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The Effect of Changing Marginal-Cost to Physical-Order Dispatch in the Power Sector

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The analysis of local environmental policies is essential when evaluating the consistency of national public policies vis-à-vis the compliance of global agreements to reduce climate change. This study explores one of these policies; the 2021 Mexican reform to change electric power dispatch from a marginal-cost-based to a command and control physical system prioritizing power generation from the state power company. The new law forces the dispatch of the state company power facilities before private power producers. We use the GENeSYS-MOD techno-economic model to determine the reform's effect on the power system's generation mix, cost structure, and anthropogenic emissions. For this, we optimize the model under three distinct scenarios; a business-as-usual scenario with no changes to the merit order, a model with the new physical order dispatch, and an additional case where in addition to the shift to the physical dispatch, we reduce the price of fuel oil below natural gas prices to simulate the current behavior of the power company. It is relevant to note that we optimize the energy system without any assumption regarding renewable targets or climate goals because of political uncertainty and the need of pinpoint the effect of the merit order change while avoiding possible variations in the state-space arising from other constraints. Our results show that by 2050, the new dispatch rule increases the market power of the state company to 99% of total generation and decreases the share of renewable technologies in the generation mix from 72% to 51%. Additionally, cumulative power sector emissions increase by 563 Megatons of CO_2, which with the current cost of carbon in the European Emissions Trading System translates to around 36 billion Euros.

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1. Introduction

The global coordination of national governments to fight climate change is a challenging endeavor. Not only the complexity of finding common ground between nations with different resources, needs, and uncertainties plays a critical role, but also the inherent instability of democratic systems in a world that seems to increase in polarization by the minute raise the hurdle of one of the biggest social and economic challenges to have faced humanity. The latest example of political ambivalence in climate goals is the US withdrawal from the Paris Agreement during the presidential term of Donald Trump.[1] And although the US withdrawal from the Paris Accord may be the most transparent and well-known example of the effects of local ambivalence in global climate commitments, there are several other examples of nations whose internal polarization threatens the attainment of international treaties for the reduction of GHG. For example, nationalistic concerns for the control of the Amazon rain forest placed president Jair Bolsonaro at odds with previous Brazilian environmental objectives coming back to the signature of the Rio declaration in 1992 (Rio Declaration, 1992; Sommerland, 2021), while its neighbor, Colombia, also provided permits for shale gas extraction through fracking technologies likely to increase GHG (Griffin, 2020).

A particular source of concern is that national policies at odds with climate agreements are often not as stark as the Trump administration's total withdrawal from the negotiation table. Usually, the modification of secondary laws can profoundly affect GHG targets while skipping the scrutiny of the scientific community and international regulators. For instance, Jair Bolsonaro dismantled Brazil's National Indian Foundation (Garcia, 2019), a government body in charge of protecting indigenous lands in the Amazon rain forest from cattle ranchers and soy plantations. The dismantling of FUNAI led to an increase in the encroachment of protected indigenous lands in the Amazonian rainforest by cattle ranching and crop agriculture (Ferrante and Fearnside, 2019). In this study, we analyze one of these secondary policies: the Mexican executive proposal to change electric power dispatch from a marginal-cost-based to a command and control physical system prioritizing power gener-

[1] Political ideologies and different social objectives made the country leave Obama's signed agreement in June 2017, back-lashing into a series of pro-fossil-fuel policies (Zhang et al., 2017; Urpelainen and Van de Graaf, 2018). However, on the first day of Joe Biden's administration, the US fully rejoined the pact and committed to reducing greenhouse gas emissions (GHG) by 50% from 2005 levels (Milman, 2021)

ation from the state power company, Comisión Federal de Electricidad (CFE). Specifically, the reform dictates that the independent system operator must dispatch CFE plants first with priority for hydroelectric dams. After it uses all the power produced by CFE, it can start using energy from Independent power producers (IPP) [2], and once it consumes the offer from CFE and IPP, it can dispatch energy from private generators. The shift from merit-order to physical-delivery dispatch relies on the idea that CFE indirectly subsidizes private generators, allowing their facilities to bid at lower costs via generation-back-up support to renewable energy, fixed-cost subsidies, and decreased transmission access prices. In addition, CFE claims that it finances private investors with around 12.4 billion dollars (Reyes, 2021) and that the change in the merit order would solve this unfair subsidy problem. However, opponents to the reform argue that it is only a pretext to favor CFE in a non-competitive way (e.g., the National Commission of Economic Competition), pointing out that the change would result in higher generation costs, increased electricity tariffs, and raises in government power subsidies to impoverished households (COFECE, 2021). Furthermore, we also explore current developments in the fuel mix of CFE thermoelectric facilities, where the company is now producing thermal power by burning fuel-oil reserves from the national oil company Petroleos Mexicanos (PEMEX), as PEMEX cannot accommodate this dirty and inefficient energy source in international markets.

Mexico constitutes an interesting case of analysis as it is among the fifteen largest economies in the world, the second-largest in Latin America (World Bank, 2021b), and the thirteenth-largest emitter of GHG (Hancevic et al., 2017). Moreover, Mexico's international and regional prominence can transfer its energy policies to other emerging economies. Policy transfer describes the reallocation of policy solutions or ideas from one place to another (Cairney, 2019). Specifically, it is the process through which "agents become aware of information relating to the policy domain of one system and subsequently transfer this into their political framework" (Dolowitz, 2010). Therefore, it is vital to analyze Mexican energy decisions since it has a reputation as a leader in developing climate and energy policies (von Lüpke and Well, 2020; Ramírez, 2014). For instance, Mexico is one of the first developing countries to have implemented a climate change law in 2012, followed by other countries in

[2] Private generators that have to sell their electricity entirety to the CFE or destined it for export.

the region like Guatemala and Honduras in 2013.

To study the effect of the new dispatch policy and the use of fuel oil in the structure of the power matrix, its generation mix, emissions, and system costs, we optimize three different scenarios with the Global Energy System Model (GENeSYS-MOD). The Business as Usual (BAU) scenario optimizes the energy sector without changing the merit order or the price of fuel oil in the generation mix.[3] The Physical Order Dispatch (POD) model changes the dispatch from merit-order to physical-delivery discharge. And the Fuel Oil Policy (FOP) adds to the physical-delivery dispatch model a reduction in the price of fuel oil to slightly below natural gas prices to simulate the current national strategy of using fuel oil for the generation of thermal electricity (Solís, 2019; Cruz Serrano, 2020).

Previous studies have already used GENeSYS-MOD to examine energy systems under different policy scenarios. For instance, Löffler et al. (2018), Oei et al. (2019), and Löffler et al. (2019) use GENeSYS-MOD to analyze the low carbon transition of the European energy system, Bartholdsen et al. (2019) use it to look for the best development pathways for low-carbon energy systems in Germany, while Lawrenz et al. (2018) do the same for India. For Mexico, Sarmiento et al. (2019) study the best cost-effective pathway for the Mexican green transition, finding that current emission and renewable targets are insufficient and sub-optimal and should be adjusted. Moreover, GENeSYS-MOD has also been used in Multi-Mod frameworks studying the role of storage technologies under power systems with large shares of renewable technologies in North America (Giarola et al., 2021), as well as the effect of fluctuations on the price of natural gas on the energy systems of the Mexico and the US (Sarmiento et al., 2021).

Our results show a decrease in renewable capacity for the POD and FOP scenarios, mainly through a displacement of wind facilities by coal and fuel oil. By the end of the optimization period, the POD and FOP scenarios bring the Mexican power system back to a state monopoly where CFE owns 99% of total generation capacity. This result makes economic sense since by changing the dispatch rules, there are no investment incentives for private generators. The share and value of renewable technologies in the generation mix varies with each model; however, by the end of the optimization, the percentage of renewable

[3] We do not include any constraint in terms of renewable shares or GHG targets.

energy in the BAU, POD, and FOP scenarios is 71.7%, 51.3%, and 51.1%, respectively.

Both the emissions of the power and energy sectors grow in the POD and FOP cases compared to the BAU. Specifically, results show that power sector emissions grow by 115.8% between the BAU and the POD scenarios and by 125.1% between BAU and FOP. In terms of total system costs, by 2050, the BAU, POD, and FOP scenarios report total discounted system costs of 9.7, 9.9, and 10.1 billion euros, respectively. However, this value only considers capital, operation, and fuel costs, disregarding the negative externalities associated with higher anthropogenic emissions of GHG. The cost of these externalities can amount to 37 billion Euros under the current cost of carbon in the European Emissions Trading System. In short, the POD and FOP scenarios imply a lower share of renewables, higher emissions, similar system costs, and higher local and global externalities in the form of air pollution and GHG.

Two days after the legislature approved the reform, the judicial branch provisionally suspended it, arguing that its characteristics went against the Constitution's antitrust guarantees. However, President Andrés Manuel López Obrador aims to continue with the reform by amending the Constitution (Graham, 2021). Therefore, in contrast to most research that is reactive to policy decisions, this paper acquires a proactive attitude that seeks to identify the effects of a currently contested policy change that could happen in the short term under the current political circumstances. Overall, results show that changing the marginal cost to a physical-order dispatch in the power sector implies an exorbitant increase in the market power of CFE, a lower share of renewable energy sources, increasing anthropogenic emissions, and growing cost associated with the adverse effects of both local and global externalities stemming from the burning of fossil fuels for power generation.

2. Background

More than thirty years ago, electricity systems were developed based on vertically and horizontally integrated industry structures under state ownership. However, in parallel to technology developments in electricity generation, regulatory reforms took place globally since the early 1990s. Such reforms aimed to unbundle the industry in search of increasing competition and efficiency. The 2013 energy reform came relatively late to the Mexican electric sector. According to the literature and international experiences on market architecture design, it was a partial reform following an independent-system-operator (ISO) market structure like other power systems in the American continent, instead of a transmission-system-operator (TSO) arrangement as in various European countries. The main features of this reform include the liberalization of electricity generation, horizontal disintegration of CFE generation plants, and the creation of a new ISO "Centro Nacional de Control de Energía (CENACE)" dispatching generation according to economic merit order. Direct transactions between large consumers and distinct types of generators were made possible for the first time in decades. However, CFE was not subject to any privatization process; it kept the property of transmission, distribution networks, and the public service to small consumers. The reform's objective was to concentrate new investments of CFE in transmission and leave new generation projects to private companies (Presidencia de la República, 2013). Finally, the reform also contemplated mechanisms to incentivize renewable energy sources like auctions for clean energy, pollution rights (CELs), and distributed generation incentive schemes, setting clean energy goals equivalent to 35% of power generation by 2024, and 50% by 2050.[4]

In 2018, Andres Manuel Lopez Obrador (AMLO) won the Mexican elections by a margin of more than twenty percentage points. His new government opposed the reforms and changes of previous administrations, considering them as "Neoliberal" policies in the interest of power groups embedded in corruption scandals and back-door deals. This antagonistic attitude, qualitatively similar but ideologically different to Donald Trump's and Jair Bolsonaro's governments, led to a series of reforms threatening the country's status quo in several sectors. Among the main actions were the cancellation of the New International Airport of Mexico City (NAICM), the withdrawal of the education reform, the cessation of long-term renewable energy auctions, and the implementation of retroactive green energy certificates.

In February 2021, The executive branch put forward the current reform to the electricity bill. In the proposal, the government argues that the 2013 reform favors private

[4]With this objective in mind, three competitive auctions contracted mainly renewable energy from independent private generators. The most recent carried out in 2017 achieved world-record low prices for wind and solar at below 20 USD/MWh (Sánchez Molina, 2017).

entrants and forces CFE to grant subsidies to the private sector, leaving the state-owned company with diminished productive capacity and subject to asymmetric regulation. As previously mentioned, the reform's core change includes redefining the generation dispatch sequence following a logic of "physical delivery." The reform also stipulates that permits for new generation plants will be subject to the national transmission system's planning criteria published by the Energy Ministry every year. Furthermore, the energy regulatory commission (CRE) can now grant green energy certificates to the residual capacity of CFE's hydro plants plummeting the market price for these instruments. CRE can also cancel self-supply permits when it suspects that generators obtained such permits through fraud or corruption, alongside a full review of power purchase agreements between CFE and IPP. Finally, CFE's distribution branch can stop buying power from renewable facilities constructed during the renewable auctions of 2014, 2015, and 2017.

Under current market rules, the centralized ISO maximizes social welfare (the sum of consumer and producer surpluses) by dispatching power from different generators subject to transmission capacity, flow-feasibility, energy balance, and generation-limit constraints over a centralized spot market (see Schweppe 1988, and Rosellón 2003). Locational marginal prices (LMPs) arise from the first-order conditions of the power-flow model. LMPs reflect supply and demand conditions at each node in a multi-nodal coordinated network system from the shadow value of congestion in the transmission network and the technological characteristics and limits in the generation park. Under the above framework, an ISO that relies on merit-order dispatch rules chooses generators according to their marginal costs, starting with the lowest cost plant and finishing with the highest cost generator that finally meets demand. Then, it determines the equilibrium price according to the last dispatched bid. The difference between the equilibrium price and the price bid by cheaper generators will ultimately determine their benefit mark-up.

However, if the current reform substitutes the merit order rule with an exogenous physical-order dispatch, the power-flow model would be subject to additional constraints and limitations that would change the structure of LMPs and the overall evolution of the power system. Of course, the outcomes on energy prices would depend on the regional characteristics of the electric system. For instance, in those regions with high transmission congestion and diverse property composition in generation technologies, one could foresee increases in LMPs since the ISO would first dispatch old and costly power plants. However, we leave the effects of the reform on LMPs to future research and focus on its consequences on the power system's capacity mix, generation profile, cost structure, and environmental losses.

Climate change requires global coordinated solutions because the mitigation of GHG implies short-term local costs with long-term global benefits (Bréchet et al., 2016); a typical example of the "tragedy of the commons" (Harrison and Sundstrom, 2010) where utility-maximizing countries exhaust environmental goods to the detriment of the general community while increasing local benefits through environmental exploitation (Ostrom, 2008; Hardin, 2009). Notably, the relevance of local environmental policies, laws, and regulations is quite significant when these policies deviate large emitters from ratified climate commitments.

3. Model and Data

3.1. Model description

GENeSYS-MOD is an extension of the Open-Source Energy Modelling System (OSeMOSYS) (Howells et al., 2011), with several new functionalities as modal split for transportation, enhanced focus on environmental budgets, improved trade systems, storage technologies, time-slices, and performance optimization (Löffler et al., 2017; Burandt et al., 2018). The model has a high level of technical detail able to endogenously optimize the power, transportation, and heating sectors while accounting for sector coupling.

Traditionally, numeric models of energy systems focus on the power sector (e.g. Bogdanov et al., 2019; Jacobson et al., 2015). However, the development of multi-sectoral models accounting for the interdependencies between transportation, heating, and electricity have increased. These last models are relevant because power models can omit relevant interdependencies between energy sectors within the optimization horizon.

GENeSYS-MOD minimizes the total costs of the energy system through a series of linear equations as inputs and constraints while securing regional energy supply, environmental restrictions, and policy commands. Equation 1 shows the objective cost function of the model.

$$min[\sum_{y,r}\beta^t(\sum_t TC_{y,r,t} + \sum_s SC_{y,r,s} + tC_{y,r} + \sum_{f,rr}\tau C_{y,t,f,rr})] \tag{1}$$

in it, the model minimizes the discounted sum of the costs of the energy system (TC_{yrt}), storage technologies (SC_{yrs}), trade ($tC_{y,r}$) and trade capacity (τC_{ytfrr}) across all periods y, regions r, generation technologies t, storage options s, energy carriers f, and region pairs rr. Specifically, the cost of each technology (TC_{yrt}) is the discounted sum of capital, operating, fuel, and emission costs minus the discounted value of outdated power facilities at the end of their life span. The additional constraints of the model take the form of greenhouse gas targets, energy balances, or renewable integration.

For intuition, figure 1 portrays the global functioning of GENeSYS-MOD. From left to right, fossil fuel energy carriers provide raw energy to traditional power technologies, domestic and industrial heat, and transportation. Renewable technologies can also satisfy these three aggregate demand sectors, while nuclear power is only an alternative for power supply. Next, sector coupling allows GENeSYS-MOD to use electricity to satisfy the transportation and heat demand through electric vehicles, hydrogen, and heat pumps. Finally, additional energy carriers as waste and biomass can also generate electricity, biofuels, or heat. The model fulfills the exogenous demand values for electricity, heat, and transportation across regions and optimization periods under the previously mentioned constraints by constructing new power facilities, coupling sectors, building transmission infrastructure, and deploying storage technologies linking the different demand sectors through electrification.[5]

The model includes sixteen time-slices for four different seasons and intraday cuts. These slices account for peak demand periods in the summer and late afternoons. It is important to notice that these sixteen-time slices can miss interesting mechanisms occurring at smaller time intervals. However, previous studies have found that moving these

[5] Howells et al. (2011), Löffler et al. (2017), and Burandt et al. (2018) provide more information on the technical aspects of the model.

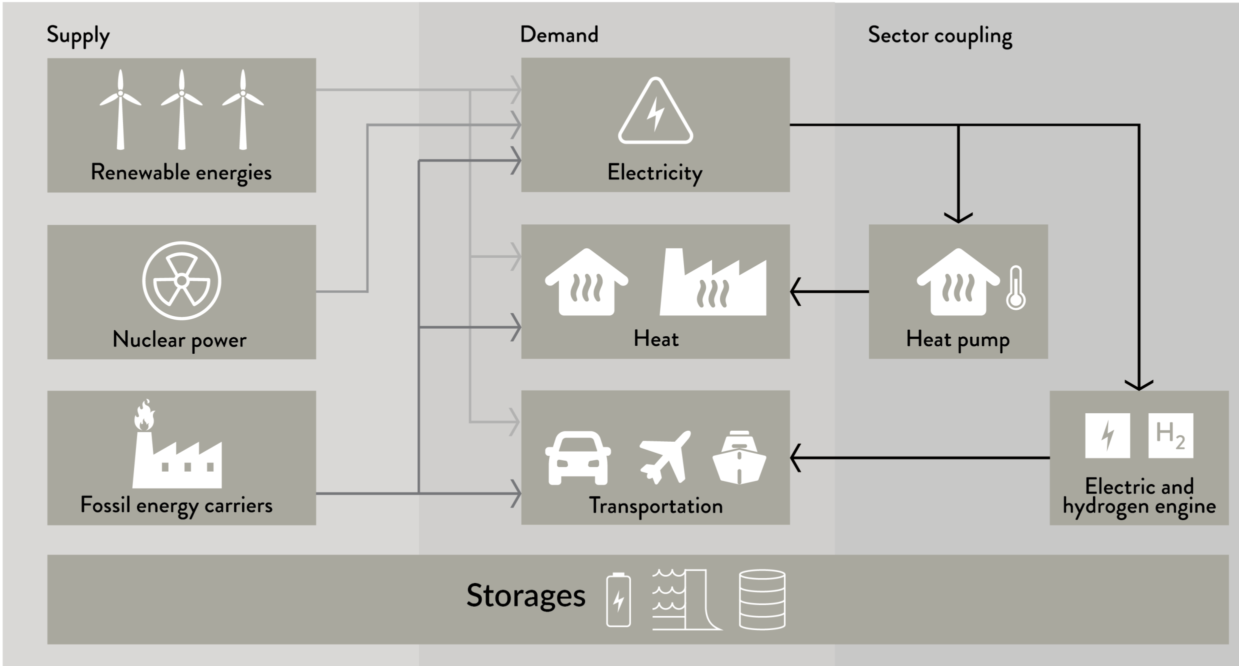


Figure 1: General structure of GENeSYS-MOD

Notes: This figure shows a simplified version of the general structure behind GENeSYS-MOD. However, it misses several sub-technologies or modal splits within each sector. For instance, the supply of renewable energy encompasses wind, solar, hydroelectric, and geothermal facilities, while the model also divides the transportation sector into passengers and freight as well as road, air, ship, and rail technologies.

models to a fully hourly dispatch does not change overall results by more than 5% Welsch et al. (2012). Furthermore, we believe that this point of discussion is less relevant when examining deviations from policy scenarios within the same model as the different scenarios over GENeSYS-MOD impose computational locality. Concerning data availability, techno-economic models of energy systems require exogenous information on demand, costs, and technological pathways. This reliance on external data sources makes transparency a critical part of any study using techno-economic modeling. We present demand, prices, and efficiency data per region and period in the appendix.

The current version of GENeSYS-MOD runs in GAMS and requires significant computational power when the number of regions and constraints increases. To enhance the replication of results and reduce the computational burden of the optimization, we transfer the GAMS version of GENeSYS-MOD to the open-source language "Julia" through the graph-based framework for energy system modeling (AnyMOD). AnyMOD is a framework for energy modeling that uses a novel approach: it employs graph theory to facilitate modeling high renewable shares and sector coupling (Göke, 2020). Additionally, AnyMOD reduces the computational burden of the optimization because its high temporal and spatial flexibility vary depending on the needs of the system under analysis, increasing flexibility without losing the detail needed to analyze complex systems (Hainsch et al., 2020). Another advantage is that CSV files fully define the model, increasing the reproducibility of optimization scenarios by third parties unfamiliar with techno-economic energy models.

AnyMOD has being used in the past to examine different policy scenarios of energy systems. For instance, Hainsch et al. (2020) use it to study whether the European Green Deal's sectorial measures are sufficient to achieve decarbonization, while Zozmann et al. (2021) explore scenarios for 100% renewable power supply in North America while considering the share of different renewable sources available in Mexico, the US, and Canada.

3.2. Scenarios

We optimize the Mexican energy system under three distinct scenarios BAU, POD, and FOP. The Business as Usual (BAU) scenario imposes no constraints in the energy system. The Physical Order Dispatch (POD) scenario changes the merit order from a marginal-costs to a physical delivery dispatch, forcing the model to optimize under the following dispatch order: 1) Hydroelectric plants owned by CFE, 2) all other CFE plants (geothermal, nuclear, combined-cycle natural gas, thermoelectric plants, and renewable facilities), 3) plants owned by IPP, 4) private renewable facilities, and, 5) all other private thermoelectric plants. In the Fuel Oil Policy (FOP) scenario, alongside the change to the physical order dispatch, we artificially reduce the price of fuel oil to competitive prices to simulate its use in CFE thermoelectric plants. Table 1 summarizes the main characteristics of our three core scenarios.

Table 1: Characteristics of optimization Scenarios

Scenario	Dispatch Type	Fuel-oil price	Renewable targets	Climate Goals
BAU	Variable cost	Global prices	None	None
POD	Physical dispatch	Global prices	None	None
FOP	Physical dispatch	90% of Natural gas prices	None	None

Notes: This table shows the characteristics of each optimization scenario; Business as Usual (BAU), Physical Order Dispatch (POD), Fuel Oil Policy (FOP)

3.3. Data

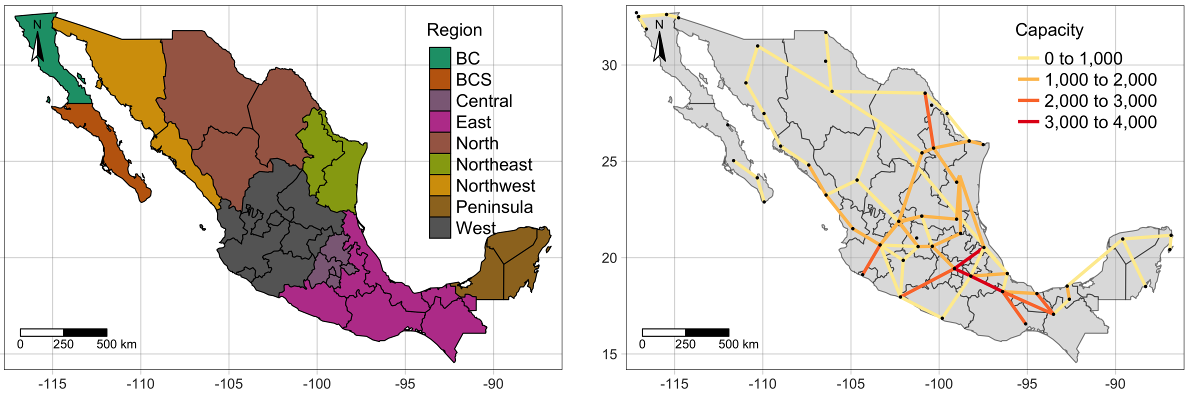
Techno-economic models require large data sets on the behavior of the electric, transportation, industrial, and residential sectors to optimize the system under different policy scenarios. We obtain regional power capacity and generation values from the Energy Information System website of the Mexican Energy Ministry (SENER) (Secretaría de Energía, 2020b), the National Electricity System Development Program (PRODESEN) (Secretaría de Energía, 2020a) and the North America Cooperation on Energy Information Platform (NACEI, 2020). Renewable potential comes from the National Atlas for the Assessment of Areas with High Renewable Potential of SENER (Secretaría de Energía, 2016), and requests to CENACE provide data on state load profiles, nodal structure, and transmission capacity.

Unfortunately, for industrial heating, there is no available data at the regional level. Consequently, we impute its values by assuming that national industrial energy demand is the sum of power and heat; then, we subtract electricity from energy demand to obtain industrial heat national demand values. Next, using national statistics on energy and power demand by industry, e.g., cement, we determine the share of national heating demand in each economic sector. Then, we use data from the 2015 economic census to calculate each industry's percentage by region. For example, if the national heating demand of the cement sector is seven Peta-Joules and 50% of cement's industrial output comes from a specific area, we assign 50% of this high-temperature heating demand to this region. Finally, transportation statistics on the use, type, and fuel of different transportation modes per region come from the statistical portal of the Mexican Transportation Ministry (Secretaría de Comunicaciones y Transportes, 2020).

We divide the Mexican energy system into nine regions; Peninsula, East, Central, West, Northwest, North, Northeast, Baja California Sur (BCS), and Baja California (BC). Figure 2(a) shows each region over the map of Mexico, and figure 2(b) contains the main transmission corridors of the power system. We base our regions on CENACE reporting subdivisions. However, as CENACE defines these areas at the county level, their exact demarcations vary slightly from ours because we do it at the state level.

The optimization model considers eight power technologies; nuclear, onshore wind,

Figure 2: Spatial Characteristics of the National Power System

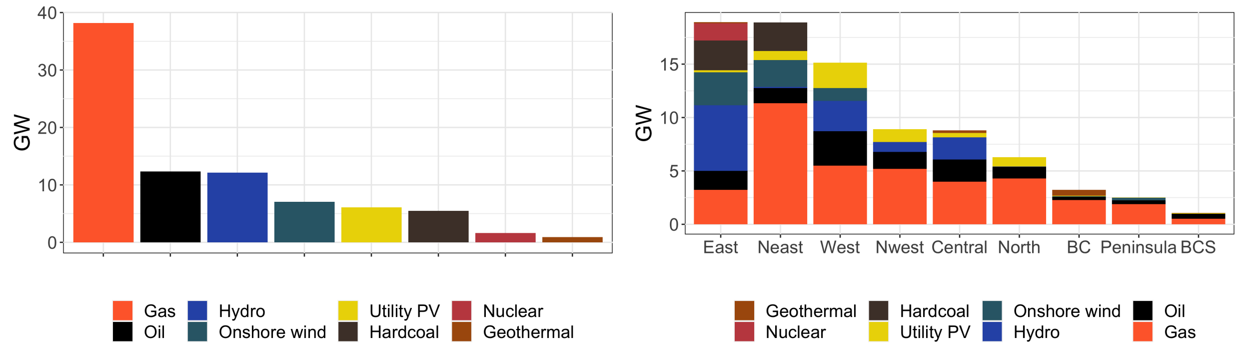


(a) Regions of the National Power System

(b) Transmission Corridors in the National Power System

thermometric hard coal, photovoltaic, geothermal, thermometric fuel-oil, hydroelectric, and thermometric natural gas. Three transportation modes: air, road, and rail. Two transportation classes, passenger and freight, and four transportation technologies: internal combustion engines, plug-in hybrid vehicles, electric vehicles, plus conventional air and rail travel. Moreover, it captures the heating sector through high temperature (industrial) and low temperature (commercial and residential) heat.

Figure 4a portrays the total system capacity by technology in 2020. In total, the national power system has 83 GW of installed capacity, the technology with the most share is natural gas (45.53%), followed by oil (14.75%), hydroelectricity (14.43%), onshore wind (8.44%), and solar (7.23%). Figure 4b plots the installed capacity by region, which is highly heterogeneous due to the diversity of resources, the ease of access to fuels, and demand differences between regions. For instance, the eastern region has a substantial share of hydroelectric and wind facilities, the North East is dominated by natural gas thermoelectric plants, the west by a combination of natural gas, hydro, hard coal, and solar technologies, while the rest of the regions rely on natural gas for the generation of electric power.



(a) Capacity by technology

(b) Power mix by region

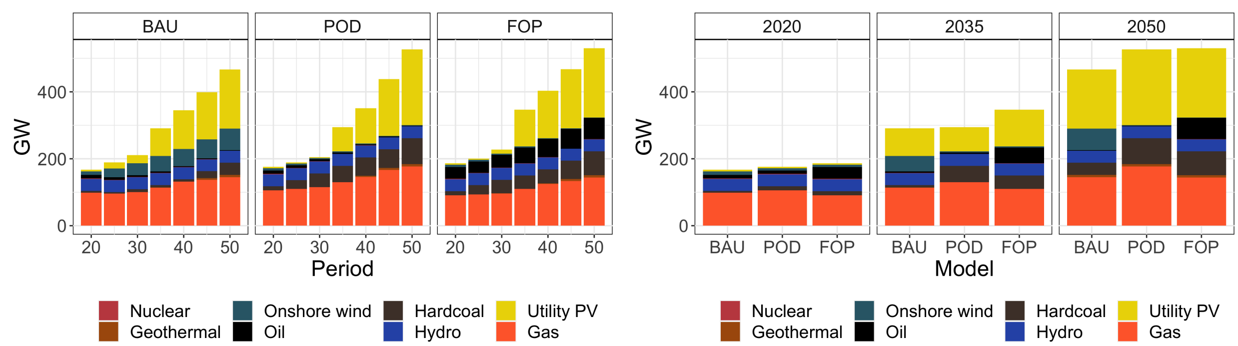
Figure 4: Capacity of the Mexican Power System 2020

Notes: This figure shows the installed capacity of the Mexican power system in total and across regions.

4. Results

4.1. Capacity

Figure 5a shows the power system's capacity between 2020 and 2050, and Figure 5b compares the models power matrix in 2020, 2035, and 2050.



(a) Across Scenarios

(b) Across Time Periods

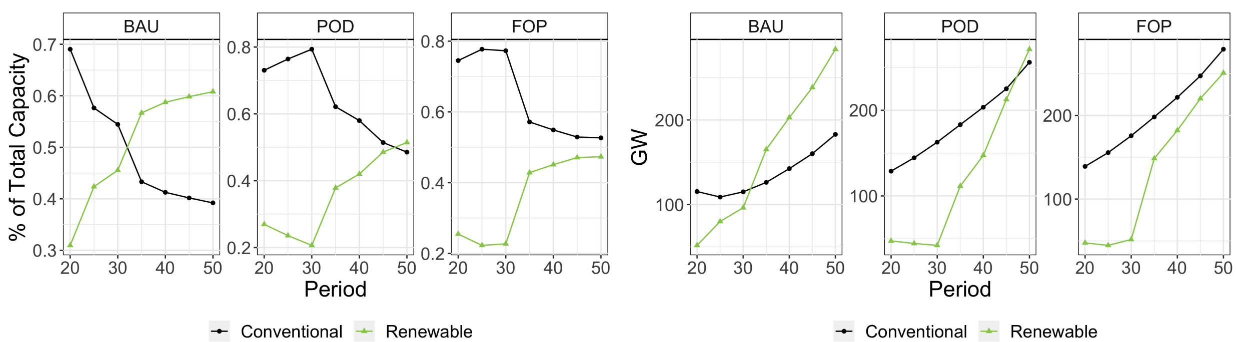
Figure 5: Capacity of the Mexican Power System under alternative scenarios

Notes: This figure shows the installed capacity of the power system. On the left-hand side, it portrays capacity as a function of time across three alternative policy scenarios; Business as Usual (BAU), Physical Order Dispatch (POD), and Fuel Oil Policy (FOP). On the right side, it depicts the same information only for 2020, 2035, and 2050. The optimization results come from the techno-economic model GENeSYS-MOD.

The first interesting outcome is the difference in the total installed capacity of the power system at the end of the optimization period. In 2050, total installed capacity amounts to 467, 527, and 530 GW in the BAU, POD, and FOP scenarios. For the BAU scenario, by 2050, solar power and natural gas dominate the installed capacity with respective shares of

37.8% and 31%, with the rest of the capacity divided between onshore wind (13.7%), hydroelectricity (7.7%), coal (7.7%), and other technologies as fuel oil, nuclear, and geothermal. Although the dominant technologies in the POD scenario remain natural gas (33%) and solar (43%), there is a significant increase in the installed capacity of hard coal. Between BAU and POD , the capacity of hard coal doubles from 7.6% to 14.7%. The increase in hard coal installed capacity alongside a higher share of PV facilities displaces onshore wind from the power mix. Next, in the FOP scenario, natural gas is displaced from the power matrix by fuel oil during the first years of the simulation. By 2050, the capacity of the power mix is solar (38.9%), natural gas (27.1%), hard coal (13.5%), fuel oil (12.0%), and hydro (6.7%).

Figure 6a portrays the share of installed capacity by renewable and conventional technologies. Renewable technologies are hydro, solar, wind, and geothermal facilities, while traditional technologies are thermoelectric gas, oil, fuel-oil, hard coal, and nuclear power plants. Panel 6b portrays the same information but in GW of capacity instead of percentage shares.



(a) Share of capacity

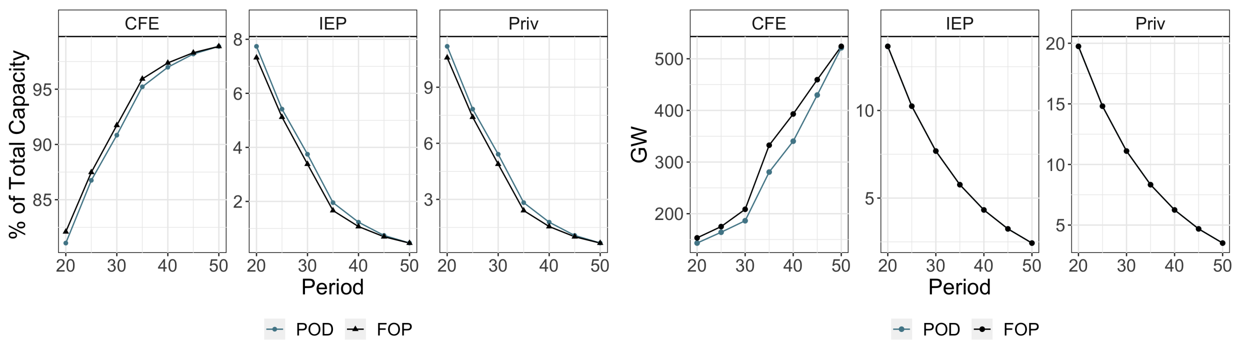
(b) Total capacity

Figure 6: Share and value of renewable and conventional capacities

Notes: This figure shows the share and capacity value for renewable and conventional technologies across three alternative policy scenarios; Business as Usual (BAU), Physical Order Dispatch (POD), and Fuel Oil Policy (FOP). Renewable technologies are photovoltaic, hydro, wind, and geothermal while conventional technologies are thermoelectric gas, oil, fuel-oil, hardcoal, and nuclear. The optimization results come from the techno-economic model GENeSYS-MOD.

The share of renewables is 60.8%, 51.4%, and 47.4% in the BAU, POD, and FOP scenarios. As expected, the largest share accrues to the BAU model followed by POD and FOP. In terms of total installed capacity, by the end of the optimization period the installed renewable and conventional capacity of the BAU scenario is 283 vs. 183 GW. The same values for the POD and FOP scenarios are 271 vs. 256, and 250 vs. 280 GW, respectively.

Next, we explore the effect of the POD and FOP policy scenarios on the share of installed capacity between CFE, IPP, and private generators. In 2020, the share of installed capacity between CFE, IPP, and private energy producers was 45%, 32%, and 12%. However, by the end of the optimization period in 2050, CFE has a functional monopoly over electricity supply by holding close to 99% of all installed capacity. The remaining 1% is only the vestige of facilities built at the outset of the 2010s. This result follows pure economic logic since changing the market rules from a marginal cost to physical dispatch favoring CFE pushes private investors away because there is no incentive to invest in new capacities if your product would always come last in the market.[6]



(a) Share of capacity

(b) Total capacity

Figure 7: Capacity distribution of the Mexican Power System under alternative scenarios

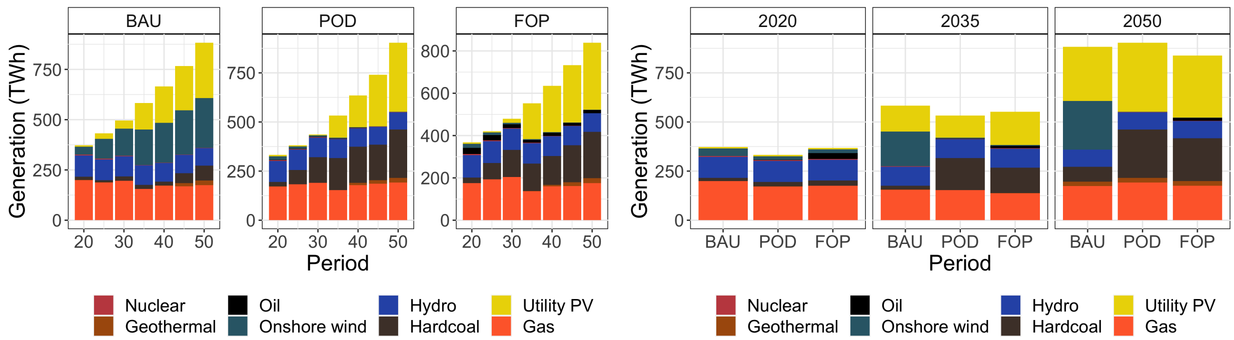
Notes: This figure shows the distribution of power system capacity across market participants. On the left-hand side, it portrays capacity as a function of time across two alternative policy scenarios; Physical Order Dispatch (POD), and Fuel Oil Policy (FOP). On the right side, it depicts the same information while showing the total capacity by participants in GW. The optimization results come from the techno-economic model GENeSYS-MOD.

4.2. Generation

Figure 8a shows the power system's total generation between 2020 and 2050 for all three models, and figure 8b zooms into the optimization results for 2020, 2035, and 2050.

For the BAU scenario, by 2050, solar power, onshore wind, and natural gas dominate the power generation with respective shares of 31.2%, 28.0%, and 19.7%. The optimization divides the rest of power production between hydroelectricity (9.9%), coal (8.5%), and other technologies as nuclear and geothermal. Looking at the effect of changing the merit order, solar power generation increases by 7.6%, natural gas by 1.6%, and wind decrease by 27.8%;

[6]Figure 19 of the appendix shows the same evolution for power generation



(a) Across Scenarios

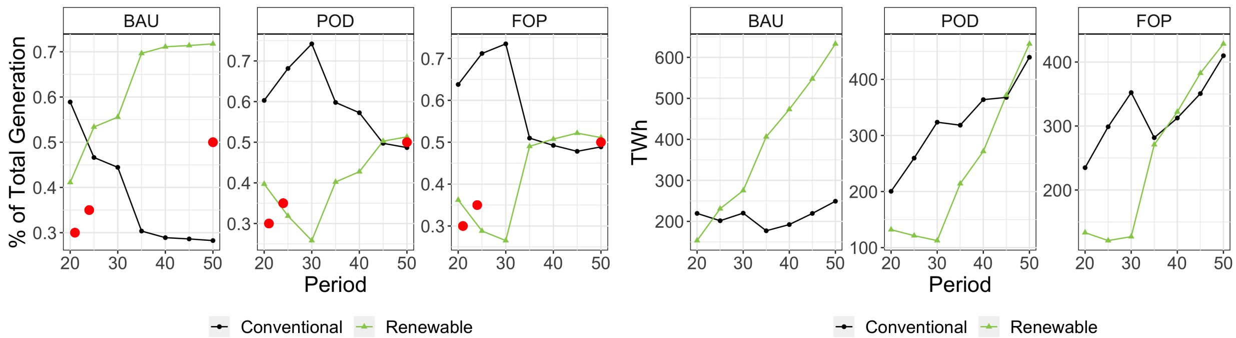
(b) Across Time Periods

Figure 8: Total power generation under alternative scenarios

Notes: This figure shows total power generation in the Mexican Power System. On the left-hand side, it portrays generation as a function of time across three alternative policy scenarios; Business as Usual (BAU), Physical Order Dispatch (POD), and Fuel Oil Policy (FOP). On the right side, it depicts the same information while zooming into 2020, 2035, and 2050. The optimization results come from the techno-economic model GENeSYS-MOD.

power production with hard coal replaces the lost wind generation, increasing its share from 8.5% to 27.2%. In the FOP scenario, electricity generation from fuel-oil shoots up in the first years of the optimization, partially displacing natural gas's from the electricity mix. However, by 2050, the power generation mix is very similar between the POD and FOP scenarios.

Figures 9a/9b portray the generation share and value of renewable and conventional technologies across all three scenarios. By the end of the optimization period, the share of renewable energy in the BAU, POD, and FOP scenarios is respectively 71.7%, 51.3%, and 51.1%. These shares are equivalent to 632.9, 463.4, and 428.4 TWh of power generation. The red dots in the picture show the government goals concerning power generation with renewable sources; 30% by 2020, 35% by 2024, and 50% by 2050. Every time the red dot is below the green line, the government complies with its mid-term renewable generation goal for that year. The optimization shows that all three scenarios fall in line with the 2021 goal, only the BAU model complies with the 2024 objective, and even though there are substantial differences between the BAU and the other two scenarios in terms of renewable penetration, the POD and FOP scenarios barely reach the 2050 renewable target of 50%. This result signals the large potential of renewable resources in Mexico that even with policy mandates actively acting against the green transition, it reaches its clean energy targets.



(a) Share of generation

(b) Total Generation

Figure 9: Share and value of renewable and conventional power generation

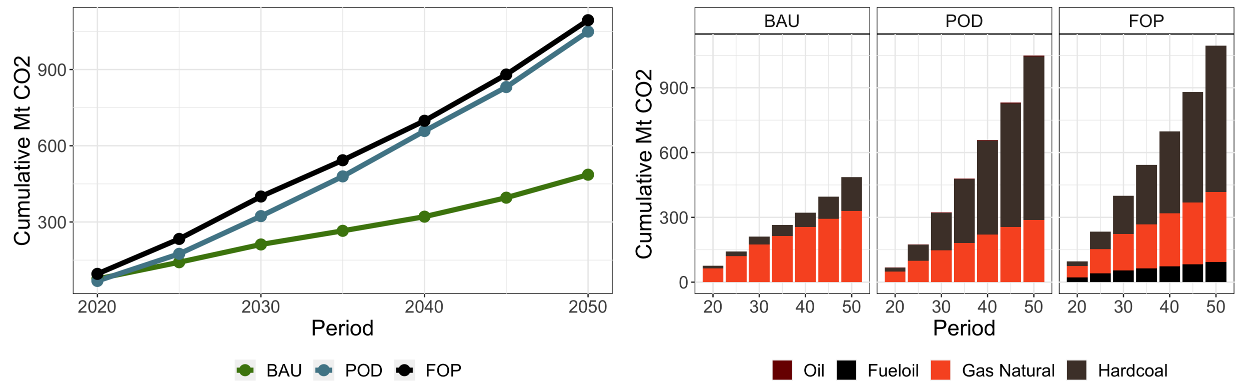
Notes: This figure shows the generation share and value for renewable and conventional technologies across three alternative policy scenarios; Business as Usual (BAU), Physical Order Dispatch (POD), and Fuel Oil Policy (FOP). Renewable technologies are photovoltaic, hydro, wind, and geothermal while conventional technologies are thermoelectric gas, oil, fuel.oil, hardcoal, and nuclear .The optimization results come from the techno-economic model GENeSYS-MOD.

4.3. Emissions

4.3.1. Power Sector

Figure 10a portrays the cumulative emissions of the Mexican power system under the three scenarios. BAU has significantly lower emissions than the other two cases. By 2050, the BAU cumulative emissions account to 486 Megatons of equivalent carbon dioxide (MT/CO_2-eq), the POD scenario almost doubles it with 1,049 MT/CO_2-eq, and the FOP case remains very similar to POD with 1,094 MT/CO_2-eq. These results show the significant effect of changing the marginal-cost merit order on cumulative emissions of carbon dioxide equivalent (CO_2-eq), overall, the physical dispatch more than doubles anthropogenic emissions of CO_2-eq in the power sector. Image 10b shows the emissions divided by energy carrier. In the BAU case, 68% of total emissions come from natural gas and 32% from hard coal. Once we impose the artificial merit order, the share of hard coal increases to 72%, natural gas decreases to 27%, and oil emits the remaining 1%. Finally, once we introduce PEMEX fuel-oil as an alternative energy source for thermoelectric power facilities, hard coal, natural gas, and fuel-oil are responsible for 62%, 29%, and 9% of total cumulative emissions.

Image 11a portrays the same information as 10b only with models instead of periods in the horizontal axis. This perspective allows us to see the great difference between models regarding emissions' total value and composition. By 2030, the difference between the BAU



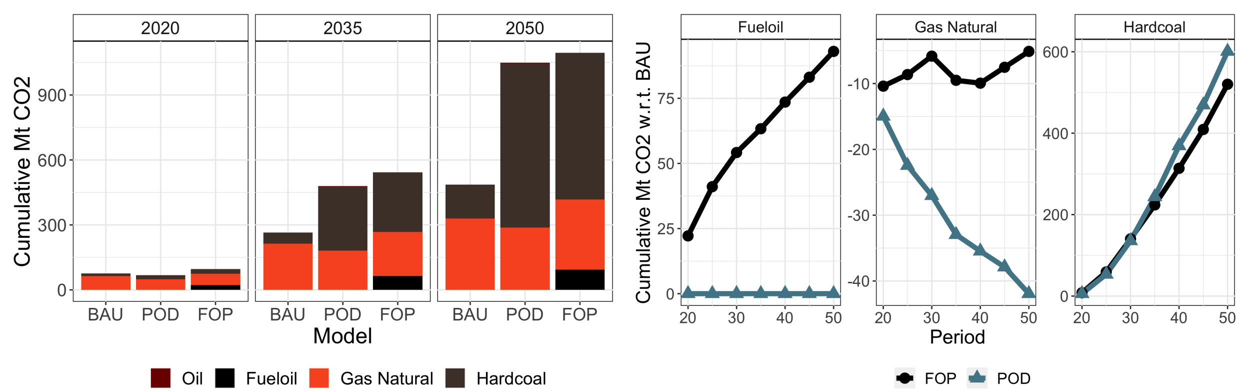
(a) Emissions across models

(b) Emissions across models and carriers

Figure 10: Emissions in the power sector

Notes: This figure shows the optimization results regarding power system emissions. On the left-hand side, it portrays Megatons of equivalent carbon dioxide (MT/CO_2-eq) as a function of time across the three policy scenarios; Business as Usual (BAU), Physical Order Dispatch (POD), and Fuel Oil Policy (FOP). On the right, it depicts the same information divided by energy carrier. The optimization results come from the techno-economic model GENeSYS-MOD.

and the other two scenarios is clear, with POD and FOP strongly relying on hard coal for the production of electricity. By 2050, POD and FOP more than double the cumulative CO_2-eq emissions of BAU by mostly relying in hard coal plus a slight share of fuel-oi in the FOP case.



(a) Emissions across models

(b) Emissions across models and carriers

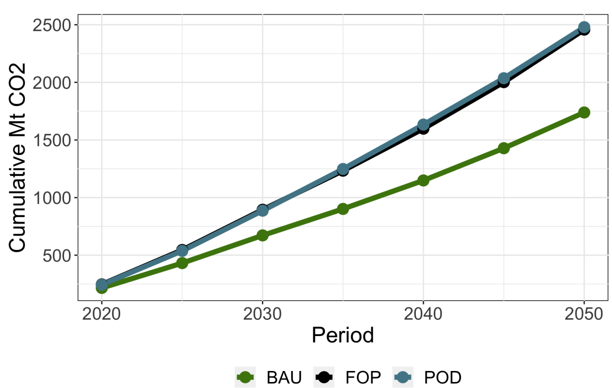
Figure 11: Power sector emissions descriptives II

Notes: This figure shows the optimization results regarding power system emissions. On the left-hand side, it portrays Megatons of equivalent carbon dioxide (MT/CO_2-eq) as a function of time across the three policy scenarios; Business as Usual (BAU), Physical Order Dispatch (POD), and Fuel Oil Policy (FOP). On the right, it depicts the same information divided by energy carrier. The optimization results come from the techno-economic model GENeSYS-MOD and the graph-based framework AnyMOD.

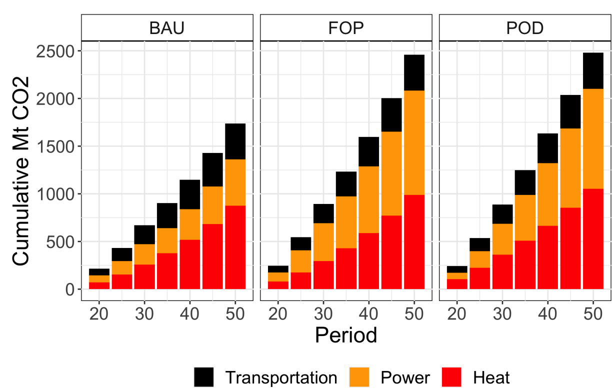
Image 11b shows the difference in cumulative CO_2-eq emissions between the BAU and the other two scenarios for the main energy carriers. As expected, only the FOP scenario increases fuel-oil emission by 94 MT/CO_2-eq in 2050. Concerning natural gas, the FOP and POD cases have lower cumulative emissions than the BAU scenario, suggesting that the change in the merit order and the entrance of fuel-oil and coal to the generation mix decreases the use of natural gas in the power sector. Finally, hard coal experiences the bulk of the increase in emissions. In 2050, cumulative coal emissions for the FOP and POD cases are 520 and 600 MT/CO_2-eq higher than for the BAU scenario. These values are similar to the total emissions of Australia in 2018 (558 MT/CO_2-eq) according to OECD (2021).[7]

4.3.2. Energy Sector

The coupling between the power, transportation, and heating sectors means that changes in the dispatch order would affect both the power sector and the entire energy system. Figure 12a looks at the impact of each policy on total system CO_2-eq emissions. Total cumulative emissions between 2020 and 2050 in the FOP and POD scenarios account for 2,458 and 2,479 MT/CO_2-eq, respectively. These values are in strong dissonance with the 1,739 MT/CO_2-eq of the BAU model. The difference between the policy change scenarios and the BAU model add to around 740 MT/CO_2-eq, which is equivalent to all Canadian emissions in 2018 (729 MT/CO_2-eq) according to OECD (2021).



(a) Emissions across models



(b) Emissions across models and sectors

Figure 12: Emissions for the power, industrial heat, and transportation sectors

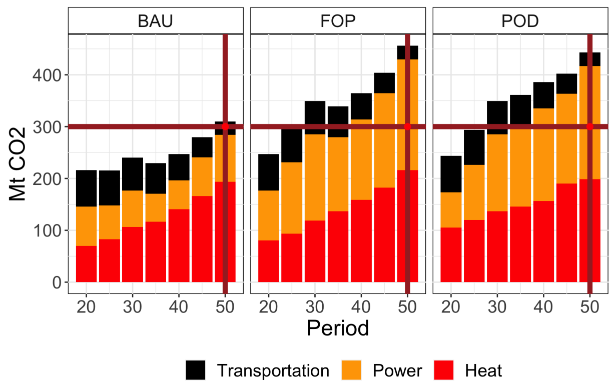
Notes: This figure shows the optimization results regarding power, heat, and transport system emissions. On the left-hand side, it portrays Megatons of equivalent carbon dioxide (MT/CO_2-eq) as a function of time across the three policy scenarios; Business as Usual (BAU), Physical Order Dispatch (POD), and Fuel Oil Policy (FOP). On the right, it depicts the same information divided by energy sector. The optimization results come from the techno-economic model GENeSYS-MOD.

[7] This value does not include land use, land-use change, or forestry

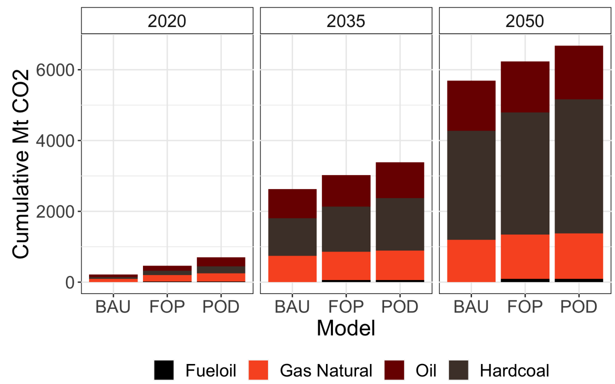
Figure 12b portrays emissions divided by energy sector. By 2050, the transportation sector accounts for 21.6%, 15.3%, and 15.1% of total emissions in the BAU, FOP, and POD scenarios. Nonetheless, the cumulative value of transportation CO_2-eq is remarkably similar between scenarios at around 376 MT/CO_2-eq. Across scenarios, the main difference accrues to the power sector, with cumulative emissions in 2050 of 486 (28%), 1,094 (44.4%), and 1,049 (42.3%) MT/CO_2-eq for the BAU, FOP, and POD scenarios. Finally, the industrial sector has slightly lower emissions for the BAU case. In total, industrial heat emits 876, 987, and 1,053 MT/CO_2-eq in the BAU, FOP, and POD scenarios. The lower share of emissions in the BAU model is due to the deployment of power-to-heat technologies driven by the higher share of renewables in the power mix.

Figure 13a portrays the yearly generation of CO_2-eq across periods and scenarios. Additionally, the plot contains Mexico's 2050 pledge to the Paris agreement, which forces Mexico to reduce emissions by 50% concerning the year 2000; this corresponds to an emission allowance of 300 MT/CO_2-eq in 2050. Our optimization model using GENeSYS-MOD only has the transportation, power, and heat sectors leaving outside the emissions from important sectors like agriculture, land use, and forestry that in 2016 accounted for more than 15% of total emissions in the country (Climate Watch, 2021). Consequently, the emissions that we estimate with GENeSYS-MOD are a lower bound of actual national values. Nonetheless, the MT/CO_2-eq emissions in 2050 are still higher than Mexico's Paris pledge across all three models. For the BAU, FOP, and POD scenarios, the 2050 emissions are 310, 456, and 443 MT/CO_2-eq, respectively. These results suggest that if Mexico wants to comply with its Paris commitments, efforts for the reduction of MT/CO_2-eq emissions in the energy sector are necessary, as even in the BAU scenario, anthropogenic emissions out-pass national pledges.

Figure 13 decomposes the system emissions by primary fuel sources across scenarios. By 2050, Oil (gasoline) emissions are 1415, 1442, and 1514 MT/CO_2-eq in the BAU, FOP, and POD scenarios. The same numbers for hardcoal are 3080, 3446, and 3784; for natural gas 1197, 1250, and 1283; and for fuel-oil, there are only emissions in the FOP scenario for 93 MT/CO_2-eq.



(a) Yearly CO_2-eq emissions across models



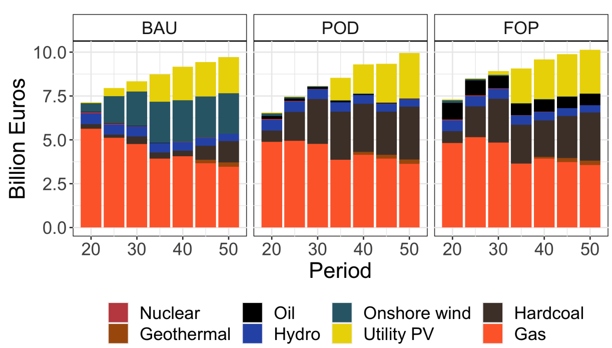
(b) Emissions across models and sectors

Figure 13: Emissions in the for the power, industrial heat, and transportation sectors

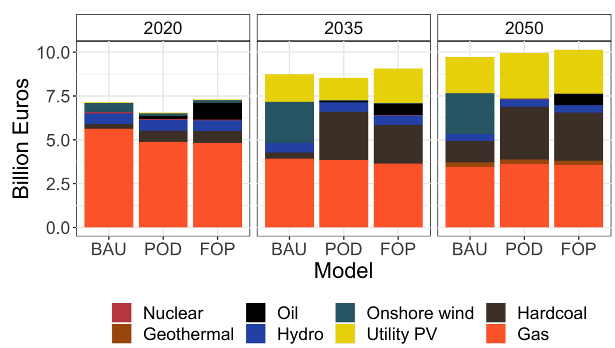
Notes: This figure shows the optimization results regarding system emissions. On the left-hand side, it portrays Megatons of equivalent carbon dioxide (MT/CO_2-eq) as a function of time across the three policy scenarios; Business as Usual (BAU), Physical Order Dispatch (POD), and Fuel Oil Policy (FOP). On the right, it depicts the same information divided by energy carrier. The optimization results come from the techno-economic model GENeSYS-MOD.

4.4. System Costs

Figure 14a portrays the period-wise total costs in Billion Euros (Bn€) by technology and scenario and Figure 14b portrays the same information with the only difference that it shows each scenario in the horizontal axis, allowing to see a more clear depiction of cost differences between models.



(a) Value



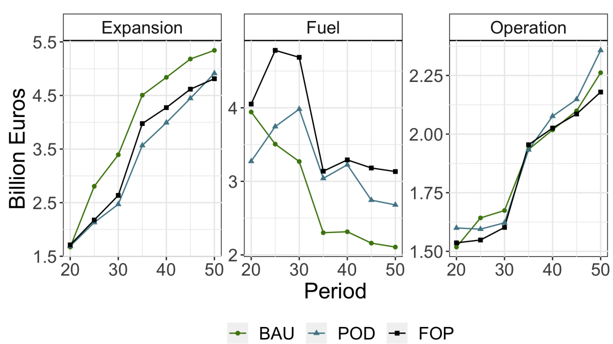
(b) Share

Figure 14: Cost across different concepts

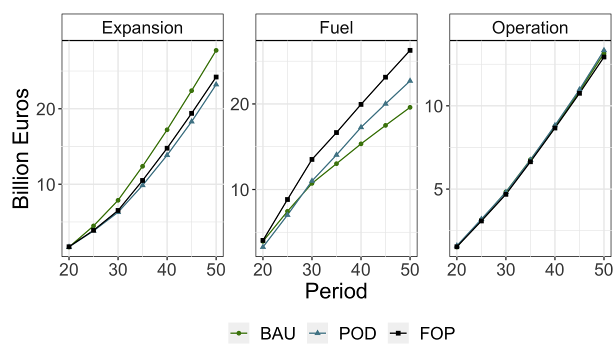
Notes: This figure shows the optimization results regarding power system costs. On the left-hand side, it portrays the costs in million of Euros as a function of time across the three policy scenarios; Business as Usual (BAU), Physical Order Dispatch (POD), and Fuel Oil Policy (FOP). On the right, it depicts the same information divided by energy carrier. The optimization results come from the techno-economic model GENeSYS-MOD and the graph-based framework AnyMOD.

By 2050, the largest expenditures in the BAU model correspond to natural gas, wind, solar, and hard coal technologies with 3.45, 2.29, 2.06, and 1.22 Bn€, respectively. In the POD scenario, we see no significant changes in the cost of natural gas (3.62 Bn€), a substatial increase in the cost of hard coal from 1.22 to 3.01 Bn€, a slight increase of 0.54 Bn€ for solar, and as expected, a very marked decrease in wind costs. In the FOP scenario, natural gas costs remain very similar (3.56 Bn€), hard coal decreases concerning POD to 2.74 Bn€, solar reports costs of 2.48 Bn€, and due to lower costs fuel oil enter the power mix and reports costs of 0.65 Bn€. By 2050, the BAU, POD, and FOP scenarios report total discounted system costs of 9.71, 9.95, and 10.1 Bn€, where it is evident that the largest share of expenditures for the POD and FOP scenarios refer to conventional technologies relying on the combustion of fossil fuels while the BAU scenario balance its costs between renewables and fossil-fuel power plants.

Figure 15a portrays the time series of discounted period costs by scenario for three cost categories; expansion, fuel, and operational costs. Figure 15b portrays the same information with the difference that it shows cumulative system costs.



(a) Period costs



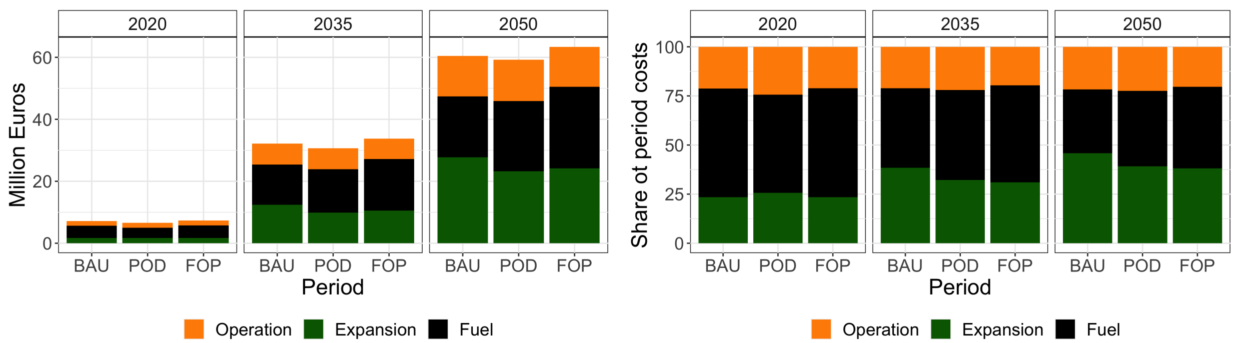
(b) Cumulative costs

Figure 15: Costs of the power system by category

Notes: This figure shows the optimization results regarding power system costs. On the left-hand side, it portrays the costs in million of Euros as a function of time across the three policy scenarios; Business as Usual (BAU), Physical Order Dispatch (POD), and Fuel Oil Policy (FOP). On the right, it depicts the same information divided by energy carrier. The optimization results come from the techno-economic model GENeSYS-MOD and the graph-based framework AnyMOD.

For every period between 2020 and 2050, the expansion costs are higher in the BAU scenario because of higher investment in renewable technologies. For the other two models, FOP expansion costs are slightly higher than POD. Concerning fuel costs, the contrary occurs, the higher share of renewables in the BAU scenario makes fuel costs significantly lower from 2025 onwards, while FOP also has significantly higher fuel costs than POD because of the introduction of fuel-oil in the energy mix. Finally, Operation costs seem quite similar across periods and scenarios. By 2050, cumulative discounted expansion costs in the BAU, POD, and FOP models are respectively 27.7, 23.2, and 24.2 Bn€, the same values for fuel costs are 19.6, 22.7, and 26.3 Bn€, while for operation costs they revolve around 13.1, 13.3, and 12.9 Bn€.

Figures 16a and 16b compare the total and share of discounted costs per cost category across all three scenarios in 2020, 2035, and 2050. Concerning total discounted cumulative costs, the BAU has total costs of 60.5 Bn€, the POD scenario is slightly cheaper with 59.2 Bn€, and the FOP scenario is the most expensive with 63.4 Bn€. Furthermore, the BAU costs are divided into 45.8% expansion, 32.4% fuel, and 21.7% operation expenditures. The same figures for the POD model are 39.2%, 38.3%, and 22.5% , while for FOP, they are 38.1%, 41.4%, and 20.3%.



(a) Period costs

(b) Cumulative costs

Figure 16: Costs of the power system by category

Notes: This figure shows the optimization results regarding power system costs. On the left-hand side, it portrays the costs in million of Euros as a function of time across the three policy scenarios; Business as Usual (BAU), Physical Order Dispatch (POD), and Fuel Oil Policy (FOP). On the right, it depicts the same information divided by energy carrier. The optimization results come from the techno-economic model GENeSYS-MOD and the graph-based framework AnyMOD.

We do not see significant cost differences between all three scenarios due to the non-convexity of the optimization process in the presence of learning curves (Grubb, 2014). In simple terms, a greener energy system entails costly investments in renewable facilities during the first periods of the optimization. However, these intense capital investments are drastically reduced in a fossil-reliant system because the learning curve arising from almost a century of using thermal power has considerably decreased capital costs. Consequently, even though the dirtier system would have higher fuel costs, this increase would be compensated by smaller expansion expenditures. Naturally, the current similarity in the price tag of all three scenarios is due to the capital, fuel, and operating costs assumed by the model and can change based on different assumptions regarding the learning curves of renewable technologies. Overall, the non-convexity of the optimization model because of varying learning curves leads to a myriad of costs optimizing energy systems with very diverse technologies. For intuition, figure 17 shows a two-dimensional representation of the non-convex hull.

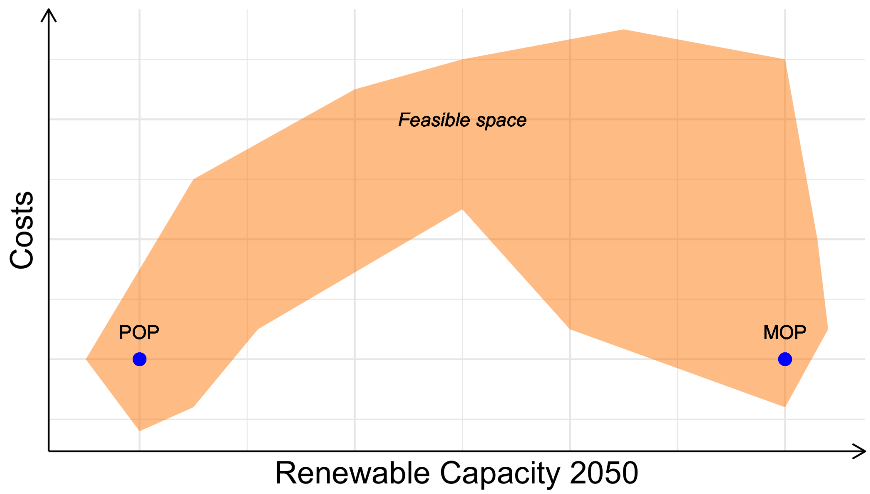


Figure 17: Non-convex feasible space for optimality

On the horizontal axis, we portray the 2050 capacity of a given renewable technology, and on the vertical axis, the costs of the system. Imagine that there are only two technologies, our renewable energy resource and some conventional fossil-fuel technology. Given the constraints that we impose on the model, we end up in a non-convex feasible space that could lead to two different cost-optimal solutions with distinct shares of renewable capacity, with the optimal solution subject to the constraints of each scenario.

4.4.1. Social costs of carbon

Naturally, we cannot ignore the costs associated with the externalities arising from the burning of fossil fuels. From health (e.g. Jayachandran, 2009; Knittel et al., 2016), productivity (e.g. Chang et al., 2019; Sarmiento, 2020), and labor supply (e.g. Hanna and Oliva, 2015) shocks related to air pollution to climate change-induced desertification, natural disasters, and seawater rise; each additional ton of CO_2 in the atmosphere entails severe consequences to Mexico and the global community. A way modelers deal with these external costs is to impose a carbon tax on emissions. However, the carbon tax changes the feasible region of the optimization model and would exogenously lead to a greener energy mix than in scenarios without them. Additionally, the implementation of a functional carbon tax is unlikely to occur under current national circumstances. Hence, we decided not to include carbon taxes within the optimization model but to estimate the costs of environmental externalities from the emission difference between all three scenarios after optimization.

Several emission trading mechanisms operate worldwide, e.g., Quebec and Nova Scotia in Canada, California in the US, or South Korea. However, the largest and oldest of them is the European Emission Trading System (ETS). Currently, the ETS values the cost of one ton of CO_2 in 51.90 €.[8] This value is very similar to the social cost of carbon estimated by the environmental defense fund of 50 USD per ton of CO_2 (Environmental Defense Fund, 2021). However, there are several assumptions and uncertainties regarding the estimations of both the social costs of carbon and the ETS system's efficacy to reflect it correctly; for instance, the price of carbon in September 2007 was as low as 0.1 € per ton of CO_2. As such, figure 18 shows the effect of multiplying the additional emissions of the POD and FOP scenarios for one hundred different carbon costs ranging from 0.5 € to 50 € in 0.5 € intervals. As expected, the costs associated with the externality increase the social burden of the POD and FOP scenarios by a minimum of 359 and 370 million Euros. Notably, this value comes from assuming a very conservative cost of carbon of 0.5 € per ton of CO_2. If we use current carbon prices in the ETS system, the weight of emissions on system costs for both scenarios increases dramatically to 36 and 37 billion Euros.

These 36 billion Euros are equivalent to the 2019 GDP of Paraguay "38 billion USD" (World Bank, 2021a) or 13% of the entire Mexican government budget for 2020 "264 billion Euros" (Transparencia presupuestaria, observatorio de gasto, 2021). Additionally, these 36 billion Euros increase cumulative costs of the system by more than 50% in either of the three scenarios.

[8]The price comes from daily EU ETS prices on the 21st of May 2021, source; https://ember-climate.org/data/carbon-price-viewer/

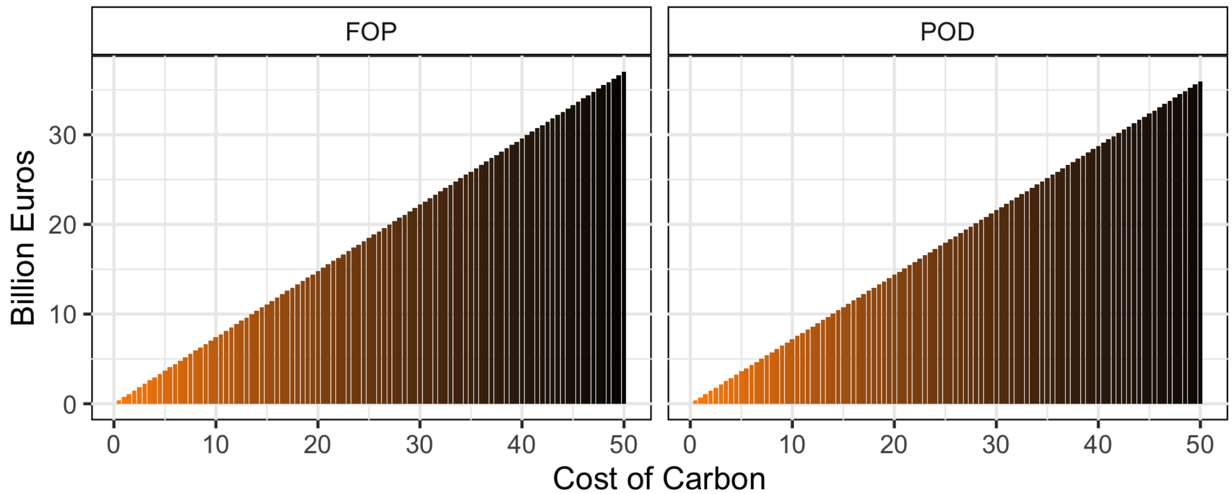


Figure 18: Total emission costs concerning the Business as Usual (BAU) scenario for different social costs of carbon

5. Policy Implications

The change from merit to physical order dispatch shifts market power back to CFE, with noticeable detrimental effects on new entrants and private generators. The precise outcome on local marginal prices of the change in dispatch policy would depend on the specific technology mix, demand, and congestion characteristics at each region. However, the continuous use of more expensive and polluting fuels to generate electricity would likely increase average electricity prices. Furthermore, the rise of anthropogenic GHG generates negative global and local externalities, increasing the cost of the physical dispatch policy well beyond the business as usual scenario. For example, using the current carbon price of the European Union Emission Trading System, the associated emissions of CO_2-eq increase system costs by around 36 billion Euros, more than 50% of cumulative system costs of either scenario.[9]

Moreover, under the new dispatch rule, using fossil fuels for power generation increase significantly, raising the national dependence on US shale gas and international coal imports. This higher dependence on global primary fuels implies that Mexico needs to rethink its energy policy regarding energy security. Notably, a more sensible energy-independent approach would rely on an aggressive and comprehensive decarbonization strategy fostering national renewable energy sources. The dispatch order change would also make Mexico's

[9]This back-of-the-envelope estimate is a lower bound as it ignores the local effects of air pollution on the health and productivity of communities living close to fossil-fuel power stations.

compliance with international agreements almost impossible under the POD and FOP scenarios, leaving the country as a weak contributor to common-good international efforts in fighting climate change.

In addition to the reform's implications regarding the system's power mix, emissions, and costs, it is equally important to consider the domestic and international legal consequences stemming from the proposed merit-order policy. Notably, these reforms are systematic deviations with profound implications for the principles and guarantees of free competition, concurrence, certainty, legal security, sustainability, and the human right to a healthy environment. Moreover, violating these principles is at odds with the Constitution and the guarantees and commitments assumed by the Mexican state in international treaties and agreements to promote and protect environmental resources. For instance, the country has signed and ratified 72 agreements that establish goals and responsibilities at the international level like The Kyoto Protocol, the Paris agreement, the Vienna agreement for protecting the ozone layer, and Chapter 24 of the free trade agreement between Mexico, the USA, and Canada. Thus, the proposed amendment to the electricity law has led to various contentious domestic law procedures claiming the violation of constitutional principles; this is why the proposal has a provisional judicial suspension with general effects. Furthermore, in addition to Mexican internal processes, there is investment arbitration for breaching commercial treaties stipulated in twelve free trade agreements and thirty-three investment promotion and protection agreements with forty-six different nations, further leading the amendment to a dispute resolution in the international arena.

6. Conclusion

Since mitigation of greenhouse gas emissions has local costs with global benefits, negotiations and ratification of international agreements are useless if domestic policies do not align with the international efforts to fight climate change. Because of the "tragedy of the commons," where utility-maximizing countries exhaust environmental goods to the detriment of the global community, energy economists should put a higher focus on domestic policies with international consequences, particularly for OECD and top emitter nations.

In this study, we analyze the impact of one of these domestic policies: the Mexican 2021 reform to the power bill aiming to change electric power dispatch from a marginal-cost-based to a command-and-control physical system prioritizing power generation from the state power company Comisión Federal de Electricidad (CFE). Additionally, we also explore the use of fuel oil in the power matrix where, in addition to changing the merit order, CFE has started producing thermal power by burning fuel oil reserves from the national oil company (PEMEX).

To examine the effect of these policies on power capacity, generation, emissions, and system costs, we propose three distinct policy scenarios and optimize them with the Global Energy System Model (GENeSYS-MOD). First, the Business as Usual (BAU) optimizes the Mexican energy sector without any constraints. Second, the Physical Order Dispatch (POD) scenario changes the marginal cost-based merit order to the physical dispatch proposed by the reform. The reform dictates that the independent system operator must dispatch CFE plants first according to the following order; hydroelectric dams, thermal power facilities, and renewables. Then, after it uses all the power produced by CFE, it can start using energy from independent power producers IPP, and finally, after it consumes the offer from CFE and IPP, it can dispatch renewable and thermal energy from private generators. Third, the Fuel Oil Policy (FOP) adds to the physical dispatch model the implications of including fuel oil in the electricity matrix by artificially decreasing its price below natural gas to make it competitive.

By changing the dispatch rules to favor CFE, the POD and FOP scenarios bring the Mexican power system back to a state monopoly where CFE owns 99% of the total capacity and generation by 2050. The share and value of renewable technologies in the generation mix vary with each model; however, coal and fuel-oil power plants in both POD and FOP scenarios displace wind energy from the generation matrix by the end of the optimization period. Emissions of the power system and energy sector grow significantly in both of these scenarios compared to the BAU model. Specifically, results show that power sector emissions grow by 115.8% between BAU and POD and by 125.1% between BAU and FOP. Moreover, total system costs remain quite similar between scenarios as the costs of expanding the installed capacity of renewable sources in BAU are compensated for fuel costs in the POD and FOP cases. However, this result only considers capital, operating, and fuel costs ignoring the negative externalities associated with higher emissions, which can amount to 37.5 billion euros with current carbon costs in the European Emissions Trading System.

Although the reform is currently suspended with general effects by the judicial branch, President Andrés Manuel López Obrador has stated that he will seek a constitutional reform. Therefore, in contrast to most research that is reactive to policy decisions, this paper acquires a proactive attitude that aims to identify the effects of a possible policy decision that would lead to a lower share of renewable energy sources, bring the power sector back to a monopolistic structure, increase anthropogenic emissions, and raise costs associated with local and global externalities. These implications are relevant since a domestic policy decision published in a secondary law can significantly affect the energy system and threaten collective efforts to mitigate climate change.

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A. Appendix

Table 2: Expansion and operation costs for power plants in GENeSYS-MOD

(a) Biomass

Technology	Period	Expansion cost (Mil.€/GW)	Operation cost (Mil.€/GW/a)
Biomass	2020	1033.26	22.73
Biomass	2025	983.97	21.65
Biomass	2030	934.67	20.56
Biomass	2035	891.29	19.61
Biomass	2040	847.91	18.65
Biomass	2045	808.47	17.79
Biomass	2050	769.03	16.92

(b) Thermal natural gas

Technology	Period	Expansion cost (Mil.€/GW)	Operation cost (Mil.€/GW/a)
Gas	2020	374.83	9.37
Gas	2025	366.41	9.16
Gas	2030	357.99	8.95
Gas	2035	349.56	8.74
Gas	2040	341.14	8.53
Gas	2045	332.72	8.32
Gas	2050	324.29	8.11

(c) Hardcoal

Technology	Period	Expansion cost (Mil.€/GW)	Operation cost (Mil.€/GW/a)
Hardcoal	2020	734	18.35
Hardcoal	2025	734	18.35
Hardcoal	2030	734	18.35
Hardcoal	2035	734	18.35
Hardcoal	2040	734	18.35
Hardcoal	2045	734	18.35
Hardcoal	2050	734	18.35

(d) Nuclear

Technology	Period	Expansion cost (Mil.€/GW)	Operation cost (Mil.€/GW/a)
Nuclear	2020	1715.53	36.03
Nuclear	2025	1666.23	33.32
Nuclear	2030	1616.94	30.72
Nuclear	2035	1557.78	28.04
Nuclear	2040	1498.63	25.48
Nuclear	2045	1488.77	25.31
Nuclear	2050	1478.91	23.66

(e) Geothermal

Technology	Period	Expansion cost (Mil.€/GW)	Operation cost (Mil.€/GW/a)
Geothermal	2020	1387.31	29.4
Geothermal	2025	1316.94	29.4
Geothermal	2030	1246.56	29.4
Geothermal	2035	1183.53	29.4
Geothermal	2040	1120.51	29.4
Geothermal	2045	1063.73	29.4
Geothermal	2050	1006.95	29.4

(f) Thermometric oil

Technology	Period	Expansion cost (Mil.€/GW)	Operation cost (Mil.€/GW/a)
Oil/Fuel-oil	2020	246.55	2.68
Oil/Fuel-oil	2025	237.56	2.62
Oil/Fuel-oil	2030	228.57	2.56
Oil/Fuel-oil	2035	219.59	2.5
Oil/Fuel-oil	2040	210.6	2.44
Oil/Fuel-oil	2045	201.62	2.38
Oil/Fuel-oil	2050	192.63	2.32

(g) Hydroelectric

Technology	Period	Expansion cost (Mil.€/GW)	Operation cost (Mil.€/GW/a)
Hydro	2020	693	6.93
Hydro	2025	693	6.93
Hydro	2030	693	6.93
Hydro	2035	693	6.93
Hydro	2040	693	6.93
Hydro	2045	693	6.93
Hydro	2050	693	6.93

(h) Utility Photovoltaic

Technology	Period	Expansion cost (Mil.€/GW)	Operation cost (Mil.€/GW/a)
Solar	2020	580	12
Solar	2025	466	10
Solar	2030	390	8
Solar	2035	337	7
Solar	2040	300	7
Solar	2045	270	6
Solar	2050	246	6

(i) Wind onshore

Technology	Period	Expansion cost (Mil.€/GW)	Operation cost (Mil.€/GW/a)
Wind	2020	1150	23
Wind	2025	1060	21
Wind	2030	1000	20
Wind	2035	965	19
Wind	2040	940	19
Wind	2045	915	18
Wind	2050	900	18

Table 4: Fossil fuel costs in GENeSYS-MOD

Technology	Period	Fuel cost (€/MWh)
Hardcoal	2020	5.29
Hardcoal	2025	5.22
Hardcoal	2030	5.18
Hardcoal	2035	4.9
Hardcoal	2040	4.64
Hardcoal	2045	4.36
Hardcoal	2050	4.1

Technology	Period	Fuel cost (€/MWh)
Gas	2020	13.25
Gas	2025	14.63
Gas	2030	15.57
Gas	2035	16.65
Gas	2040	17.42
Gas	2045	18.42
Gas	2050	20.15

Technology	Period	Fuel cost (€/MWh)
Nuclear	2020	2.94
Nuclear	2025	2.94
Nuclear	2030	2.94
Nuclear	2035	2.94
Nuclear	2040	2.94
Nuclear	2045	2.94
Nuclear	2050	2.94

Technology	Period	Fuel cost (€/MWh)
Oil	2020	34.34
Oil	2025	38.37
Oil	2030	43.02
Oil	2035	46.88
Oil	2040	49.34
Oil	2045	50.99
Oil	2050	51.48

Technology	Period	Fuel cost (€/MWh)
Biomass	2020	0.2
Biomass	2025	0.2
Biomass	2030	0.2
Biomass	2035	0.2
Biomass	2040	0.2
Biomass	2045	0.2
Biomass	2050	0.2

Notes: Source: SENER and International Energy Agency

Table 6: Mexico's renewables potential (GW) in GENeSYS-MOD

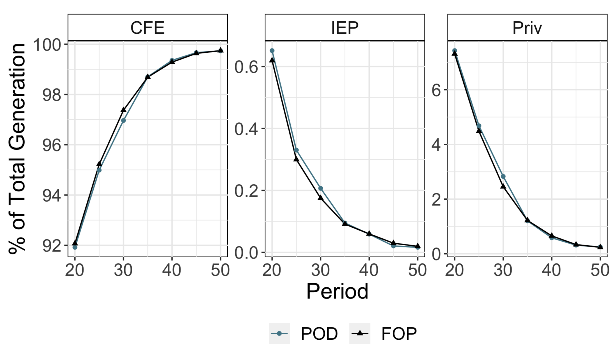
Region	Biomass	Geothermal	Hydro	Solar	Wind
Baja California	0.03	0.06	0	679.83	17.72
Baja California Sur	0	0	0	1246.89	2.5
Norte	0.53	0.01	2.45	8321.06	119.35
Noreste	0.03	0	0.55	6240.19	267.79
Noroeste	0.06	0.07	0	5763.57	11.88
Occidental	0.19	0.22	34.11	4810.85	88.11
Central	0.12	0.05	9.94	1825.64	10.69
Oriental	0.15	0.08	57.05	1775.79	104.28
Peninsular	0.03	0	0	2818.47	10.91

Notes: Sources: National inventory of clean energies and National Atlas of Areas with High Potential for Clean Energy, México

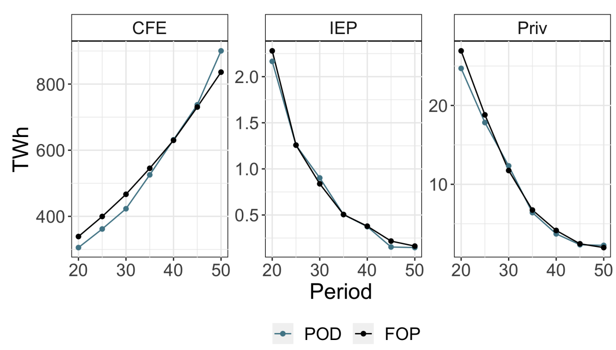
Table 7: 2020 Installed capacity by technology and type of producer in GENeSYS-MOD

	Region	Hardcoal	Gas	Oil	Wind	Solar	Geothermal	Hydro	Nuclear
CFE	Baja California	0	1.18	0.32	0	0.01	0.57	0	0
	Baja California Sur	0	0.52	0.47	0	0	0.01	0	0
	Norte	0	1.56	0.94	0	0	0	0.03	0
	Noreste	2.69	1.34	0.8	0	0	0	0.1	0
	Noroeste	0	2.35	1.57	0	0	0	0.94	0
	Occidental	0	2.44	2.55	0	0	0	2.86	0
	Central	0	2.95	2.06	0	0	0.25	2.06	0
	Oriental	2.78	0.86	1.75	0.08	0	0.1	6.14	1.61
	Peninsular	0	0.61	0.36	0	0	0	0	0
IPPs	Baja California	0	0.78	0	0	0	0	0	0
	Baja California Sur	0	0	0	0	0	0	0	0
	Norte	0	2.55	0	0	0	0	0	0
	Noreste	0	5.7	0	0	0	0	0	0
	Noroeste	0	2.19	0	0	0	0	0	0
	Occidental	0	1.63	0	0	0	0	0	0
	Central	0	0	0	0	0	0	0	0
	Oriental	0	1.91	0	0.61	0	0	0	0
	Peninsular	0	1.26	0	0	0	0	0	0
Private	Baja California	0	0.3	0	0.04	0.04	0	0	0
	Baja California Sur	0	0	0	0	0.06	0	0	0
	Norte	0	0.17	0.16	0	0.87	0	0	0
	Noreste	0	4.3	0.62	2.52	0.84	0	0	0
	Noroeste	0	0.65	0.02	0	1.19	0	0	0
	Occidental	0	1.42	0.67	1.18	2.4	0	0	0
	Central	0	1.03	0.04	0	0.41	0	0	0
	Oriental	0	0.45	0.03	2.4	0.2	0	0	0
	Peninsular	0	0.01	0	0.24	0.05	0	0	0

Notes: Source: PRODESEN 2020-2034, SENER



(a) Emissions across models



(b) Emissions across models and carriers

Figure 19: Share of generation by producer

Notes: This figure shows the distribution of total power generation across market participants. On the left-hand side, it portrays generation as a function of time across the two alternative policy scenarios; Physical Order Dispatch (POD), and Fuel Oil Policy (FOP). On the right side, it depicts the same information while showing the total generation by participant in TWh. The optimization results come from the techno-economic model GENeSYS-MOD