important features in a CDMC, because it supports stakeholders based on potential scenarios. These potential scenarios are products of the model and real data. In reality, these scenarios are "What if scenarios" that allow us to simulate potential situations under different conditions, or options selected or adjusted for the stakeholders. In the context of a CDMC, there is not an optimal solution in a mathematical sense. Either, the solution is reached for stakeholders (with different interests), or else not. For example, in the time of COVID-19, we may have one group of stakeholders representing the health minister and another group of stakeholders representing the economy minister. The health group wants to close all kinds of commerce as soon as possible, meanwhile, the economy group wants to delay the closure of all kinds of commerce as late as possible.

3.2 Visualisation

Data visualisation allows graphical representation of information and data. To facilitate the visualisation and understanding of trends, data patterns and study of outliers, it is helpful to have visual elements such as charts, graphs and maps (Lurie 2007). Data visualisation tools and technologies are essential for analysing massive amounts of information and making data-driven decisions. However, in most applications, information is displayed on a single screen, hindering an integrative approach, especially when a group of decision makers meet.

Fig. 6 A group in the CDMC presents a case

A CDMC offers important advantages by allowing the visualisation of data to be carried out on seven different screens, simultaneously, facilitating the observation, assimilation and analysis of information, allowing storytelling with a purpose, showing evidence and allowing collaborative decision making in an agile way. CDMC was designed to provide an adequate space in which a group of decision-makers can meet, consult and make consensual decisions related to a matter of concern. The decision-making process is supported through specialised software, which allows the display of information visualisation, evidence, analysis and the different possible options, integrating knowledge and IT infrastructure, to structure and solve complex real-world problems.

The use of the decision-making centre is a key element to achieve visualization goals, such as exploring data and facilitating analysis with immediate access to available information. Results and discussion when a group is presenting their proposed solution is shown in Fig. 6 (Navarrete-Corella et al. 2019).

3.3 Facilitation

Collaborative decision making is an interactive process for negotiating action plans to achieve a shared objective (Groten et al. 2010), which implies that there must be a structured and dynamic process, so that those involved can receive the information and, in a collaborative way, make the best decisions.

Because decision-makers face complex problems, the level of assistance should be rationally assigned to each decision-maker and the resources that can be modified should be coordinated, as appropriate in each scenario to be evaluated, seeking to choose and optimise each scenario to get the most benefit from making a decision (Xiao et al. 2014).

In this process, the main factor for achieving a satisfactory consensus in decision-making is the exchange of knowledge and communication among all decision-makers (Indiramma and Anandakumar 2008; Smari et al. 2005). Considering this factor, the decision-making process is generally divided into three stages: knowledge extraction, design and optimization. Due to the characteristics of collaborative decision-making, knowledge extraction largely involves decisions about what is needed, to carry out an in-depth analysis through the state of resources, this phase can be aligned with Coordination and an analysis of decisions. In the design stage, as desired, the different possible scenarios are generated. Finally, in the optimization stage, an optimal decision must be chosen from among several options, where each option must be analysed and evaluated as established by decision makers (Xiao et al. 2014).

A CDMC makes it easy for decision-makers to visualise solutions to complex problems. Experience is provided under cutting-edge technologies in collaboration, modelling, data simulation, visualisation, prototyping, and experience enhancement in the decision-making process. The facilitation process also provides an input mechanism for stakeholders to enter values for specific variables during the decision-making session.

4 CDMC Case: Mexican Electrical Model for Sustainable Energy Decision-Making

4.1 Mexican Electric Model Overview and Stakeholders

A mathematical model of the Mexican Electricity Sector was built as a case study to test the capabilities of the CDMC created at Tecnologico de Monterrey. This model was considered to be deterministic, based on scenarios since the data was obtained from validated sources, and the necessary information to carry out a decision-making process. Uncertainty values from variables were not considered. The model seeks to evaluate the implications of the processes of decision making within the electricity sector, using various projected scenarios to help the decision makers understand the impact of their actions could have on the sector, over time. These scenarios are built on aspects reviewed in Chap. 2 and that relate the complexity of building environmental and energy policy frameworks that work to achieve economic growth and sustainable development in Mexico.

The model was structured based on four fundamental parts: inputs; calculations; outputs; and, creation of a visualisation scheme. The first step in the sequence of operation is the model input. The input indicators are data and information that stakeholders enter into the model seeking to reflect their decisions related to various aspects of the Mexican electricity sector, covering a time horizon from 2017 until 2036. Model execution is based on the relationships that define the behaviour of the macro indicators for the electricity sector. Model execution calculates the output indicators, and these are represented via a multi-screen display scheme. The model is based on time series analysis and curve fitting from data collected on the behaviour of the sector from 2009 to 2017. The model outputs represent the trends of the variables in the period from 2017 to 2036. Output indicators are organised as a dashboard that seeks to reflect the impact of the data entered into the model. The visualisation scheme is displayed on the video-wall (seven screen) feature of the CDMC.

4.2 Model Environment of the Mexican Electricity Sector

In the development of the Mexican electricity sector model, two groups of power generators were considered: the Federal Electricity Commission (CFE) and Private Industry (NO CFE). Emulating the segmentation carried out by the Ministry of Energy in its Energy Information System.

The Federal Electricity Commission is a company belonging to the Mexican government, which is in charge of generating, transmitting, distributing and marketing electricity for more than 100 million inhabitants within the country, incorporating more than one million new customers each year. The CFE is a productive state company with legal personality and its own assets. On the other hand, the Private Industry considers all those private electricity companies that operate within the country electricity generation.

To describe the Mexican electricity sector, it is necessary to distinguish the different energy sources that are used for electricity generation in Mexico which are described below:

- **Fuel oil**. Fuel oil is a product obtained from the refining of crude oil. This fuel is made up of carbon molecules, it is characterised by its high viscosity and for being insoluble in water. Its main uses are in electricity generation, mainly in thermoelectric steam plants, and in the industrial sector (Pemex 2017).
- **Natural gas**. Natural gas is a fuel consisting mainly of molecules of hydrogen and carbon in the gaseous state, the most widely used natural gas in Electric generation is dry gas, which is composed, for the most part, of methane (CH_4) molecules (Pemex 2015). Natural gas is used as fuel in combined cycle power plants and gas turbines for electricity generation (CFE 2007).
- **Coal**. Coal can be defined as a sedimentary rock impregnated with a large amount of carbon from adjacent organic matter (Direction General of Industry, Energy and Mines of the Community of Madrid 2007). It is a common fuel for electricity generation, widely used in thermoelectric and dual-type plants (Secretary of Energy 2018).
- **Nuclear**. Nuclear energy consists of releasing a large amount of energy from the internal structure of atoms, which can occur through two types of complex nuclear reactions: fission and nuclear fusion. Nuclear fission is the process that occurs when an atomic nucleus decomposes, this generates two atomic nuclei of equal size and allows the release of a large amount of energy. Nuclear fusion

is a reaction in which two atomic nuclei combine, releasing a large amount of energy and thus generating a larger stable nucleus (Kha 2004). The energy that is released in nuclear fission and fusion processes can be used for the generation of electricity in nuclear power plants.

- **Hydroelectric**. Power generation that takes advantage of the potential energy contained in elevated water to convert it into electricity, through a turbine-generator system (Juárez 1992).
- **Geothermal**. Geothermal energy is that type of energy which comes from inside the crust of planet Earth, being generally found in the form of steam at high temperatures, and by means of thermodynamic cycles it is converted into electricity (Secretariat of Energy of Argentina, SD).
- **Wind**. Wind energy is the type of energy obtained by taking advantage of the movement of air due to pressure gradients in the atmosphere. This type of energy can be transformed into electricity by wind turbines, which are in charge of converting the kinetic energy of the wind into mechanical energy, and later, with the help of a motor-generator system, transforming it into electrical energy (Tong 2010).
- **Solar**. Solar energy is that which is obtained from solar radiation and is converted into thermal energy or electrical energy, through active or passive technologies. Active technologies are those that take advantage of the sun directly, some of them are solar panels (electrical energy) and solar collectors (thermal energy) (Díaz 2015). Passive technologies are those that are usually implemented in architecture, to provide thermal comfort and decrease energy consumption in buildings. For this model, the Solar Energy section only considers solar energy that is transformed into electrical energy.

4.3 Model Key Performance Indicators

The model is driven by a set of Key Performance Indicators (KPI) that simulates behaviour of the electricity generation and consumption in Mexico. KPIs are divided into input and output indicators or variables. KPIs involve the environmental, technological, economic or social aspects, which have implications for the electric sector model, and are related to the topics discussed in previous chapters on the complexity in the balance of the use of sustainable energies versus fossil energies towards economic growth in Mexico.

Input indicators of the model correspond to the variables that decision makers can manipulate within their scope of action or whose value comes from the economic environment (for example, Mexican peso-US dollar parity), current regulations and laws for the sector or development plans that impact the sector. Output indicators represent the results from the execution of the model where the benefits or consequences resulting from any change in value of the input variables are presented.

Representation of the behaviour of the electricity sector in Mexico involved the use of around 1,500 variables. In order to carry out decision-making sessions where a group of stakeholders could discuss alternatives about the future of electricity generation, 12 input indicators and 17 output indicators were chosen. Table 1 presents the names and descriptions of input variables, and Table 2 presents the names and descriptions of output indicators.

Table 1 Definition of model input indicators

Name of input indicator	Description
Electricity consumption growth	Refers to electricity consumption annual growth by end consumers in Mexico. The input value is expressed as a percentage
Peso-dollar parity	It is the annual exchange value of the Mexican peso in relation to the US dollar. The value is shown in pesos per dollars (MXN/USD)
Profit margin on production cost	It refers to the desired profits on electrical energy production cost for each of the different types of technologies. The desired profit margin is projected for CFE and for private companies (NO CFE). The value is expressed in percentage
Fuel estimated cost	It is the cost that the different fuels (oil, fuel oil, natural gas and coal) will have in the years to model. The format of the input values of the estimated fuel costs that are managed in the model are: US Dollars per barrel (US $/Barrel) for oil and fuel oil US Dollars per million BTU (US $/MMBTU) for natural gas US Dollars per ton (US $/Ton) for coal
New demand coverage	It refers to which participant (CFE or NO CFE) and with what type of technology (fuel oil, natural gas, coal, nuclear, hydroelectric, geothermal, wind or solar) the new demand generated by the growth of electricity consumption in the country will be covered. The value is expressed in percentage
Installed capacity closure	It is the closure of the plants by type of technology given by the user. The value is expressed as a percentage (%) and is based on a capacity closure of up to 100% by technology
Increased capacity utilisation efficiency	It refers to the increase in the amount of electricity generated in relation to the generation plants time of use for the different types of technology. The value is expressed in percentage
Decrease in capital costs	It is the annual decrease in capital costs associated with the different types of generation. The value is expressed in percentage
Increase in fuel use efficiency	It is the annual increase in the use of fuel to generate electrical energy. The value is expressed in percentage
Increased efficiency of operating costs	Refers to the decrease in annual operating costs. The value is expressed in percentage
Increased efficiency due to transmission costs	The improvement in the annual performance of electric power transmission lines and is reflected in a decrease in the cost of electric transmission. The value is expressed as a percentage
Increased efficiency in reducing CO_2 emissions	Refers to the percentage reduction in the generation of CO_2 emissions in electricity generation processes. The value is expressed as a percentage

Table 2 Model output indicators

Name of output indicator	Description
Electricity production	It is the amount of electrical energy, measured in Gigawatt-hours (GWh), that was consumed in a given year in Mexico
Installed capacity by type of technology	It is the installed capacity available in a specific year by type of technology, measured in Megawatts (MW)
New installed capacity to meet new demand	It is the capacity that is installed to cover the increase in the demand for electrical energy, its unit of measurement is Megawatt (MW)
Production associated with newly installed capacity to satisfy the new demand	It is the amount of electricity produced by the new capacity when added to the electrical system
New installed capacity for replacement	The installed capacity due to the closure of electricity generation plants; its unit of measurement is Megawatt (MW)
Production associated with the newly installed capacity due to replacement	It refers to the electricity produced by the new installed capacity due to the replacement of closed capacity, measured in Gigawatt-hours (GWh)
Closed capacity	Identifies the number of power generation plants that closed in a given year; its unit of measurement is Megawatt (MW)
Production associated with closed capacity (GWh)	Refers to the amount of energy no longer generated due to the capacity closure; measured in Gigawatt-hour (GWh)
Total electrical production by type of fuel	It shows the proportion of electrical energy that is produced with renewable sources, hydrocarbons and others, its reference unit is a percentage
Investment	It is the monetary investment that is required to install new capacity in the Mexican electricity system. Investments are measured in millions of Mexican pesos (millions of MXN)
Electricity cost	The cost of producing electrical energy measured in Mexican pesos per kilowatt-hour (MXN/kwh) of electrical energy
Electricity sale price	The cost of electrical energy for consumers is measured in Mexican pesos per kilowatt-hour (MXN/kwh)
Income	The amount of money collected from electrical energy sales, measured in millions of Mexican pesos
Gross profit	The economic benefits generated by the sale of electricity measured in millions of Mexican pesos
Jobs	Refers to the number of jobs generated in the Mexican electricity sector
Carbon footprint	The amount of carbon dioxide emitted into the environment as a consequence of electricity generation measured in tonnes of CO_2
Clean energy certificates	It is the number of clean energy certificates (CEL's)[a] generated by the electricity production from renewable energy sources

[a]It is a mechanism that certifies that a percentage of the energy comes from clean energy sources

4.4 Scenarios of the Mexican Electricity Sector Model

A model of the electric sector in Mexico was built whose trigger is the growth of electricity demand. The growth of electricity consumption means that it is necessary to install new power generation plants, which operate under certain different efficiency criteria for each type of technology. This newly installed capacity is added to the capacity that previously existed within the system; however, it can happen that for regulatory reasons or for term of service life, power generation plants are shut down, which decreases the capacity of the whole system.

The capacity installed in the electrical system, when used, produces electrical power; this electrical production involves the generation of polluting emissions, determined by the type of technology used for generation, and some technologies generate more pollution than others. Likewise, the production of electricity involves a production expense, which is due to fuel consumption, the cost of capital and the cost of operation. Once the energy is produced, the sales process occurs, which includes the transmission costs and the expected profit margin, this process generates economic income to the electricity generating companies.

Electricity producers must cover the costs of electricity production, such as capital expenditures and operating expenses. The difference between revenue and expenses results in gross profits from the electricity system. Electricity generators must provide the corresponding taxes, which are subtracted from gross profits and give rise to the net profits of the system. Net profits can be withdrawn as part of investors' profits, but they can also be reinvested into the system. This reinvestment in the Mexican electricity system, in addition to the investment made by new investors, allows to sustain the growth of installed capacity in the electricity sector.

To reduce complexity in the representation of the input variables that decision makers can change, the variables are grouped into scenarios. A scenario is a set of input variables that refer to the different alternatives that the electricity sector can follow in the coming years. Scenarios define the data to be entered into the model and include variables that can be modified by stakeholders and values that come from economic and regulatory environment. The evaluation process for a case always contains 4 scenarios which need to be analysed in order to achieve a final agreement: Scenario 1. Corresponds to the current policy or inertial scenario; Scenario 2. Corresponds to the current development plan, designed according to the forecasts. Scenario 3. represents a drastic change in current public policy. And Scenario 4. The interactive scenario, which is usually the product of collaboration between the parties at the decision-making level and whose sustainability has yet to be validated but it is a powerful tool to reach consensus among stakeholders.

The scenarios can be predefined or interactive. The objective of the predefined scenarios is to give the user a reference with respect to the impacts that each variable has as part of the model, on the output indicators. Predefined scenarios are considered a didactic tool that allows stakeholders to explore different paths that leads decision makers to obtain their conclusions and own scenarios. On the other hand, interactive scenarios input values can be modified in their input values by decision makers to create new scenarios. This is achievable by introducing and modifying the model data according to their role, and it is even it is possible to create scenarios in which input values that come from economic or political environments are modified; for example, it is possible to modify the change rate in Mexican peso- US dollar parity.

Three predefined scenarios were created. The first is a scenario called "inertial" that describes the behaviour of the output variables without any decision being made on the input variables, that is, the values of the output variables are calculated based on the trend detected from using the data obtained for 2009–2017. The second scenario called "SENER" presents the behaviour of the electricity sector according to the planning data published by the Ministry of Energy in Mexico for 2017. The third scenario corresponds to a disruptive change through the application of renewable energy consumption and generation in the sector, this scenario is called "Technological change".

The interactive scenario is presented as a fourth option in which decision makers can manipulate input variables and create new scenarios according to their own proposals.

4.4.1 Scenario 1. Inertial Scenario

A set of selected input values establish that the new electricity demands within the Mexican electricity sector will be covered by the CFE by natural gas; additionally, CFE keeps operating its plants. Other input values considered there to be: no increase in efficiency; fuel prices remaining constant; demand growth; and, no changes in the peso/dollar parity.

After running this scenario, the following insights are obtained, and form the basis for decision making in the sector.

Electricity production by fuel type

We find that gas-fired electrical production increases from 148,596 GWh in 2017 to 366,030 GWh in 2036. This is because the new electricity demand and the capacity of closed generation is completely covered by gas-fired production. Generation technologies such as fuel oil, coal, wind power, and geothermal generate less electricity because the closure of these kinds of power plants, due to terminal lifespan. Electricity production based on nuclear, hydropower and solar technologies are maintained as constant throughout the timeline of the scenario.

Electricity production

This scenario shows an increment in electricity production in CFE sector, which moves from 67% in 2017 to cover Mexican demand to 79% by 2036. This increment is because new demand will be covered only by CFE, thus, NO CFEs power plants will remain at their initial level.

Installed capacity

The total capacity of the Mexican electricity system increases from 56,474 MW in 2017 to 70,944 MW in 2036.

Tons of CO_2 produced per year

Due to the significant increase in natural gas electricity production, emissions go from 146,220,333 metric tons of CO_2 in 2017 to 223,947,709 metric tons of CO_2 in 2036.

Investment per year

The total investment in the sector goes from 15,282 million of Mexican pesos per year to 29,656 by the end of 2036. Closure of a significant fuel oil and geothermal power plants on 2031, due to their end of life cycle, generates a peak in investment around 125,000 million of Mexican pesos for this particular year. Private industry investment (No CFEs power plants) remains at zero as it was defined at the beginning of the scenario.

Price of sale of electricity to the end user

The results of the scenario show that the price of sale of electricity decreases. The price starts at 1.32 Mexican pesos per kilowatt-hour on 2017 and ends at 0.96 Mexican pesos per kilowatt-hour by the end of 2036. The decrement is because of the lower prices for natural gas for power generation, and the closure of fuel oil power plants. It is important to state that input prices of fuels are considered as constants during the time window of this scenario.

Revenue from energy sales

Energy sales revenues are seen as an increase in CFE revenue generated by sales from 239,761 million pesos in 2017 to 328,192 million pesos in 2036. Private industry revenue (NO CFE) declines from 116,954 million Mexican pesos in 2017 to 84,674 million Mexican pesos in 2036. This is due that all new electricity demand and capacity will replaced by CFE industry.

Generation and requirements of Clean Energy Certificates (CEL's)

The generation number of Clean Generation Energy Certificates (CEL's) is kept constant since, given the assumptions of entry, it is not considered the installation of new renewable power plants (main generators of CEL's). The number of generated CEL's on 2017 is about 48,212 and at the end of 2036 will be of 42,090. On the other hand, the number of required CEL's start at zero on 2017 and increases up to 150,922 on 2036. Thus, the demand of CEL's required by the electric sector is not met.

4.4.2 Scenario 2. SENER Scenario

It is defined that for the year 2017, 80% of the new electricity demand is covered by CFE, while the remaining 20% is covered by private entreprises (NO CFE). Meanwhile, towards the year 2036, private participation will grow to cover 90% of the new demand and the contribution of the CFE will decrease until reaching 10%. The new demand is covered by 46% of natural gas, 3.4% of coal, 7.3% of nuclear energy, 3% of hydroelectric energy, 2.3% of geothermal energy, 24.2% of wind energy and 13.8% of solar energy.

Regarding the withdrawal of electricity generation plants, CFE closures by 2036, include 94% of fuel oil plants, 12% of natural gas plants, 36% of coal plants and 7% of geothermal energy. These generation plants would be replaced with 46% of natural gas, 3.4% of coal, 7.3% of nuclear energy, 3% of hydroelectric energy, 2.3% of geothermal energy, 24.2% of wind energy and 13.8% of solar energy. On the other hand, there is a slight increase in efficiency, fuel oil prices rise to $88.36 USD/Barrel in 2036, natural gas prices rise to $7.15 USD/MMBTU in 2036, coal prices rise to 61.76 USD/metric Ton in the year 2036, the growth of demand is constant, while the Mexican peso-US dollar parity increases to 21.8 pesos per dollar, and the profits for CFE and NO CFE are 0% and 5% respectively.

After running this scenario, the following insights are obtained that are the basis for the decision making in the sector.

Electricity production by fuel type

We find that gas-fired electrical production increases from 145,450 GWh in 2017 to 243,753 GWh in 2036. This is because the new electricity demand and the capacity of closed generation are mostly covered with this type of fuel. Generation technologies such as geothermal, generate less electricity due to the shutdown of these kind of power plants at the end of their life cycle. Electricity production based on nuclear, hydropower and solar technologies are maintained with increasing output along the time line of the scenario.

Electricity production

This scenario shows a reduction in electricity production from CFE, which moves from 66% in 2017 to cover Mexican demand, up 43% by 2036. This reduction is because the private sector will be more relevant, covering 57% of the total demand.

Installed capacity

The total capacity of the Mexican electricity system increases from 57,231 MW in 2017 to 97,668 MW in 2036.

Tons of CO_2 produced per year

Due to the significant increase in natural gas electricity production, and to the increment in the use of renewable energies, emissions go from 142,785,088 metric tons of CO_2 in 2017 to 136,477,498 metric tons of CO_2 in 2036.

Investment per year

The total investment in the sector goes from 66,077 million Mexican pesos per year to 82,738 million by the end of 2036. Programmed oil power plants in this scenario predict that for 2023 a considerable investment will be required to replace those plants. In addition, an increase in private sector investments is forecasted, since for 2036 they will handle 84% of the required total investments.

Price of sale of electricity to the end user

The results of the scenario show that the price of sale of electricity tends to raise, given the installation to produce additional 40,438 MW between 2017 and 2036, and due to a preponderance in the installation of facilities to produce renewable energies. The price starts at 1.23 Mexican pesos per kilowatt-hour in 2017 and ends at 1.56 Mexican pesos per kilowatt-hour by the end of 2036.

Revenue from energy sales

The revenue generated by CFE energy sales increases from 221,041 million pesos in 2017 to 309,657 million pesos in 2036. Private industry revenue (NO CFE) increases from 113,165 million Mexican pesos in 2017, to 417,190 million Mexican pesos in 2036, since this scenario has as a premise that NO CFE has an increasing participation in new electricity power plants.

Generation and requirements of Clean Energy Certificates (CEL's)

The generation number of clean Generation Energy Certificates (CEL's) is increasing constantly since, given the preset inputs, installation of new renewable power plants (main generators of CEL's) is considered. The number of generated thousands of CEL's in 2017 was around 53,719, but at the end of 2036 will be of 205,929. On the other hand, the number of required CEL's start at zero in 2017 and increases up to 163,149 in 2036. Thus, the demand of CEL's required by the electric sector is met starting from 2028.

4.4.3 Scenario 3. Scenario of Technological Change

It is established that all new demand is covered by the private enterprises (NO CFE). The new demand is covered using natural gas in a proportion of 50%, and is complemented by solar energy by 25% and wind energy by 25%. Furthermore, it is considered that there is a significant increase in the following efficiencies: capacity utilisation; a decrease in investment cost per MW; a decrease in capital cost, increase in fuel use efficiency, increase in the efficiency of operating costs; and, increased efficiency in reducing CO_2 emissions. In addition, it is considered that the peso-dollar parity increases 1% annually and that fuel prices remain constant at December 2016 prices.

After running this scenario, the following insights are obtained to form the basis for the decision making in the sector.

Electricity production by fuel type

We find that gas-fired electrical production increases from 148,940 GWh in 2017 to 245,374 GWh in 2036. This is because 50% of the new electricity demand and the capacity of closed generation is covered by this type of fuel. Generation technologies such as geothermal, generate less electricity in 2026, due to the shutdown of these kind of power plants at the end of their life cycle. Electricity production based on wind and solar technologies are maintained with increasing output along the timeline of the scenario up to 2036.

Electricity production

This scenario shows a reduction in electricity production from CFE: by 2017, 65% of the total electricity production is covered by CFE and 35% is covered by the private sector. By 2036, according to this scenario, the private sector will generate 60% of the electricity required by Mexico.

Installed capacity

The total capacity of the Mexican electricity system increases from 57,431 MW in 2017 to 91,156 MW in 2036.

Tons of CO_2 produced per year

Due to the significant increase in wind and solar electricity production, emissions go from 138,624,772 metric tons of CO_2 in 2017 to 111,267,545 metric tons of CO_2 in 2036.

Investment per year

Total investment in the sector goes from 86,529 million Mexican pesos per year to 41,390 million by the end of 2036. Programmed end of life cycle for oil and coal power plants in this scenario preview that for 2023 a considerable investment will be required to replace those plants. The private sector investments remain around 40,000 million Mexican pesos, since this scenario assumes that the private sector will satisfy new electricity demand.

Price of sale of electricity to the end user

The results of the scenario show that the price of sale of electricity tends to decrease starting at year 2020, given the closure of oil and coal power plants that have the greatest fuel prices. However, by 2036, the price keeps rising due to the high capital cost of renewable energies. The price starts at 1.33 Mexican pesos per kilowatt-hour in 2017 and ends at 1.33 Mexican pesos per kilowatt-hour by the end of 2036.

Revenue from energy sales

Energy sales revenues increase in CFE revenue generated by the sale from 231,755 million Mexican pesos in 2017 to 232,050 million pesos in 2036. CFE revenue is maintained in values over 200,000 million pesos per year, while the private industry revenue (NO CFE) increases from 126,032 million Mexican pesos in 2017 to 340,655 million Mexican pesos in 2036, since this scenario has as a premise that NO CFE has an increasing participation in new electrical power plants.

Generation and requirements for Clean Energy Certificates (CEL's)

The generation number of clean Generation Energy Certificates (CEL's) is increasing constantly since, given the preset inputs, installation of new renewable power plants (main generators of CEL's) is considered. The number of CELs generated in 2017 is 55,160, and by the end of 2036 it will be of 185,833. On the other hand, the number of required CEL's start at cero in 2017 and increases up to 150,922 in 2036. As the electricity consumption rises, the number of CEL's become insufficient to satisfy the demand.

4.4.4 Scenario 4. Interactive Scenarios

Scenario 4 refers to some new solution scenario, not previously agreed upon and even proposed in real time by the user group (or stakeholders) attending the CDMC, as part of the Decision-Making process. This scenario sets out to explore the performance of previously agreed scenarios. When stakeholders meet at the CDMC, they sometimes generate new proposals collaboratively, to be compared with the performance of scenarios already established and previously validated by technical experts.

The planned scenarios are solidly constructed from the technological point of view, are economically viable and environmentally responsible. However, decision makers frequently have quantitative and non-quantitative elements, updated, which allow the generation of new solution options, without a technical-economic and environmental validation, but with great potential for utility. They are of great help for achieving consensus in decision making and in non-optimisable problems where the criterion of complete rationality is not applied in the decision making. In this way, Decision making evaluation processes in CDMC always include 4 scenarios, in an iterative process in order to reach a final agreement.

5 Conclusion

The process of making decisions on sustainable energy issues represents a challenge, because such decisions are made as a result of analysing wicked problems that contain a large amount of data to process and visualise, raising the need for a technological platform tool for decision makers, to aid them in the task of reaching a consensus.

Most of the time, these problems cannot be solved through an optimisation algorithm, but rather through a facilitation session, in which a group of decision makers can reach a consensus using real-time evaluation of scenarios that show the benefits and implications of each decision.

This chapter presented the development of methodological and technological tools that make up a multi-screen and interactive decision-making centre; the Collaborative Decision-Making Centre (CDMC). We showed that, with the aid of this type of decision-making room, it is possible to promote the application of decision-making models, by presenting a group of decision-makers with several, real-time computed indicators for scenarios, that allow the group to find the best alternative for problems in the field of management of energy sustainability.

A CDMC allows to present a large amount of data that is calculated by an evidence model that depicts specific behavior of a real situation. CDMC permits a dynamic interaction between simulation model and stakeholders. The aim of a decision-making session is not to obtain an optimal solution but a consensus where all particular objectives from each stakeholder's point of view is considered as acceptable by the entire group. This consensus can be reached by the use of dynamic scenarios that allow changing input variables and analysing output values for model key performance indicators.

The concept of CDMC was tested through a model of the electricity sector in Mexico. The model represents the behaviour in the generation, transmission, distribution and consumption of electricity based on the different technologies that are currently used in Mexico. The model was tested through 4 scenarios that represented data trends from 2017 to 2036. The first 3 scenarios served to teach decision makers about the current behaviour of the sector as well as for the identification of the main drivers in the sector.

- In the inertial scenario (scenario 1), historical trends of output variables were considered according to the recorded behavior of 2009–2017, where the new demand for electric energy will be met by CFE generating plants and where the participation of private initiative (non CFE parties) remains constant, based on existing plants in 2017.
- The second scenario proposes that Mexico's new electricity demand will be mostly covered by private initiative and that CFE's participation is only 10% of it. Electricity generation for new demand is mainly based on natural gas (46%), and renewable energies: wind (24%) and solar photovoltaic (14%). This scenario shows a decrease in CO_2 tonnages produced per year but shows an increase in the investment required per year because new renewable technologies are more expensive than traditional ones.
- In Scenario 3, called the technological change, all new electricity demand will be covered by private enterprises using the following distribution: 50% based on natural gas; 25% by wind energy; and, 25% from solar. This scenario shows a large investment by the private enterprises for the construction of electricity generation plants based on renewable technologies.
- Lastly, the interactive scenario (scenario 4), allowed stakeholders to gradually modify input variables and analyse the effects and benefits of said changes in the output indicators shown in the visualisation scheme. In this way, each participant was able to determine the acceptable values for the input variables that suited the interests they represent.

This interactive process allows participants to have an evidence-based discussion since the execution of the model is instantaneous, so the changes in the output are shown just a few seconds after the modification in the input. In a CDMC session interactive scenarios can be fine-tuned by the stakeholder group in an iterative process, until achieve performance is acceptable (or discarded) to all parties. This makes the process useful in public and private sectors to address complex problems that cannot be optimised with the complete rationality method, such as in Sustainability problems, since they originally imply non-comparable KPIs.

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