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Drivers of Electricity GHG Emissions and the Role of Natural Gas in Mexican Energy Transition

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Key words: Electricity GHG Emissions, Natural Gas, Decomposition Analysis, Energy Transition, Renewable Energy

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Abstract

In the last three decades, the high growth of natural gas as an energy source of Mexican electricity production was the most significant change in the sector. Natural gas went from being the source for 7% of electricity in 1990 to 62.3% in 2020. A co-dependence of electricity and natural gas systems has been established. Is this fact consistent with the objective of decarbonizing the electricity sector? We study this question through a decomposition analysis of electricity GHG emissions in Mexico between 1990 and 2015. We use a Logarithmic Mean Divisia Index (LMDI) to quantify the changes of electricity GHG

[1] This research gives continuity to recent work on natural gas infrastructure in Mexico, in particular:
- de la Vega Navarro, A. (2018). Nuevos riesgos y requerimientos de regulación: infraestructuras energéticas y actividades de exploración y producción en las fronteras con Estados Unidos. In A. Elizondo & M. Dussauge Laguna, *ASEA. Un nuevo modelo de institución del estado mexicano* (pp. 25-58). México: ASEA, CIDE, PIERCE.
- de la Vega Navarro, A. and Santillán Vera, M. (2019). *Natural Gas Cross-Border Infrastructures: New Risks and Regulatory Requirements in the Mexico–United States Energy Integration*, 42nd International Conference of the IAEE (International Association for Energy Economics), Session Hydrocarbons 6 - Natural Gas.

emissions related to activity, carbon coefficient, structure, and energy intensity effects. Activity effect was the most significant driver of GHG emissions growth, while structure and energy intensity effects contributed to limiting that growth. Although natural gas is the cleanest fossil fuel and its share in the electricity mix increased significantly, the effect of the carbon coefficient effect has shown a limited contribution to mitigating GHG emissions. From these results, we raise concerns about the role of natural gas, which could lead to carbon lock-in and stranded assets in the long term. To avoid this, an energy policy aiming towards a low-carbon energy system should consider the composition "natural gas + renewable energies + energy efficiency".

Keywords

Electricity GHG Emissions, Natural Gas, Decomposition Analysis, Energy Transition, Renewable Energy

1. Introduction

Mexico signed and ratified the Paris Agreement in 2016, in which the country committed to reducing unconditionally 22% of its Greenhouse Gas (GHG) emissions by 2030 relative to a Business As Usual (BAU) baseline. The highest reduction target within the Nationally Determined Contribution (NDC) was assigned to the electricity sector: 31% GHG reduction by 2030. According to this target, the electricity sector could emit 139 megatons of carbon dioxide equivalent ($MtCO_2e$) in 2030 instead of 202 $MtCO_2e$ in the BAU scenario in the same year.

The electricity sector has a high potential to reduce emissions, mainly because of the variety of primary energy sources and technologies to produce electricity with low carbon emissions. Nowadays, the possibilities of contributing to decarbonization are broader in the electricity sector than in other ones such as transport or heavy industries. Additionally, growing electrification in the end-use sectors and energy efficiency improvements of electric equipment and appliances widen the decarbonization perspectives (Bellocchi, Manno, Noussan, Giacomo Prina, & Vellini, 2020; DDPP, 2015; Lechtenböhmer, Nilsson, Åhman, & Schneider, 2016; Steinberg, et al., 2017; Sugiyama, 2012).

A central policy issue is to define which energy sources and technologies will be used to produce electricity. Between 1990 and 2020, the structure of Mexican electricity production changed significantly. There was a high increase in the installation of combined cycle power plants, which use natural gas as fuel, while thermoelectric plants, which mainly use fuel oil, recorded a substantial decrease. In Mexico 2020, electricity production by energy source was composed as follows: 74.6% fossil fuels (62.3% natural gas, 8.2% oil, 4.1% coal), 20.6% renewable energy sources (8.8% hydraulic, 5.9% wind, 4.3% solar, 1.5% geothermal, and 0.2% bioenergy), 3.6% nuclear, and 1.2% efficient cogeneration (Sener, 2021). The high share of natural gas is evident. The replacement of higher GHG emitting sources —mainly fuel oil— by natural gas in Mexico plays a key role in offsetting the impact of growing electricity production on GHG emissions. However, as we will discuss below, there was a significant growth both in GHG emissions from electricity production and in the share of natural gas in these emissions.

In light of these facts, it is a policy concerning the role of natural gas as a "transition fuel" to the decarbonization of the electricity sector. To the best of our knowledge, this concern has not been studied sufficiently for the case of Mexico to give a clear picture that can inform policy making. The objective of this work is to close this research gap in Mexico by performing a decomposition analysis from 1990 to 2015, which represents a possibility to quantitatively study this issue. By a decomposition analysis we quantify whether the changes in the level of GHG emissions are due to the growth of electricity production (activity effect), the change in GHG emission coefficient per unit of energy use (carbon coefficient effect), the change in the mix of electricity production by fuel (structure effect), or the change in the energy intensity in electricity production (energy intensity effect). The results of this analysis, particularly the estimation of the structure effect, will help us to discuss the consequences of the growing natural gas share in Mexican electricity production. To accomplish this, the remainder of this paper is organized as follows. The Literature Review section presents a short revision of the role of natural gas as a transition fuel to decarbonization. The Methodology and Data section presents the Logarithm Mean Divisia Index Methodology applied, as well as the data and sources used. The Results and Discussion section shows the main results and relates them to features, problems, and opportunities in the sector. Finally, the Conclusion and Policy Implications section summarizes key concluding points and reflections on energy and climate policies.

2. Literature Review

Natural gas has been identified as an essential element of the energy transition to mitigate climate change because of its low carbon intensity when combusted compared to other fossil fuels. Some authors argue that natural gas could play a significant role in satisfying energy demand and providing a bridge for largescale renewable energy use, mainly in the short- and medium-term transition phases (Aguilera & Aguilera, 2020; Gürsan & de Gooyert, 2021; Levi, 2013; Safari, Das, Langhelle, Roy, & Assadi, 2019). Some research has analyzed the role of natural gas in electricity production as a substitute for coal, mainly in countries with a high share of coal in their electricity matrix. While natural gas could represent a near-term emission reduction in these cases, it also could limit emission mitigation in the long run (without carbon capture and storage, CCS). This characteristic is because natural gas does generate emissions and has a long-lived infrastructure[2] (González-Mahecha, Lecuyer, Hallack, Bazilian, & Vogt-Schilb, 2019; McGlade, Pye, Ekins, Bradshaw, & Watson, 2018). Moreover, there are concerns about the methane leakage of natural gas production, which potentially undermines the climate benefits of fuel switching (Gilbert & Sovacool, 2017; Zhang, Myhrvold, & Caldeira, 2014).

Gürsan and de Gooyert (2021) identified direct and indirect effects related to natural gas as an energy transition fuel. Direct effects produce advantages of using natural gas, e. g., reducing CO2 emissions, improving energy reliability when intermittent renewable energy is used, and reducing cost in power generation. Indirect effects produce drawbacks of using natural gas, e. g., crowd-out effect, carbon lock-in, and energy rebound. Crowd-out effect could be defined as a constant redirection of investments from a desired technology to another technology due to the attractiveness of the second one. Carbon lock-in constitutes the dependency on fossil fuel technology pathways as a result of the crowd-out effect. Carbon

[2] Power plants' lifetime may range from 30 to 50 years (González-Mahecha, Lecuyer, Hallack, Bazilian, & Vogt-Schilb, 2019). 50 years for coal and oil power plants, 30 years for gas-fired power plants (Caldecott, Saygin, Rigter, & Gielen, 2027).

lock-in “creates persistent market and policy failures that can inhibit the diffusion of carbon-saving technologies despite their apparent environmental and economic advantages” (Unruh, 2000, p. 1). Energy rebound could happen when energy costs drop (i.e., affordable natural gas), which motivates an increase in global production and energy consumption.

In the same line of concerns of the indirect effects described by Gürsan and de Gooyert (2021), some authors argue that the growing use of natural gas fosters a greater dependence on fossil fuels. Consequently, the growing use of natural gas is an insufficient strategy, in the long run, to achieve the minimum targets to mitigate climate change (Dupont & Oberthür, 2012; Stephenson, Doukas, & Shaw, 2012). Additionally, rising energy infrastructure assets focusing on natural gas-based power plants could potentially become stranded assets if climate pressures rise in the future. Stranded assets could be defined as assets that lose economic value well ahead of their anticipated useful life. Some authors estimated the potential for a global wealth loss from stranded assets as US$1–4 trillion (du Pont, Gueguenteil, & Johnson, 2020).

For the case of Mexico, Valenzuela and Studer (2017) considered that during the administration 2012-2018, the federal government’s climate strategy was to rely heavily on natural gas as a transition fuel. That strategy prevailed because the central policy objective in the Mexican power sector was to lower power production costs, mainly taking immediate advantage of the benefits of low-cost gas in North America. The consequence of that strategy was the low penetration of renewable energy in the Mexican electricity matrix despite the country's leadership on climate issues. In the same line, Sarmiento et al. (2021) estimated that if natural gas prices remain low, the Mexican power production of natural gas facilities will continue increasing.

3. Methodology and Data

3.1 Decomposition analysis: an overview

Decomposition analysis is a flexible method that allows an aggregate magnitude to be separated into structural components. These components are defined in the objective function according to the research interests. There are different decomposition methods, the index decomposition analysis (IDA) being the most common one in the literature related to energy and GHG emissions. This methodology was first used during the late 1970s to analyze structural changes in energy consumption within the industrial sector. After the 1990s, the literature also focused on quantifying factors inducing changes in GHG emissions (Ang, 2004; Xu & Ang, 2013).

Within the IDA methodology, it is possible to construct different kinds of indices. These indices include the following: the Laspeyres Index, the Paasche Index, the Arithmetic Mean Divisia Index (AMDI), and the Logarithmic Mean Divisia Index (LMDI). The LMDI has advantages compared to the Laspeyres, Paasche, and Arithmetic Mean Divisia indices. The Laspeyres Index is complex and difficult to estimate. The AMDI is not possible to calculate when there are values equal to zero. The results of the Laspeyres, Paasche, and Arithmetic Mean Divisia indices present residual terms, which hinder their interpretation (Ang & Liu, 2007). By contrast, the LMDI —using an additive decomposition based on a logarithmic function of mean weight— satisfies the three main requirements of the Fisher Index: factor-reversal, circular, and time-reversal tests (Frisch, 1930). Satisfying a factor-reversal test means a perfect decomposition (no residual in the results). A circular test refers to the possibility of handling zero-value data when substituting zeros by small numbers without further effect in the perfect decomposition. Satisfying a time-reversal test means that the effect from year 0 to T is reciprocal to the effect from year T to 0. The LMDI analysis is theoretically proven, easy to use, adaptable, and flexible for interpretation (Ang, Zhang, & Choi, 1998; Ang, 2004; Jia, Jian, Xie, Gu, & Chen, 2019).

The LMDI for studying GHG emissions of the electricity sector was proposed by Ang, Zhang, & Choi (1998). In recent years there has been updated literature in this regard, mainly with a focus on China (De Oliveira, 2019; Goh, Ang, & Xu, 2018; Kim, Kim, Kim, & Park, 2020; Liao, Wang, Zhang, Song, & Zhang, 2019; Lin & Raza, 2019; Wang, Wang, He, Lu, & Zhou, 2020). For the case of Mexico, there is relevant literature using LMDI for quantifying the underlying energy demand and GHG emissions factors from the industrial sector (Sheinbaum, Ozawa, & Castillo, 2010; Sheinbaum, Mora, & Robles, 2012; González & Martínez, 2012; Puyana, Santillán, & Pérez, 2014). However, no relevant study uses a decomposition analysis for the Mexican electricity sector. This paper contributes to the literature by using the LMDI method to analyze GHG emissions of the Mexican electricity sector and the role of natural gas on the energy transition.

3.2 Logarithm Mean Divisia Index Methodology

Given the suitable properties of the LMDI method, this research followed the index proposed by Ang, Zhang, & Choi (1998) to study GHG emissions in electricity production. Change in GHG emissions from the total electricity production (ΔG_{tot}) from year 0 to T can be decomposed into the following components:

$$\Delta G_{tot} = \Delta G_{pdn} + \Delta G_{emc} + \Delta G_{gmx} + \Delta G_{int} \qquad [1]$$

The terms on the right-hand side of Eq. (1) give the contributions from changes in the total electricity production level (ΔG_{pdn}), CO_2 emission coefficients of fuels (ΔG_{emc}), generation mix by fuel type (ΔG_{gmx}), and energy intensity in electricity generation (ΔG_{int}). We named these changes as activity, carbon coefficient, structure, and energy intensity effects, respectively. Applying the LMDI methodology, this is our model:

$$\Delta G_{tot} = \sum_i L(G_{i,T}, G_{i,0}) ln\left(\frac{P_T}{P_0}\right) + \sum_i L(G_{i,T}, G_{i,0}) ln\left(\frac{U_{i,T}}{U_{i,0}}\right) + \sum_i L(G_{i,T}, G_{i,0}) ln\left(\frac{F_{i,T}}{F_{i,0}}\right) + \sum_i L(G_{i,T}, G_{i,0}) ln\left(\frac{R_{i,T}}{R_{i,0}}\right) \quad [2]$$

where,

G_{tot}: CO_2e emissions from all power plants.

G_i: CO_2e emissions from power plants using fuel *i*.

P: Total electricity production.

P_i: Electricity production based on fuel *i*.

U_i: CO_2e emission coefficient of fuel *i*, given by CO_2e emissions per unit of energy use (G_i/Q_i).

F_i: Share of electricity production based on fuel *i* (P_i/P).

Q_i: Energy input to all power plants using fuel *i*.

R_i: Energy intensity (i.e., the inverse of energy efficiency) for power plants using fuel *i* (Q_i/P_i).

The logarithmic function is defined as:

$$L(G_{i,T}, G_{i,0}) = \frac{G_{i,T} - G_{i,0}}{\ln\left(\frac{G_{i,T}}{G_{i,0}}\right)} \quad [3]$$

Where $G_{i,T}$ and $G_{i,0}$ are positive integers and $G_{i,T} \neq G_{i,0}$. For the case where emission values are equal to zero[3], we define L(0,0) = 0.

3.3 Data

We used data from the Mexican electricity sector for ten different energy sources: coal, oil, natural gas, nuclear, hydro, geothermal, solar, wind, biofuels, and waste. Given the availability of data, the analysis was applied for five-year periods from 1990 to 2015. We employed data, of the three variables referred to below, which was obtained from the indicated sources.

i. Energy production by energy source is measured in gigawatts-hour (GWh). This data was obtained from the data browser of the International Energy Agency (IEA), category "Electricity generation by source, Mexico 1990-2020" (IEA, 2021).

ii. GHG emissions from electricity production in Mexico by fuel are measured in $MtCO_2e$. This data was obtained from the National Greenhouse Gas Emissions Inventory (*Inventario Nacional de Emisiones de Gases y Compuestos de Efecto Invernadero*, INEGyCEI), which reports GHG emissions using the IPCC classification. We used the INEGyCEI 1990-2015 (INECC-SEMARNAT, 2018), which informs GHG emission from electricity production disaggregated by fuel every five years[4].

[3] Refer to Ang, et al. (1998) for working with zeros in the data.

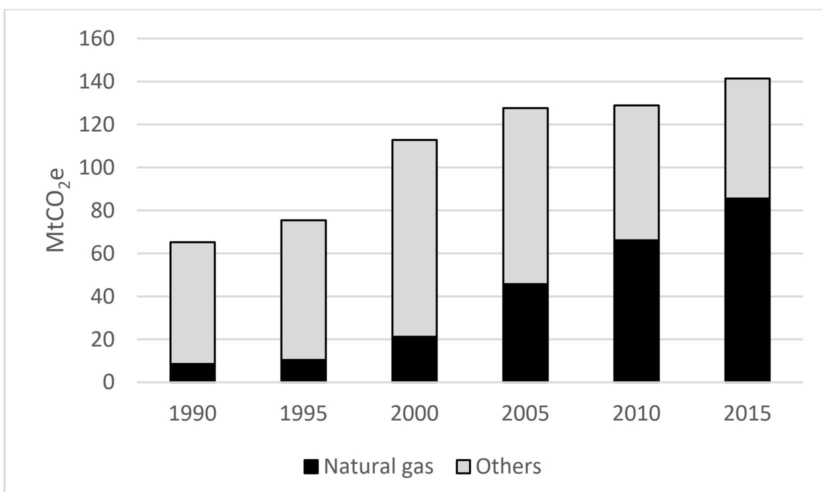
[4] Although the last actualization of the INEGyCEI reports a more recent period (1990-2019), it was not feasible using it because the dataset available does not include disaggregated information of the electricity GHG emissions (INECC, 2021).

iii. Fossil energy input for electricity production by fuel is measured in petajoules (PJ). This data also was obtained from INEGyCEI 1990-2015 (INECC-SEMARNAT, 2018).

4. Results and Discussion

Between 1990 and 2015, CO_2e emissions from electricity production in Mexico grew 76.2 MtCO_2e, passing from 65.2 to 141.4 MtCO_2e, which is equivalent to 117% of growth. It is worth noting that the share of natural gas on these emissions showed significant growth, passing from 13% to 61% during the period (see Figure 1).

Figure 1. GHG emissions from Mexican electricity production and share of natural gas 1990-2015



Based on (INECC-SEMARNAT, 2018).

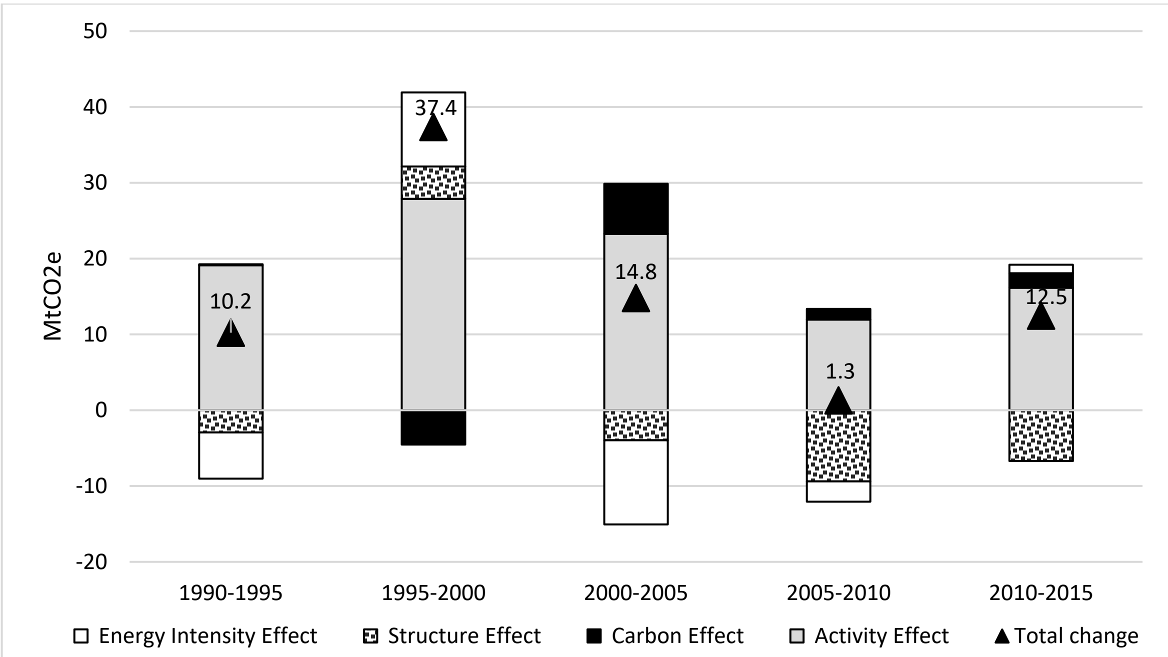
To analyze the drivers of this GHG emission growth, we decomposed it by LMDI methodology. We found that the activity effect is the most critical component to induce rising GHG emissions, while structure and energy intensity effects contributed to limit the growth of the GHG emissions. Carbon coefficient effect showed a limited participation on the change of GHG emissions (see Table 1).

Table 1. Results of CO_2e decomposition analysis of electricity production in Mexico 1990-2015

	Activity Effect (ΔG_{pdn})	Carbon Coefficient Effect (ΔG_{emc})	Structure Effect (ΔG_{gmx})	Energy Intensity Effect (ΔG_{int})	Total change (ΔG_{tot})
Change ($MtCO_2$e)	98.38	5.50	-18.69	-8.98	76.20
Change (%)	150.90	8.44	-28.67	-13.78	116.88

Figure 2 shows the decomposition of these effects every five years from 1990 to 2015. The bars of the figure show the shares of each effect on the five-year emission change in $MtCO_2$e, which could be positive or negative effects. The triangles and labels of the figure show the five-year total emission changes in $MtCO_2$e, which were always positive.

Figure 2. Five-year decomposition of the change in GHG emissions from electricity production in Mexico 1990-2015 ($MtCO_2e$)



4.1 Activity Effect

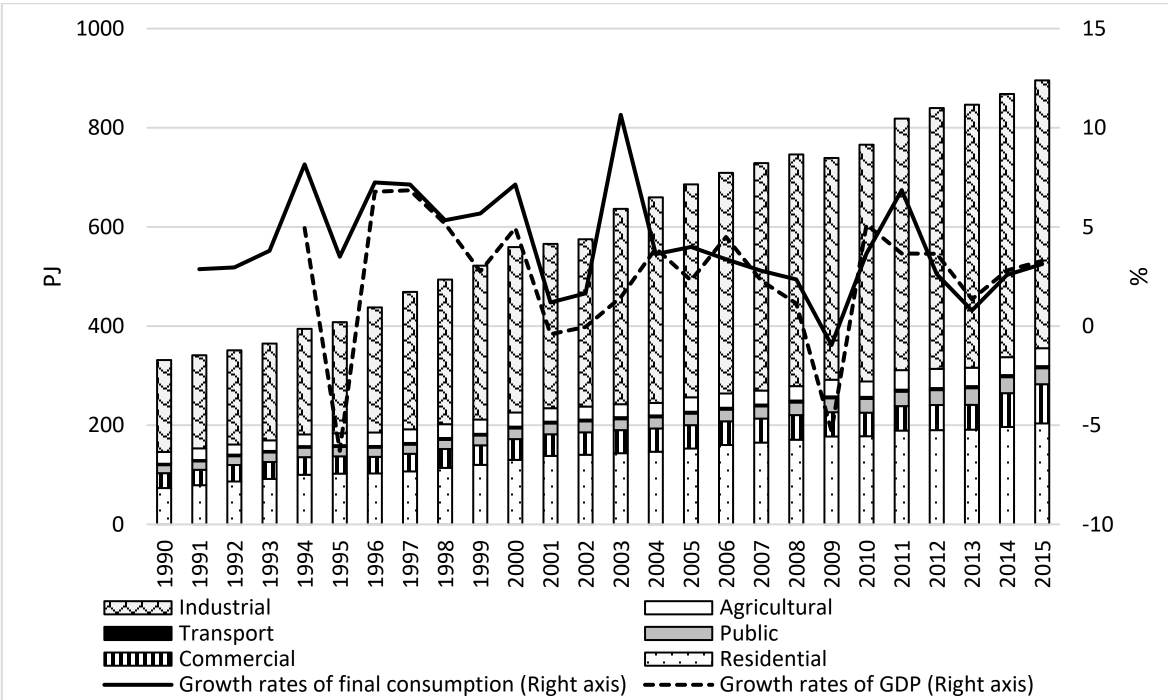
The CO_2e emission growth of electricity production is mainly explained by the activity effect (98.38 $MtCO_2e$), by the growth of electricity production in the country. The activity effect shows that CO_2e emissions would have grown by 150.9% if the other effects (carbon coefficient, structure, and energy intensity) had been constant at their 1990 value (see Table 1). The activity effect that induced emissions upward was the most significant in all periods (see Figure 2). The rising electricity demand could explain the relevance of the activity effect in the country, which in turn is related to several factors like economic growth, population growth, and rising electrification. On an aggregate level, Mexico consumed a total of 117.59

terawatts-hour (TWh) in 1990. By 2015 this amount was a total of 294.39 TWh. That was a total increase of 150%.

GDP and electricity consumption are intertwined, which is clearly shown by the lines of Figure 3. During the period 1990-2015, there were three economic recessions. They happened in 1995, 2001, and 2009, showing drops of total GDP of 6%, 1%, and 6%, respectively. Simultaneously, the electricity consumption growth rate showed clear drops too. Throughout the study period, electricity consumption reported a negative growth rate only in 2009. The long-lasting impacts of the global economic crisis 2009 could be reflected on smaller activity effects in the periods 2005-2010 and 2010-2015 compared to the periods 1990-1995, 1995-2000, and 2000-2005 (see Figure 2).

The influence of GDP on electricity consumption could be related to the high share of industrial electricity consumption to the total electricity consumption (see bars of Figure 3). During the study period, industry consumed 60% of the electricity on average, creating in that way a strong relationship between GDP and energy consumption.

Figure 3. GDP and electricity consumption in Mexico 1990-2015



Based on (SIE, 2021).

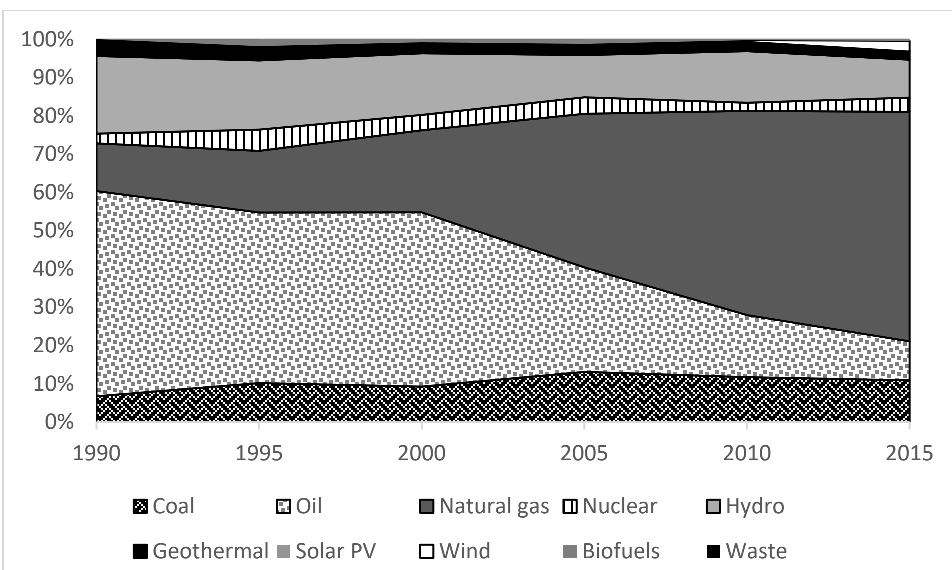
From 1990 to 2015, there was a constant increase in electricity access in the country. In 1992 93.15% of the population had electricity access, whereas in 2015, it was 99%. Additionally, there was a considerable increase in electricity consumption per capita, passing from 1,401 kilowatts-hour (kWh) in 1990 to 2,416 kWh in 2015 (Ritchie & Roser, 2020) This increase represents a growth of 72.44% during the period. From 2005 to 2015, there was a total increase of 5.8% of electricity users. The main part of this increment was due to constant electricity prices that allowed a cheaper provision of energy. The increase of users during these ten years was 88% from households, 9.8% commercial sector, 0.8% industrial sector, 0.5% services, and 0.3% agriculture.

4.2 Structure Effect

The structure effect contributed to limiting the growth of GHG emissions. Between 1990 and 2015, GHG emissions would have dropped by 18.69 MtCO2e (-28.67%) if only the structure effect had occurred (see Table 1). The structure effect drove emission reductions in all periods except 1995-2000 (see Figure 2).

The energy mix to produce electricity in Mexico changed a lot in this period. Figure 4 shows the Mexican electricity production mix by fuel between 1990 and 2015. The most marked changes are the growth of natural gas and the reduction of oil. Simultaneously, there has been a reduction in the share of hydropower and a minimal increase of other renewables. All this context makes it seem that Mexico is carrying out a Natural Gas strategy to decarbonize the electricity sector. Natural gas has been used as a transition fuel, showing a preponderant role. In contrast, the role of renewable energy remains very limited.

Figure 4. Structure of electricity production by energy source in Mexico 1990-2015



The significant growth of using natural gas for electricity production in recent decades in Mexico could be explained by three factors:

i. The growing natural gas availability in the United States and falling prices (Joskow, 2013), which have stimulated expanding demand for natural gas, growing imports of natural gas, and rising internal and cross-border natural gas infrastructure in Mexico (de la Vega Navarro, 2018; Lajous, 2013; Sarmiento, et al., 2021).
ii. The reform of the Mexican electricity sector in 1992 that opened generation to the private sector joined with the technological progress in gas turbines, which made it possible to install less capital-intensive and more efficient plants (Rodríguez Padilla, 1999).
iii. The lower emission factor of natural gas than the emission factor of other fossil fuels, which leads to the argument that natural gas is a green energy and is used to justify its increasing use.

The predominance of natural gas for electricity production is concerning. The high share of natural gas in the Mexican power sector could limit the incorporation of renewable energy in the long run. A forecast of the energy sector in North America demonstrates that there could only be a shift from natural gas to renewable energy under a carbon tax policy. Also, this forecast shows that natural gas can displace renewable energy when it is abundant and less expensive (Huntington, et al., 2020).

In Mexico, natural gas has become an abundant and less expensive resource by means of imports. There has been an expansion of natural gas consumption, much of which is imported from the United States through pipelines. Imports covered a growing share of the national demand for natural gas: 7% in 2000, 23% in 2010, and 70% in 2020 (EIA, 2021; CNH, 2021). Consequently, it has required an intense creation of infrastructure. In 2012 there were 16 natural gas cross-border pipelines between Mexico and the U.S., growing to 22 by 2017 and reaching 24 by 2019. This change represents a significant growth of the capacity from 2,758 to 11,000 million standard cubic feet per day (MMscfd) between 2012 and 2019 (Sener, 2019). Although natural gas imports from the United States seem to guarantee a constant flow of natural gas at low prices, it poses risks to energy security and has consequences for the transformation of the energy system.

The characteristics of natural gas infrastructure demand heavy investments and derive in long-lasting constructions. This situation creates risks in the electricity sector: carbon lock-in and stranded assets. As Solano-Rodríguez, Pizarro-Alonso, Vaillancourt, & Martín-del-Campo (2018, p. 1) highlighted: "An over-investment in gas infrastructure in the next 15 years may delay the power sector's transition to lower carbon sources and put at risk either meeting carbon targets cost-effectively or leaving some gas assets stranded". The presence of natural gas has acquired structural characteristics.

4.3 Carbon Coefficient Effect

There was a small increase in GHG emissions (5.5 $MtCO_2e$) derived from the carbon coefficient per unit of energy used during the period 1990-2015. In other words, if the other effects (activity, structure, and energy intensity) had been constant at their 1990 value, GHG emissions from electricity production would have grown about 8.44% (see Table 1). At first glance, this may seem inconsistent when considering climate change mitigation efforts.

However, if we ponder the diversity of GHG emission coefficients and all the changes in the energy sources used, the estimated carbon effect makes sense.

GHG emission factors of fossil fuels are varied. Without a doubt, natural gas is the least GHG emitter fossil fuel, both considering the quantity of fuel used (see Table 2) or the quantity of electricity produced (see Table 3).

Table 2. Emission factors of electricity production by fuel per mass used

Fuel	*Units*	*CO_2*	*CH_4*	*N_2O*
Bituminous coal	kg/ton	2,017	0.0209	0.0315
Light fuel oil	kg/m3	3,097	0.1203	0.0241
Diesel	kg/m3	2,596	0.1078	0.0216
Natural gas	kg/m3	2.27	0.0000411	0.00000411

Source: Inventario Nacional de Emisiones de Gases y Compuestos de Efecto Invernadero (INECC-SEMARNAT, 2018).

Table 3. Emission factors of electricity production by fuel per kWh produced*

Fuel	**Kilograms of CO_2 per kWh**
Coal	1.004
Natural gas	0.412
Petroleum	0.970

*Data based on U.S. electricity generation 2019.

Source: FAQS. How much carbon dioxide is produced per kilowatt-hour of U.S. electricity generation? (EIA, 2020).

Although the use of natural gas for electricity production grew significantly and the use of fuel oil was reduced, the carbon coefficient effect increased a little due to the reduction in the share of other zero-emission energy sources, like hydro[5] and geothermal. Additionally, the growth of other low-carbon energy sources like wind and solar has been limited during the period.

4.4 Energy Intensity Effect

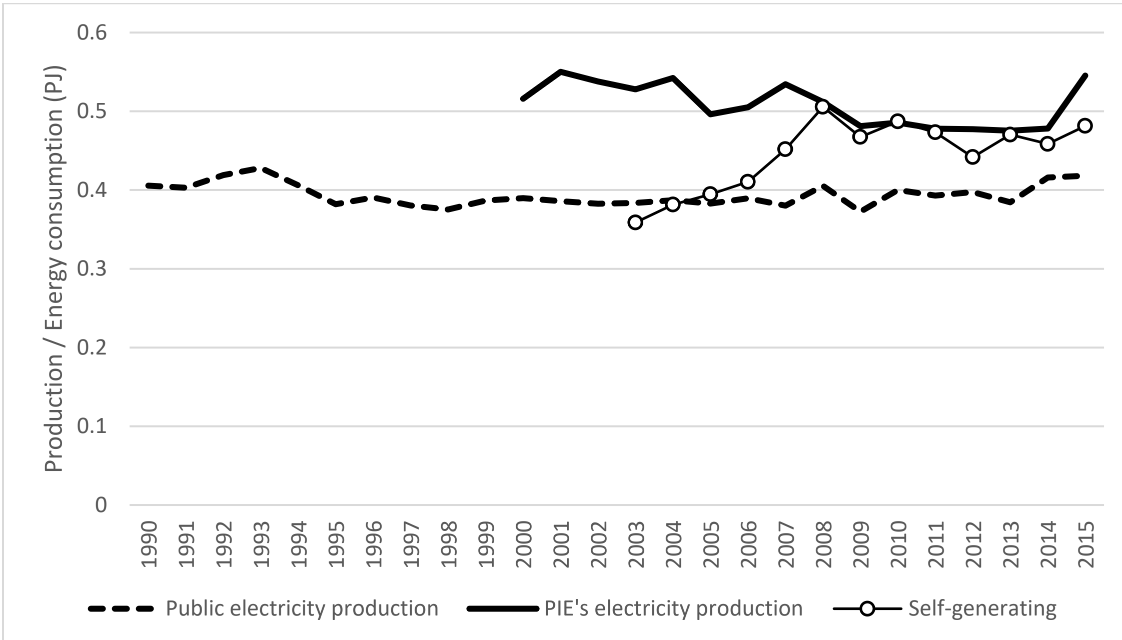
The energy intensity effect limited GHG emissions from total electricity production (-8.98 MtCO2e) between 1990 and 2015. CO_2e emissions would have been reduced by 13.78% if only the energy intensity effect had occurred (see Table 1). The energy intensity effect contributed to the decline in emissions during the periods 1990-1995, 2000-2005, and 2005-2010 (see Figure 2).

Energy intensity is the inverse of energy efficiency. Energy efficiency in electricity production —commonly known as thermal efficiency— is measured by the ratio of electricity produced to energy used for electricity production. Following available data, we found that energy efficiency in electricity generation in Mexico has been variable. The thermal efficiency of the public[6] electricity production has been lower than the energy efficiency of independent producers of energy (*productores independientes de energía*, PIEs) and self-generating plants (see Figure 5).

[5] In other regions, such as Brazil and Quebec, a change from hydro to natural gas has been observed, a phenomenon that is causing concerns about the consequences for the mitigation of climate change.

[6] Public electricity production include the production of independent producers of energy that sold their production to the Federal Electricity Commission (*Comisión Federal de Electricidad*, CFE).

Figure 5. Energy efficiency of Mexican electricity production, 1990-2015.



Based on (SIE, 2021).

On the one hand, thermal efficiency is related to the technology used to produce electricity. The change in the energy sources used for electricity production also implies changes in the technologies used. Table 4 shows these last changes between 1990 and 2015 in Mexico. The improvement in energy efficiency could be explained by the growth of combined cycle plants, whose share of Mexican electricity production went from 6.5% to 51.5% between 1990 and 2015. The thermal efficiency of combined cycle plants rose during the study period. In the public sector, efficiency of the thermal plants using gas went from 40% in 2000 to 49.7% in 2015 (CEPAL, 2018). Nowadays, the thermal efficiency of combined cycle plants is 1.4 times more than the thermal efficiency of traditional thermal plants (CFE, 2021).

Table 4. Structure of electricity production by technology in Mexico 1990-2015 (%)

Technology / Year	**1990**	**2000**	**2010**	**2015**	**Change 1990-2015**
Coal-fired power	6.8	9.7	6.8	11.5	4.7
Combined cycle	6.5	9.2	47.5	51.5	45.0
Internal combustion	0.1	0.2	0.5	0.7	0.6
Traditional thermal (including steam and double-cycle)	58.5	53.7	23.3	15.0	-43.5
Turbo gas	0.6	2.7	1.4	2.0	1.4
Nuclear power	2.6	4.3	2.4	4.4	1.9
Hydroelectric power	20.4	17.2	15.2	11.5	-8.9
Geothermal	4.5	3.1	2.7	2.4	-2.1
Wind power	0.0	0.0	0.1	0.9	0.9
Solar photovoltaic	0.0	0.0	0.0	0.0	0.0
Bioenergy	0.0	0.0	0.0	0.0	0.0
Efficient cogeneration	0.0	0.0	0.0	0.0	0.0
Total	**100.0**	**100.0**	**100.0**	**100.0**	**-**

Based on (INEGI, 2014; SIE, 2021; Sener, 2021).

On the other hand, thermal efficiency is related to innovation and technological improvements. On these issues, technical efficiency in Mexico has not evolved towards an optimum level of efficiency (Navarro Chávez, Delfin Ortega, & Díaz Pulido). However, to the best of our knowledge, there is not enough evidence of these issues for the case of Mexico, and more research is needed on them.

5. Conclusions and Policy Implications

We have presented a decomposition analysis to study the drivers of the GHG emissions from Mexican electricity production from 1990 to 2015. These emissions grew 76.2 $MtCO_2e$ during the study period and were driven by the following effects.

i. The activity effect was the most important driver to GHG emissions growth (98.38 $MtCO_2e$). The rising electricity demand could explain the relevance of the activity effect in the country, which in turn is related to several factors like economic growth, population growth, and rising electrification.

ii. The structure effect limited the growth of GHG emissions by 18.69 $MtCO_2e$. Although there was a transformation of the electricity matrix and a tendency to increase the use of natural gas (the cleanest fossil fuel), there was also a reduction of the share of other zero-emission energy sources, like hydro. This context raises concerns about the high share of natural gas on the electricity matrix. There are risks of carbon lock-in and stranded assets in the long run. The higher reliance on natural gas for electricity production crowded out clean energy technologies. The presence of natural gas has acquired structural characteristics.

iii. The effect of the carbon coefficient showed limited participation in the change in GHG emissions (5.5 $MtCO_2e$), which is related to the fact that the Mexican power sector continues to be based on fossil fuels.

iv. The energy intensity effect contributed to limiting the growth of GHG emissions (-8.98 $MtCO_2e$). The improvements in thermal efficiency (the inverse of energy intensity) were mainly related to the growth of cycle combined power plants that use natural gas, which poses the same risks described in point ii.

The high growth of combined cycle plants using natural gas for electricity production has been the main feature of the Mexican power sector in the last three decades. However, this increase in natural gas consumption for electricity production is not enough to move to a low-carbon electricity system. The idea of natural gas as a bridge to the energy transition is not fulfilling the objective of decarbonizing the Mexican electricity sector. There is a rising demand for electricity, which strongly induces GHG emissions. Additionally, the increase of natural gas has not been accompanied by greater participation of renewable energy in electricity production nor improvements in technical efficiency. In the light of these results, we conclude that a model based on fossil fuels for the production of electricity in Mexico has been consolidated.

Several policy questions arise from this analysis. The increased consumption of natural gas for electricity production jeopardizes energy security due to the high dependence on a single product and a single trading partner, the United States. Although Mexico has benefited from low U.S. natural gas prices, the country has also experienced adverse effects like the natural gas shortfalls during the critical alerts in 2011-2013 and 2021. At the beginning of 2021, intense frosts in Texas cut off the gas supply to Mexico, leaving around 5 million users in the states of Nuevo León, Coahuila, Tamaulipas, and Chihuahua without electricity service, triggering failures in the electrical system in the rest of the country. Moreover, there is no guarantee that natural gas prices will remain low. In fact, in the second half of 2021, an increase in natural gas prices has been observed.

In this context, climate and energy policies must explore a strategy "natural gas + energy efficiency + renewables" to achieve the commitments to mitigate climate change, move towards a low-carbon future, and improve energy security. The pledge should be an energy policy that increases the efficiency of electricity production while promoting clean energy instead of an energy policy that increases the dependency on natural gas.

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