



Integrated analysis of the Mexican electricity sector: Changes during the Covid-19 pandemic

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ABSTRACT

The COVID-19 pandemic has nonlinear impacts. These impacts have collaterally affected systems such as economic and energy. The fragility of these systems has also been shown, including the electric system. In Mexico, the weakness of dependence on US fuels, of the transmission system, and the management reduction of one of the most crucial state companies in Mexico, the Federal Electricity Commission (CFE), was evidenced. The changes during the COVID-19 pandemic were the decrease in electric demand and consumption. This prevented the transmission nodes from saturating, although about 15% of the energy generated was still lost. Private companies, which own most of the intermittent renewable generation, and natural gas have been favored by the changes during the COVID-19 pandemic, generation sources such as wind and solar have had a noticeable increase, because of the 2013 energy reform that created an electricity market in which private companies and the state company started to compete. On the other hand, during the 2020 winter, natural gas imported mostly from the United States had volatile prices, considerably increasing its cost, and putting the combined cycle generation at risk. This technology represents around 60% of the generation, and its primary owners are private companies. This situation led to great discussions in the current administration, thus originating an electricity reform in which the state company wants to have control again. This paper opens the debate on whether the Mexican electricity system should continue with the same generation pattern or make substantial changes that benefit the country's energy security, distributed generation, and the relationship between the state company and the Mexican electricity system.

1. Introduction

The COVID-19 pandemic changed our way of living, altering the economy and undoubtedly the energy consumption and generation patterns (Delgado et al., 2021). The situation triggered protests by national and international organizations, leaving the world in shock and making us question how everything works (Sovacool et al., 2020).

This pandemic has also revealed the weakness of the electrical system. In the case of Mexico, it evidenced the failures of the 2013 energy reform in which private power generators were the most benefited, the fragility of the transmission system, and the dependence on natural gas to generate electricity. The price of natural gas depends on the US market (Sarmiento et al., 2021), as occurred in the 2020 winter when prices were volatile, affecting electric generation in Mexico since this resource is mainly imported from the US, and as can be seen in the electricity markets of Europe, dependence on natural gas influences consumer electricity prices.

The Federal Electricity Commission is critical in this analysis because it constitutes the second most crucial state-owned company in Mexico, after PEMEX (Petróleos Mexicanos), the Mexican state-owned oil

company. It is also relevant because it lost importance in generation after the 2013 energy reform, as the private companies were charged with generating mainly intermittent renewable electricity. Now, in the COVID-19 pandemic, the fragility of this company and the effects of the 2013 energy reform are notorious, as can be highlighted in the content of this paper.

In addition, Mexico and the United States have an important relationship on bilateral energy issues. Mexico exports crude oil and imports refined products from the United States. Finally, many energy products used in Mexico have the industry as their end-use, which plays an essential role in the maquila under the NAFTA free trade agreement (Jiménez, 2000; Alvarez Béjar, 2014).

There are no recent articles that integrate the Mexican electrical system (Pérez-Denicia et al., 2017) and there have been many changes in recent periods as can be highlighted in this article. Current works talk about energy poverty (García Ochoa et al., 2022; García Ochoa and Graizbord, 2016), or are only based on the optimization of demand (Ramírez-Sánchez et al., 2022). There is one article of the evolution of clean energies (Castrejon-Campos, 2022), but not of the integrated electrical system as proposed in this article. Nor is there an integrated

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analysis carried out by the government (SENER, 2020; CENACE, 2020).

This work goes further by integrating the entire electrical system, and explains changes occurred during the COVID-19 pandemic in this sector, both in demand and generation and their current impacts on the electrical system, which are being evaluated if there is an electricity reform.

2. Methods and data

For the analysis of the evolution of the installed capacity, generation, and losses of the electricity sector during the COVID-19 pandemic, several databases from the public and private sectors were integrated. Mainly, the installed capacity data was taken from the annual publications of the National Electricity System Development Program (PRO-DESEN) published by the Ministry of Energy (SENER), together with other databases (SENER, 2020; CENACE, 2020; OBTREN, 2020; INEL, 2020; Palacios Fonseca, 2017). Electricity generation and losses data pertains to the National Center for Energy Control (CENACE) (CENACE, 2017; CENACE, n.d.).

The geographical distribution of the installed capacity by control regions (Fig. 1) was obtained using a GIS where the distribution of the electricity generation plants was made.

Statistics of annual percentage change were made for generation by technology and control regions.

Sankey diagrams were made to represent the country's complexity using eSankey software.

Data mining was used to collapse all the data without losing information per hour using tools from the PowerBi software.

3. Results

3.1. Installed capacity

The total installed capacity in Mexico for 2020 was 88.8 GW, according to the database compiled from different sources as previously mentioned. There is no consensus in the information presented by

official institutions (Secretary of energy SENER and Energy regulatory commission CRE) on annual installed capacity; therefore, the information and analysis of the data described here are approximate.

This analysis on the geographical distribution of installed capacity considered eight control regions of the National Electric System (SEN), as shown in Fig. 1.

The ORI region has the highest installed capacity in Mexico (21.2 GW), followed by the NES and OCC regions with 19.7 and 14.5 GW, respectively (Fig. 2).

According to technology, combined-cycle plants constitute most of the installed capacity in the country with 35.3 GW, which is equivalent to 39.8%. This type of technology predominates in 5 regions (BCA, NOR, NTE, NES, and PEN). In second place are hydroelectric plants with a total installed capacity of 13.1 GW, representing 14.8% and constituting the primary power generation sources in the ORI and OCC regions. Wind and solar photovoltaic plants are the leading renewable energy resources, with installed capacities of 5.9 and 5.8 GW, respectively (6.6% and 6.5%). Turbogas plants dominate BCA and PEN regions, which are part of the total 5.6 GW installed, and correspond to 6.3%. Coal-fired plants stand out in the CEN and NES regions, with 5.5 GW (6.2%) of installed capacity. Internal combustion plants have a more significant presence in BCA, whose installed capacity throughout the country is 2 GW, with a percentage of 2.3%. There is only one nuclear plant (1.6 GW) in Mexico, located in the ORI region, constituting 1.8% of the country's installed capacity. The NES, OCC, and ORI regions have the highest number of biomass plants, whose total installed capacity is 1.2 GW (1.4%). Finally, geothermal power plants are present in the regions: BCA and OCC, whose installed capacity totals 0.9 GW and represents 1% of the total installed capacity in the country.

3.2. Generation, demand, and losses

The total electricity generation in Mexico for 2018 was 310.4 TWh, while 2019 generated 317.5 TWh, and 2020 generated 311.4 TWh.

In 2020, combined-cycle plants generated 183.3 TWh (58.9% of the total), hydroelectric plants contributed with 26.8 TWh (8.6%), heavy oil



Fig. 1. Control regions. BCA: Baja California y Baja California Sur; NOR: Noroeste; NTE: Norte; NES: Noreste; OCC: Occidente; CEN: Central; ORI: Oriental; PEN: Peninsular.

Source: Own elaboration based on data from SENER.

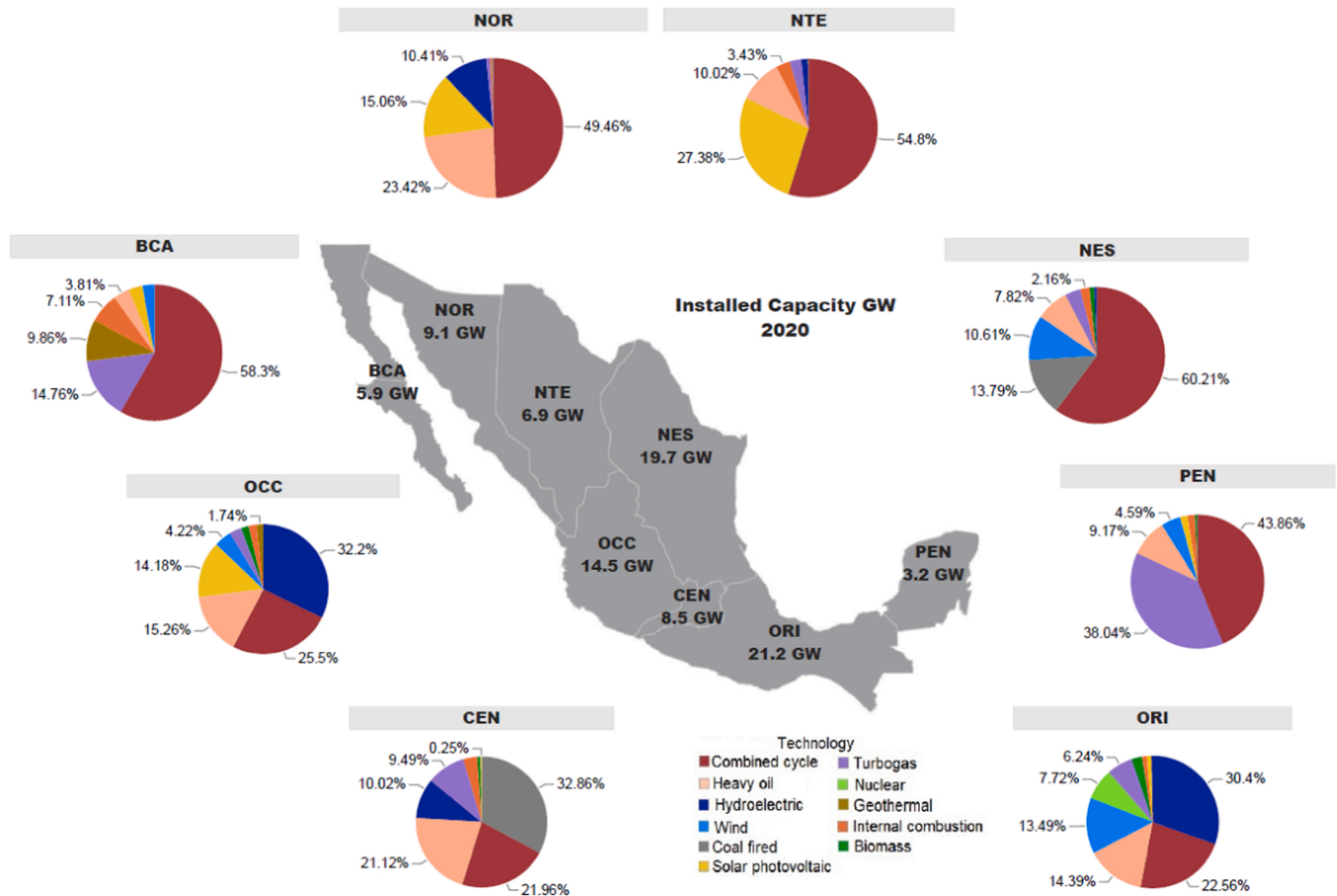


Fig. 2. Installed capacity (GW) technology 2020. Source: Own elaboration based on data compiled from different sources.

plants supplied 23.4 TWh (7.5%), wind plants provided 19.6 TWh (6.3%), coal-fired plants generated 14.1 TWh (4%), turbogas plants contributed with 14.1 TWh (4.5%), photovoltaic plants supplied 13.5 TWh (4.3%), nuclear plants provided 10.8 TWh (3.5%), geothermal plants generated 4.5 TWh (1.5%), internal combustion plants contributed with 2.9 TWh (0.9%), and biomass plants supplied 0.09 TWh (0.03%) (Fig. 3).

Regarding the changes of the 2018–2019 period in electricity generation (Table 1), there was an increase of 2.3%; the total generation during 2018 was 310.4 TWh, while 2019 generated 317.4 TWh. A 287% generation increase of solar photovoltaic sources stands out in this period, from 2.5 TWh to 8.4 TWh. Biomass sources increased by 37%, from 0.07 TWh to 0.1 TWh. Wind sources increased by 34%, from 12.4 TWh to 16.7 TWh. Internal combustion source increased by 24%, from 2. TWh to 3. TWh. Turbogas source increased by 14%, from 14.3 to 16.3 TWh. The combined-cycle source increased by 8%, from 160.6 to 172.7 TWh, while the geothermal sources did not change, remaining at 4.9 TWh. On the other hand, there was a reduction in the generation of heavy oil sources of 4%, from 40.4 TWh to 38.9 TWh. There was a reduction of 18% in the nuclear power source, from 13.2 TWh to 10.9 TWh. The coal-fired sources had a reduction of 21%, from 27.4 TWh to 21.6 TWh. Finally, the hydroelectric source had a reduction of 27%, from 32.2 TWh to 23.6 TWh.

During the COVID-19 pandemic (2019–2020), there was a reduction in electric generation; in 2019 total generation was 317.4 TWh, while in 2020 was generated 311.4 TWh representing a reduction of 1.9% (Table 1). Again, in this period, a noteworthy increase in the solar photovoltaic source was recorded from 8.4 TWh to 13.5 TWh, corresponding to 61%. On the other hand, wind sources increased by 17%,

from 16.7 TWh to 19.6 TWh. Hydroelectric sources increased 14%, from 23.6 TWh to 26.8 TWh. The combined cycle source increased by 6%, from 172.7 TWh to 183.3 TWh. The nuclear power source was unchanged, generating 10.8 TWh. Internal combustion source had a reduction of 9%, going from 3.2 TWh to 2.9 TWh. The geothermal source had a reduction of 9%, from 5 TWh to 4.5 TWh. Turbogas source had a reduction of 14%, from 16.3 TWh to 14.1 TWh. Biomass sources had a reduction of 17%, going from 0.11 TWh to 0.09 TWh. Heavy oil sources had a reduction of 40%, going from 39 TWh to 23.3 TWh. Finally, coal-fired sources had a reduction of 42%, from 21.6 TWh to 12.5 TWh.

At the national level, between 2019 and 2020, generation, demand, and losses decreased. Generation fell 1.49%, from 316.2 to 311.5 TWh. Similarly, demand decreased from 316.6 to 309.5 TWh, represented by 2.24%. Losses decreased as well from 48 to 36 TWh represented by 25% of reduction (Fig. 4 and Fig. 5).

The NES region generated the most electricity in 2020, contributing 92.8 TWh, representing 29.8% of the total generation, with a decrease of 4.7% compared to the previous year. Next, the ORI region generated 63.1 TWh (20.3%) with a decrease of 0.2%, followed by the OCC region with 44.2 TWh (14.2%), with a decrease of 3.1%. Only two regions reported an increase in generation: NTE and NOR. The NTE region with 30.8 TWh (9.9%) increased by 5.8%, followed by the NOR region with 30.6 TWh (9.8%) with an increase of 22.4%. The CEN region with 27.2 TWh (8.7%) had the greatest decrease with 17.3%. The BCA region with 16.2 TWh (5.2%) had no changes in generation and finally, the PEN region with 6.6 TWh (2.1%) showed a decrease of 2.9%.

OCC region presented the highest demand in 2020 with 65.7 TWh represented by 21.1% of the total, with a decrease of 2.1% compared to

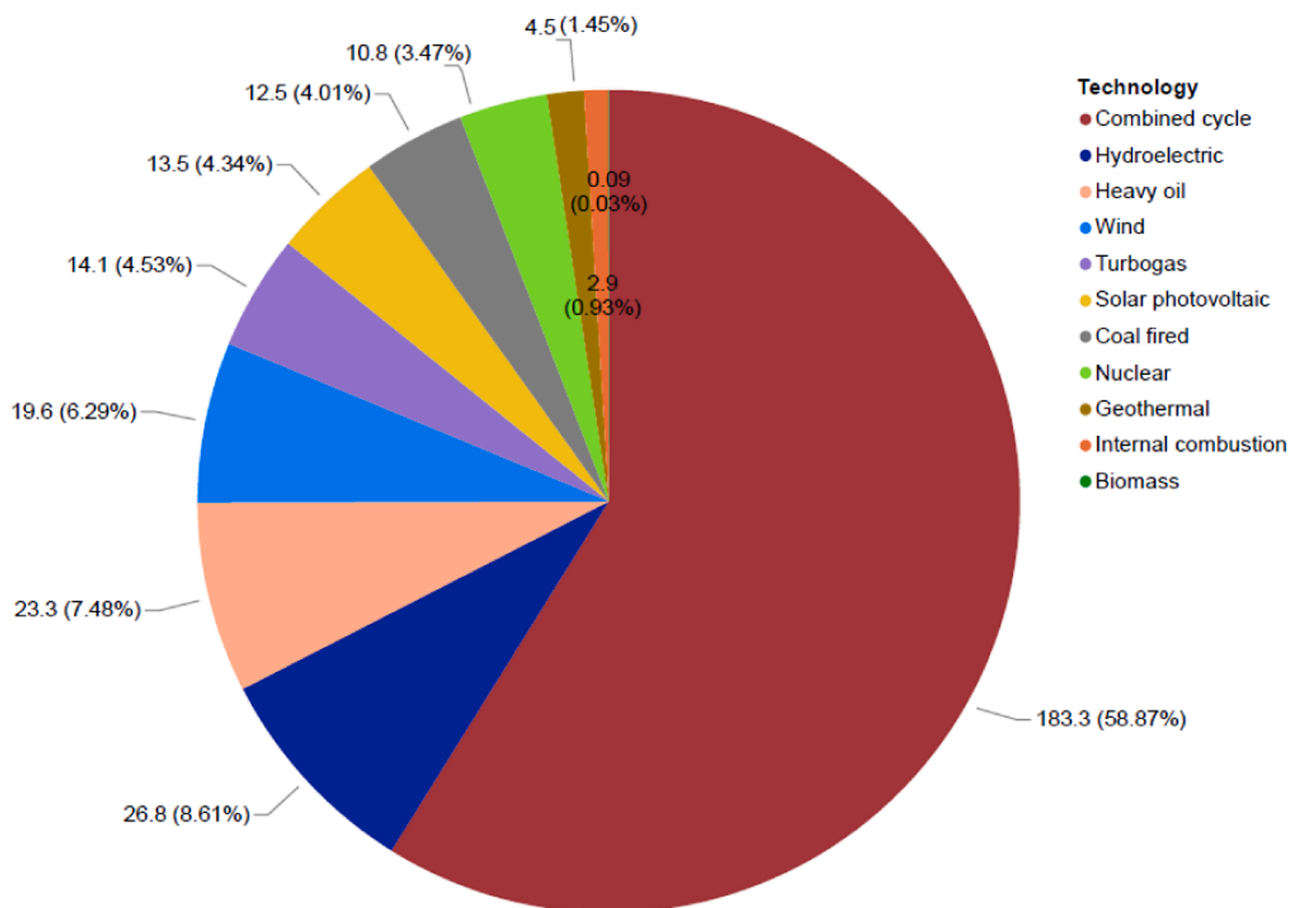


Fig. 3. GENERATION PERCENTAGE BY TECHNOLOGY, 2020. Source: Own elaboration based on data from CENACE.

Table 1 Evolution of the electric generation from 2018 to 2020.

Technology	2018 TWh	2019 TWh	2020 TWh	2018–2019 (% change)	2019–2020 (% change)
Biomass	0.1	0.11	0.09	37	-17
Coal fired	27.4	21.6	12.5	-21	-42
Combined cycle	160.6	172.7	183.3	8	6
Geothermal	5	5	4.5	0	-9
Heavy oil	40.4	39	23.3	-4	-40
Hydroelectric	32.2	23.6	26.8	-27	14
Internal combustion	2.6	3.2	2.9	24	-9
Nuclear	13.2	10.9	10.8	-18	0
Solar photovoltaic	2.2	8.4	13.5	287	61
Turbogas	14.3	16.3	14.1	14	-14
Wind	12.4	16.7	19.6	34	17

the previous year. Followed by the CEN region which demanded 54.8 TWh (17.6%) with a decrease of 4.2%. ORI region demanded 53.3 TWh (17.1%) representing a decrease of 1.5%. In the same way, NES decreased its demand to 53 TWh (17%) representing a 4.7% of reduction. Only two regions showed an increase in demand: NTE and NOR. NTE region demanded 28.2 TWh (9%) rose 4.1% and the NOR region demanded 24.6 TWh (7.9%) rose 3.8%. BCA region demanded 17.6 TWh (5.6%) represented in a reduction of 2.8%. The region that had the greatest percentage change was the PEN with 12.3 TWh (3.9%) with a decrease of 10.2%.

In 2020, the National Electrical System had 36 TWh in losses representing 11.6% of the total energy generated (311.5 TWh) (Fig. 5). The CEN presented the most losses with 7.4 TWh, representing 2.4% of the total generation, of which 4.80 TWh were non-technical losses while

2.61 TWh were technical losses. The OCC region presented losses of 5.6 TWh, representing 1.8% of the total generation, of which 2.38 TWh were non-technical losses, while 3.25 TWh were technical. The ORI region presented losses of 5.4 TWh, representing 1.7% of the total generation, of which 2.59 TWh were non-technical losses while 2.81 TWh were technical losses. The NES region had 3.6 TWh in losses, representing 1.1% of the total generation, of which 1.87 TWh were non-technical losses while 1.70 TWh were technical losses. The NTE region lost 2.3 TWh, representing 0.7% of total generation, of which 1.14 TWh were non-technical losses while 1.16 TWh were technical losses. The NOR region lost 1.8 TWh, representing 0.6% of total generation, of which 1 TWh are non-technical losses while 0.78 TWh are technical losses. The PEN region lost 1.1 TWh, representing 0.4% of total generation, of which 0.56 TWh were non-technical losses while 0.54 TWh

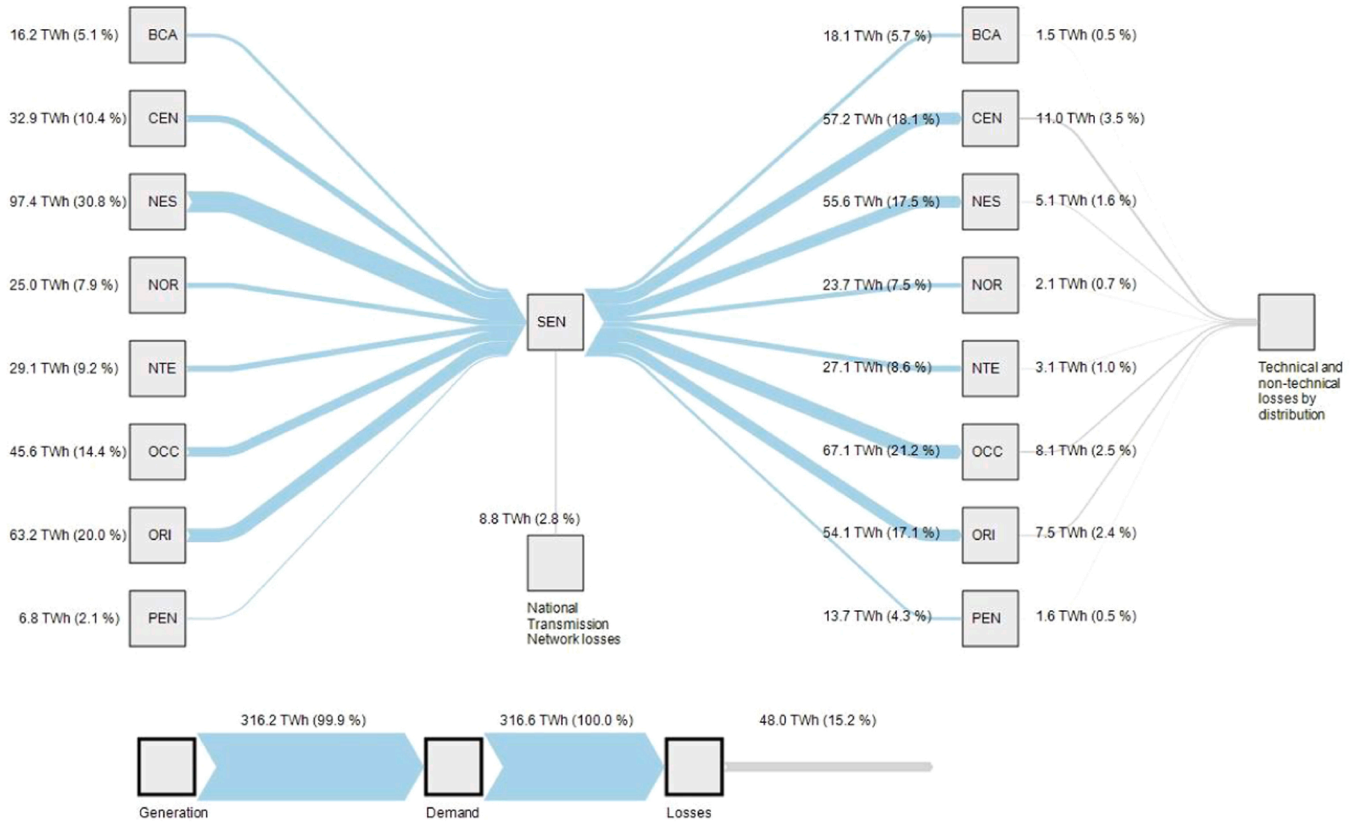


Fig. 4. GENERATION, DEMAND, AND LOSSES PER CONTROL REGION, AND TOTAL IN 2019. Source: Own elaboration based on data from CENACE.

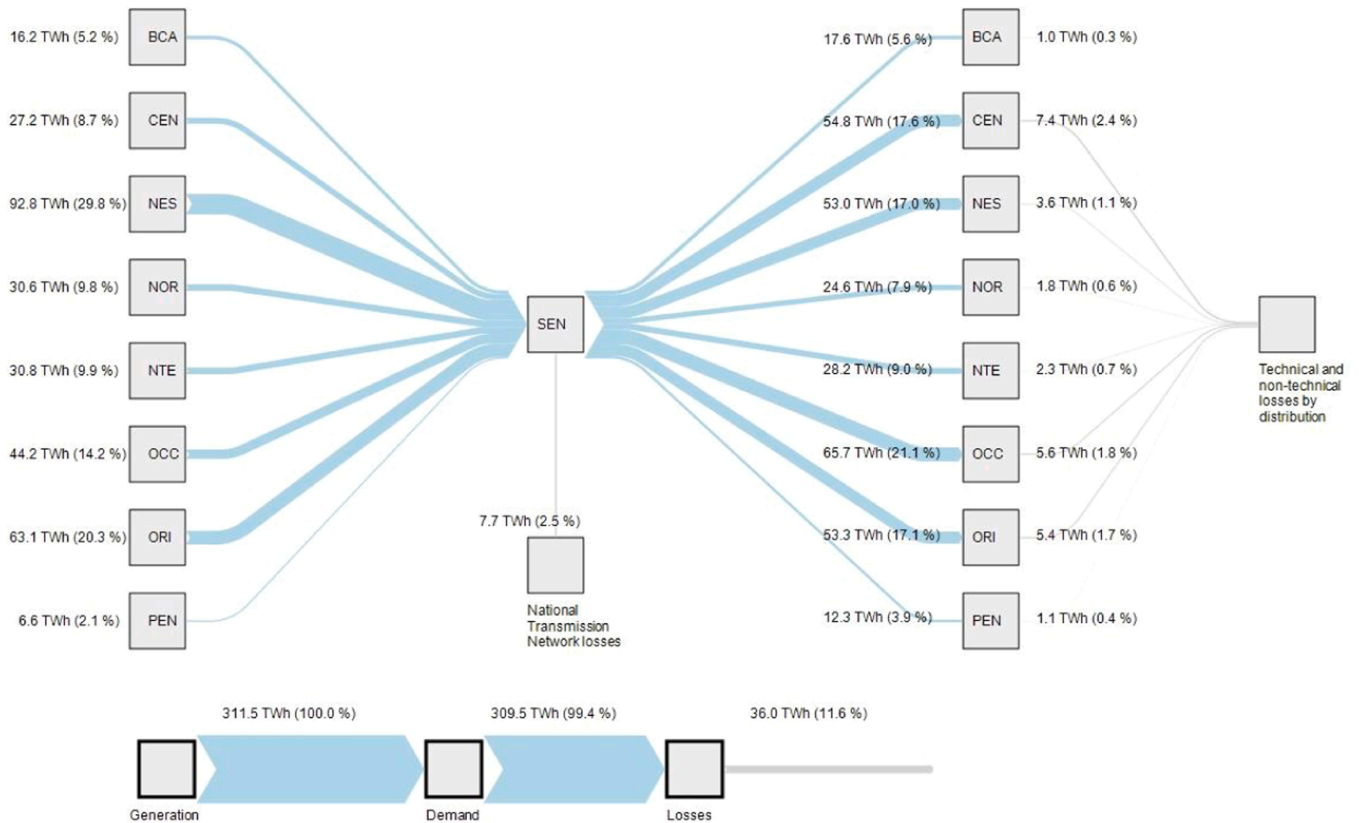


Fig. 5. GENERATION, DEMAND, AND LOSSES PER CONTROL REGION, AND TOTAL IN 2020. Source: Own elaboration based on data from CENACE.

were technical losses. BCA lost 1.1 TWh, of which 0.55 TWh were non-technical losses while 0.5 TWh were technical, representing 0.3% of the total generation.

Technical and non-technical losses due to distribution in 2020 notably decreased compared to 2019 in all regions (Fig. 4 and Fig. 5). The CEN region had a reduction of 32.7% compared to the previous year; the OCC region decreased by 30.9%; the ORI region had a reduction of 28%; the NES region decreased by 29.2%, followed by the NTE region with a reduction of 25.8%. The NOR region presented a decrease of 14.3%; the PEN region had a reduction of 31.3%; and finally, the BCA region showed the most significant percentage decrease concerning the previous year represented by 33.3%.

Fig. 6 (2018, 2019 and 2020) show the evolution of hourly generation patterns by technology from 2018 to 2020. The increase in solar energy presented during these three years stands out. During these three years combined cycle was the predominant type of energy, heavy oil occupied second place in generation during 2018 and 2019, but in 2020 solar photovoltaic moved to the second place of generation, between 10 am and 5 pm, displacing heavy oil. In the same year, hydroelectric occupied second place of generation after 6 pm when it comes necessary to cover the peak of demand that solar photovoltaic cannot cover (Fig. 6, 2020).

On the other hand, wind energy has displaced coal-fired energy, increasing its proportion over the years. Turbogás has also been displaced by hydroelectric, while biomass, nuclear power, and geothermal power remain the generators that dispatch the least.

In 2020, the total electricity generation was 311.4 TWh (Fig. 3), of which 46.47% corresponds to the CFE (144.72 TWh). Independent Energy Producers (PIE) generated 91 TWh which constitutes 29.22%. Privates produced 74.22 TWh (23.83%), and finally PEMEX generated 1.46 TWh, equivalent to 0.47% (Fig. 7).

4. Discussion

During the COVID-19 pandemic, installed capacity and generation of renewable energies increased (Table 1). In addition, generation by private producers also increased (Fig. 7). This brought a series of events, such as the proposal of an electricity reform, where the state seeks to participate more in the country's electricity generation again (AMLO, 2021).

Moreover, during this period, demand decreased. Consequently, the distribution points were less saturated, and therefore there were fewer losses.

Unforeseen generation peaks from renewable sources altered the generation patterns in December 2019, which produced a series of effects on the Mexican electricity system. Additionally, blackouts occurred at the beginning of 2021 because of a generation deficit caused by a winter storm in Texas, limiting access to natural gas; its price rose to 5000% (BBC NEWS, 2021).

The problem of distribution losses must be seriously addressed, since they represent a large percentage of the energy generated (15% for 2019 and 11% for 2020). The government has plans to improve the existing transmission network (CENACE, 2021), but it is time to question whether the long-distance transmission is worth it, since Mexico is a large country (1,964,375 km²), or whether efforts should focus on improving distributed generation.

Similarly, combined-cycle generation represents a problem in terms of safety and dependency, since Mexico imports around 60% of the natural gas it consumes, and uses 100% of the imported gas to generate electricity.

The electricity reform proposal aims to "regain control" by the State since the dispatch was based mainly on a wholesale electricity market where private companies were benefited, whose energy sources are mainly combined cycle and intermittent energies (Fig. 7). Additionally, the generation security control or system reliability was regulated by the market and not by the functions of the different sources (base-loader,

peak-loader, intermittent). This way of operating led to dispatch problems in 2019 and caused blackouts in the electrical system (Forbes, 2019; El Financiero, 2020).

In addition, the rise in natural gas prices significantly affected the Federal Electricity Company. With the electricity reform, the Energy Secretary proposes to manage the dispatch, allowing the state company to dispatch before the private energy companies and prevent the state company from having monetary losses. Also, it is urgent to rearrange the prices of services to distribute energy, since they can be reflected in the losses with severe consequences. This situation shows the necessity of a renewal or operation restructuring (CENACE, 2021).

Generation from energies with higher emissions than renewables such as fuel oil and coal-fired plants was reduced, but the function of baseload energies was not supplied. Intermittent renewable energies in Mexico still do not have a storage system available (Morales-Mora et al., 2021), therefore, the services to maintain the stability of the electrical system increased.

Generation patterns do not match demand. Data shows that the regions that demand the most, such as the central region (Figs. 4, 5), do not coincide with the regions that generate the most, so the amount of energy required to be transmitted is considerable. Thus, losses increase, as can be seen in the case of the central region, which presents most of them. Therefore, if losses are not managed differently, increasing renewable energies will not have a noticeable effect since, as mentioned before, more energy is lost by transmission than is generated by intermittent renewable sources. Analysis of the data shows that, with the demand reduction, losses were also reduced (from 48 TWh in 2019 to 36 TWh in 2020) due to a decrease in the saturation of the nodes (Figs. 4,5).

These non-normal events suggest whether the electrical system should continue to operate in the same way as now or perhaps it is time to analyze small, distributed energy projects that geographically match the demand instead of continuing with megaprojects, where generation and demand do not coincide, forcing energy to travel enormous distances to satisfy economic patterns.

It is also time to rethink whether it is safe in energy terms to continue importing 60% of natural gas from the United States or to try to substitute this fuel to be able to generate electricity from other sources since, as mentioned in the paragraphs above, natural gas prices are volatile. We have seen the consequences of this in Europe and the United States. Therefore, this black swan shows the fragility of the Mexican electrical system.

The series of phenomena that evidenced the fragility of the electrical system demands reflecting upon the distribution of electricity generation, since although private companies have overtaken the state company in electric generation, it may be time for the latter to restructure, given the problems we have seen in various electricity markets around the world such as what happened in Europe (The New York Times, 2021).

5. Conclusion

There was a reduction in demand and generation patterns during the COVID-19 pandemic. These patterns changed in quantity and sources, increasing the generation of different types of renewable energy, mainly owned by private companies. Consequently, an electricity reform proposal emerged as a counter-reform to the previous one, which mainly benefited private generators.

With the decrease in demand, there was a reduction in generation and a reduction in losses during the COVID-19 pandemic. This suggests that the transmission network becomes saturated when the demand is higher than a certain level. The distribution network should be updated to reduce considerable losses (15% in 2019), or more distributed generation should be implemented.

Finally, the participation of other sources in the energy matrix must be rearranged to allow a decrease in the natural gas demand since there

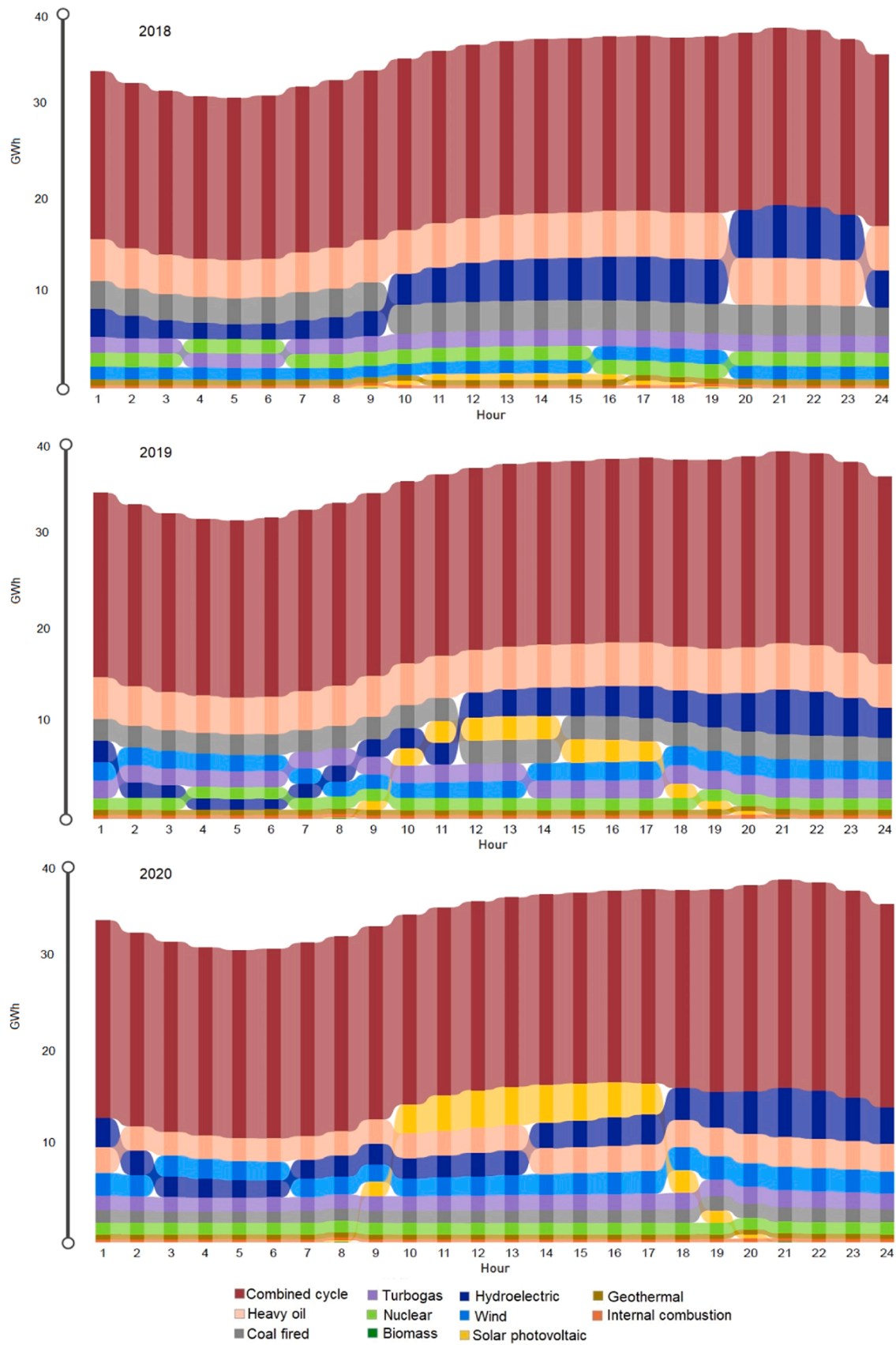


Fig. 6. HOURLY GENERATION PATTERNS BY TECHNOLOGY FROM 2018 TO 2020 (MWh).
 Source: Own elaboration based on data from CENACE.

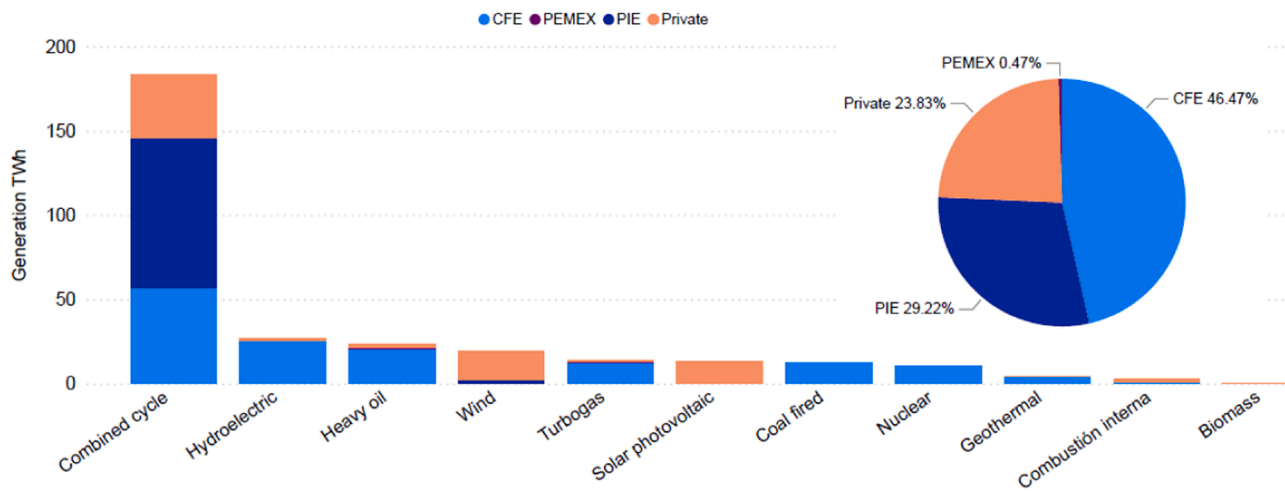


Fig. 7. Generation (TWh) by owner 2020. Source: Own elaboration based on data from SENER and CENACE.

is a high dependence on it (60%) which has increased the fragility of the National Electric System.

CRedit authorship contribution statement

Rafael González-López: Design, Writing, Visualization, Data curation, Revision. **Natalie Ortiz-Guerrero:** Writing, Data curation, Visualization, Revision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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