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A development of indicators for the sustainability assessment of the Mexican power system planning

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ABSTRACT

Countries with emerging economies face a significant challenge when developing strategies to move towards a low emission energy system and also keep their economies growing. The power system plays a crucial role in these strategies and by correctly measuring its sustainability it is possible to identify which alternative improves the sustainability the most. This article proposes indicators for the assessment of the sustainability of the Mexican power system planning scenarios that have been put forward by two government administrations, with a study horizon to 2030. The scenarios are characterized by the programming of additions and retirements of the generating capacity throughout the period of 2019 to 2030. Eventually, the optimal dispatch was obtained to be able to accomplish the hourly demand. Sustainability indicators were developed and calculated to evaluate the energy security, energy equity, and environmental sustainability dimensions. Subsequently, the indicators were fed into the Position Vector of Minimum Regret Analysis as a multicriteria decision analysis. By analyzing the results, it is highlighted that increasing the power transmission, as well as the hourly availability of hydro plants, improve the sustainability of the generation system. The comparison between both scenarios' performance indicates that the current government's planning is slightly more sustainable.

Keywords

Minimal Global Regret Analysis;
Energy Trilemma;
Sustainability indicators;
Mexican power system;
Mexico INDCs

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1. Introduction

The economic development of a country, for most cases, is strongly correlated to its energy consumption, e.g., the country-members of the North American Free Trade Agreement showed a causal relationship between energy consumptions and the increase of their gross domestic product for the period 1971-2015 [1], however, other countries such as Taiwan or the Philippines are fewer energy-dependent economies [2]. It is a given fact that an increase in energy consumption implies a greater demand for natural resources and therefore, the emission of a larger amount of greenhouse gases (GHG). These emissions are primarily responsible for climate change [3], which has become an essential concern for all countries worldwide since its consequences could have catastrophic global environmental impacts [4]. It is well-known that developed countries are more adapted to undesirable climate change effects than developing countries [5], for instance, poor nations suffer negative changes for agricultural production which is a crucial global economic activity [6]. Energy systems that play a key role in human life are expected to undergo climate change consequences, particularly renewable energy that is envisaged to bear a relevant role in future low-carbon-mitigation [7]. This climate change concern has led to placing a more concentrated emphasis on the

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development of strategies in order to maintain annual global emissions well below 40 gigatons of carbon dioxide equivalent, and thereby limiting the increase in global average temperature to 2 ºC, with aspirations of getting to 1.5 ºC in comparison with pre-industrial levels, as mentioned in [8].

The twenty-first session of the Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) set a starting point to begin facing climate change, where nearly 200 countries joined the cause. However, developing countries face a bigger challenge implementing strategies to move towards reducing emissions, preserving economic growth, and carrying out sustainable exploitation of natural resources. This situation comes about because most of them do not yet count on low-emission technologies. The transfer of low carbon technologies to developing countries must perform a critical role in reducing carbon emissions [9], for example, carbon capture and storage are an attractive option for this purpose since these countries are heavier fossil fuel consumers [10]. Mexico fit in this situation because its energy consumption is expected to increase over the next decades in order to serve the population and keep the economy growing [11]. Additionally, Mexico has important national and international commitments to reduce emissions in the medium and long-term. These goals are pointed out in the General Climate Change Law, the Energy Transition Law and Mexico's Intended Nationally Determined Contributions (INDCs), issued in 2012, 2014 and 2016 respectively. According to the National Emissions Inventory of 2015, developed by the National Institute of Ecology and Climate Change [12], almost 50% of Mexico's emissions are produced from activities due to transport and energy sectors. These sectors are the largest room to reduce GHG emissions.

There is a great collection of studies on the energy sector that propose different scenarios and strategies to decarbonize by the year 2050. However, only in some cases are the three pillars of sustainability considered, these being environmental, economic, and social. For example, Grande-Acosta et al. [13] analyze scenarios for the deep decarbonization of the Mexican power sector with an aim towards the year 2035 through an environmental and economic approach. While Elizondo et al. [14] use well-known tools such as "The Mexico 2050 Calculator" to evaluate political strategies in the energy sector by comparing four low carbon scenarios. Veysey et al. [15] explore various pathways to hit the decarbonization targets by 2050, by analyzing the results obtained from different energy systems and economic models, focusing mainly on the environmental and economic aspects and slightly on the social aspects. Nevertheless, to make a final decision about what strategy could have the best results it is substantial to develop tools to evaluate the sustainability of an energy system by adequately integrating environmental, economic and social dimensions.

Various methodologies that use indicators and multi-criteria analysis methods have been developed, for example, Santoyo-Castelazo et al. [16], chose ten indicators to assess the environmental dimension, three for the economic, and four for the social, and then they applied the "multi-attribute value theory" method to compare the performance of eleven different scenarios. Bonacloche et al. [17] selected six indicators and a single-indicator-value-function was applied to compare two scenarios that aim to meet Mexico's goals by 2030. Rodríguez-Serrano et al. [18] used a multiregional input-output model applied to socio-economic and environmental impact assessment to evaluate the sustainability of a solar thermal power plant project in Mexico. Roldán et al. [19] used four dimensions to evaluate the sustainability of specific technological systems of electric power plants: economic, social, environmental, and institutional. The authors proposed the multi-criteria method of "Analytic Hierarchy Process" to carry out the decision-making to qualify the technologies. However, despite many studies, the proposed indicators were not developed to evaluate a power system specifically, so, aspects of great relevance are not considered, such as the annual energy exchanges between interconnected regions. Furthermore, the methodologies proposed in these studies are mostly limited to evaluating scenarios that include technology, share in annual gross generation and/or emission reduction targets, to determine the data that feeds the selected indicators. On the other hand, this article integrates the evaluation of scenarios which include only the annual installation and retirements of power plants. This led us to integrate it as part of the methodology used as an optimizer for the power dispatch to find the annual regional energy generation by technology, thereby proposing new indicators that more adequately evaluate the sustainability of other scenarios that involved in this sector. This paper aims to identify and develop indicators to assess the sustainability of the Mexican power system planning of the two scenarios proposed by different government administrations by using the installation and retirement of capacity.

2. Characterization of the Mexican power system planning scenarios

The configuration of both administration's planning is described in the National Power System Developed Program or "Programa de Desarrollo del Sistema Eléctrico Nacional (PRODESEN)", which is a document release annually by the Secretariat of Energy of Mexico (SENER). Among the most relevant information that the PRODESEN contains is the plan of addition and retirement of power plants and the fuel prices forecast for the future fifteen years period.

The current administration developed a plan of addition and retirement of power plants with significant differences from the previous administration planning. Figures 1 and 2 show addition and retirement of capacity for both of the administrations in the period of 2019-2030, where it is observable that the planning carried out by each administration clearly differs. However, the plan should be aligned in compliance with commitments of COP21 and move towards a more sustainable power system.

The National Center for Energy Control or "Centro Nacional de Control de Energía (CENACE)", which is the institution in charge of operating the electricity market in Mexico, and developing the planning activities of the National Transmission Grid [20], segregate the country into ten control regions (Figure 3). This partition is used to evaluate some indicators and to characterize the base year capacity; such information is detailed in [21] and [22].

3. Methodology

This section describes the methodology employed to choose and develop the sustainability indicators. The main steps are set out briefly following. First, it was necessary to define the sustainability dimensions and the indicators corresponding to each one. Secondly, the mathematical expressions to calculate every indicator were formulated. The following step corresponds to the operation of the power dispatch optimizer that allows getting the input data to feed the indicators' equations

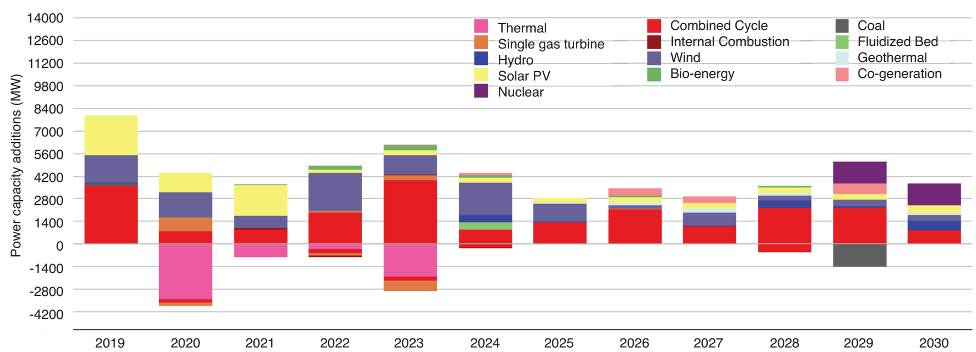

Figure 1: Addition and retirement of power plants capacity of government 2012-2018 for the period 2019-2030 [21].

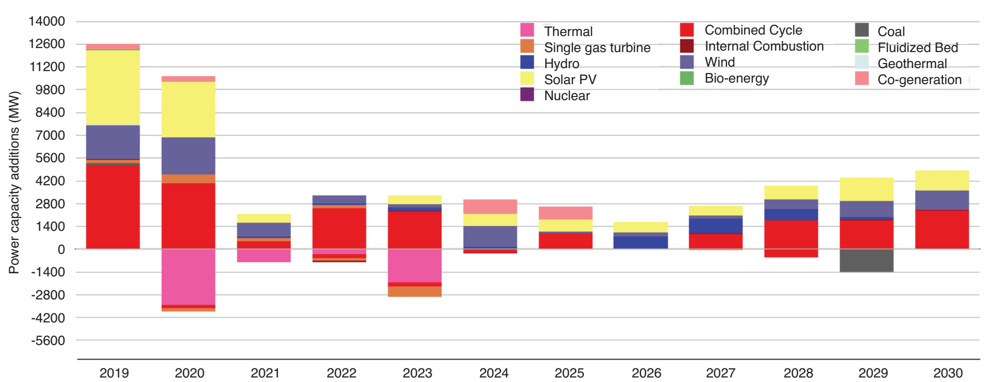

Figure 2: Addition and retirement of power plants capacity of government 2018-2024 for the period 2019-2030 [22].

Figure 3: Mexican power system Control Regions used by CENACE [20].

and finally, the multicriteria decision method was used to determine the best option using the indicators' results.

3.1. Criteria selection for the development of the sustainability indicators

Since the power system is a branch of the Energy System, the indicators were based on the dimensions proposed by the World Energy Council (WEC) in the Energy Trilemma. These dimensions describe the sustainability of an energy system and are defined as follows [23].

- Energy Security: *Reflects a nation's capacity to meet current and future energy demand reliably, withstand and bounce back swiftly from system shocks with minimal disruption to supplies.*
- Energy Equity: *Assesses a country's ability to provide universal access to affordable, fairly priced and abundant energy for domestic and commercial use.*
- Environmental Sustainability of Energy Systems: *Represents the transition of a country's energy system towards mitigating and avoiding potential environmental harm and climate change impacts.*

This research utilizes seven indicators of which five were developed and two were selected from other studies. The aim in using seven indicators is to obtain a good assessment of the sustainability of a power system, even with only limited information about the strategies or scenarios. Every indicator was developed or selected to provide relevant information about the dimension to be evaluated, thereby avoiding the use of the same input information for another indicator. Subsection 3.2 describes each indicator and the mathematical equation developed or used for its calculation and Table 1, detail the indicators, their units, and ultimate goal. When the indicator's goal is "max", then the scenario or alternative with the higher value will obtain the best performance. For a goal equal to "min" the opposite is true.

3.2. Mathematical formulation of sustainability indicators

In this subsection, the development of the mathematical formulation for each sustainability indicator is presented.

Table 1: Quantitative indicators to evaluate the sustainability of the Mexican power system.

Dimension	Indicator name	Unit	Goal
Energy Security	1. Average capacity diversification (H′)	Fraction	Max
	2. Natural gas importation (NGII)	Million cubic meters	Min
	3. New clean power plants (NCPPI)	%	Max
Energy Equity	4. Total cost (CTOT)	USD_{2017}	Min
	5. Generation-consumption regional balance (CGGI)	Fraction	Min
Environmental Sustainability of Energy Systems	6. Average emission factor (SEF)	$kgCO_{2eq}$/MWh	Min
	7. INDCs goals met (NDCM)	%	Max

Table A1 in Appendix 1.1 shows the sets included in the following equations.

3.2.1. Average capacity diversification

The diversification indicator represents an important piece of the energy security dimension, if a system is diversified, then it will possess the capability to better respond to problems induced from the shortage of a specific fuel or primary energy source. In this study, the Shannon-Wiener diversification index was decided on, which has been used in various fields of science such as communication or biology [24], however, it can also be applied in the estimation of the diversification of the capacity mix or generation of a power system. Eq. (1) and (2) show the operation of the Shannon-Wiener index applied to the capacity mix.

$$H' = \sum_{t=1}^{T}\sum_{i=1}^{I} -f_{i,t} \cdot \ln(f_{i,t}) \qquad (1)$$

$$f_{i,t} = \frac{F_{i,t}}{\sum_{i=1}^{I} F_{i,t}} \qquad \forall t \in T \qquad (2)$$

Where *H'* stands for the average diversification indicator of the Mexican power system capacity during the study period, *I* for the total annual number of existing technologies in the system, *T* for the number of years of the period, and $f_{i,t}$ for the fraction of technology *i* of the total capacity in year *t*, which is calculated through (2) where $F_{i,t}$ is the capacity (MW) of technology *i* in year *t*.

3.2.2. Natural gas importation

The intention of this indicator is to evaluate the country's dependence on the natural gas it will have in the coming years if either of the two scenarios studied were carried out, for which it is assumed that the generation with combined cycle technologies would be with imported fuel during the period, in such a way that this indicator was calculated using Eq. (3):

$$NGII = \sum_{t=1}^{T}\sum_{g=1}^{G} \frac{HR_g \cdot EG_{g,t}}{NGAHV} \qquad (3)$$

Where NGII is the natural gas imported indicator (million cubic meter) of the Mexican power system during the study period, HR_g is the heat-rate (GJ/MWh) of gas technology *g*, *G* is the number of technologies that use natural gas as fuel, $EG_{g,t}$ is the electricity produced (MWh) by technology *g* in year *t*, and *NGAHV* is the natural gas average heat value (kJ/m3).

3.2.3. New clean power plant

According to the sixteenth transitory in the tenth title of the Energy Transition Law, published in the Federal Official Daily of Mexico [25], a power generation technology is clean if its emission factor is no larger than 100 $kgCO_{2eq}$/MWh. This quantity was the reference used to define the status of the different technologies contemplated. The construction of new clean power plants contributes to an increase in the country's energy security because most of them use the country's natural resources as a primary source of energy, which was calculated by this indicator using Eq. (4). The interval of possible results for this indicator is between 0% and 100%. 0% when no new clean power capacity is installed during the period, and 100% when all the new power capacity is clear.

$$NCPPI = \left[\frac{100}{T}\right]\sum_{t=1}^{T}\sum_{n=1}^{N}\left[\frac{CPPC_{n,t}}{F_t}\right] \qquad (4)$$

Where *NCPPI* represents the (%) of new clean power technologies, $CPPC_{n,t}$ represents the capacity (MW) of clean technology *n* in year *t*, F_t represents the sum of all installed capacity (MW) in year *t*, *N* represents the number of clean technologies, and *T* is the number of years for the period.

3.2.4. Total cost

This indicator was calculated by adding the total investment, fixed and variable operation and maintenance (O&M), fuel, and unserved load cost, as presented in Eq. (5), and every single cost was calculated through Eq. (6), (7), (8) and (9) respectively. The value for each variable used in determining the total cost was obtained from the information pointed out in PRODESEN 2018-2032, PRODESEN 2019-2033, and the report *"Costos y Parámetros de Referencia: Generación 2018"* [26].

$$C_{TOT} = C_{INV} + C_{O\&M} + C_{COM} + C_{UL} \qquad (5)$$

Where C_{TOT} is the total cost (USD) for each scenario, C_{INV} is the total investment cost (USD), $C_{O\&M}$ is the total fixed and variable O&M cost (USD), C_{COM} is the total fuel cost (USD) and C_{UL} is the total unserved load cost (USD).

3.2.4.1. Total investment cost

$$C_{INV} = \sum_{t=1}^{T}\sum_{i=1}^{I} \frac{IC_i \,.\, NPV}{(1+y)^t} . TA_{i,t} \qquad (6)$$

Where I is the number of technologies, T is the number of years, IC_i is the unitary investment cost (USD/kW) of technology i, NPV is the net present value (fraction) at the start of the operation, $TA_{i,t}$ is the added capacity (kW) of technology i in year t and y is the discount rate. For this research, the discount rate was 10%.

3.2.4.2. Total O&M cost

$$C_{O\&M} = \sum_{t=1}^{T}\sum_{i=1}^{I} \frac{FO\&M_i \cdot F_{i,t} + VO\&M_i \cdot EG_{i,t}}{(1+y)^t} \quad (7)$$

Where $FO\&M_i$ is the fixed O&M annual cost (USD/MW) of technology i, $VO\&M_i$ is the variable O&M cost (USD/MWh) of technology i and $EG_{i,t}$ is the electricity produced by technology i in year t (MWh).

3.2.4.3. Total fuel cost

$$C_{COM} = \sum_{t=1}^{T}\sum_{i=1}^{I} \frac{HR_i \cdot FP_{i,t} \cdot EG_{i,t}}{(1+y)^t} \quad (8)$$

Where HR_i is the heat-rate (GJ/MWh) of technology i, and $FP_{i,t}$ is the forecasted fuel price (USD/GJ) of technology i in year t.

3.2.4.4. Total unserved load cost

$$C_{UL} = \sum_{t=1}^{T} \frac{CF_t \cdot UL_t}{(1+y)^t} \quad (9)$$

Where CF_t is the average cost per energy unit (USD/MWh) of unserved load and UL_t is the amount of unserved load (MWh) in year t. For this study, the value of CF_t was 2610 USD_{2017}/MWh over all the period.

3.2.5. Generation-consumption regional balance

The purpose of developing this indicator is to have knowledge of the divergence that exists between electricity generation and consumption in each control region. Regions with over-generation, it will lead to important industrial development around the area. On the other hand, a region with the opposite situation could have low industrial development or dependence on the other regions to supply its own demand. Furthermore, generally a wide gap between generation and demand in a region corresponds to poor use of natural resources. Eq. (10) was used to calculate this indicator. The ideal value is the lowest possible value which means that the regions are importing little energy thus avoiding the dependence of transmission lines.

$$CGGI = \frac{1}{T \cdot R}\sum_{t=1}^{T}\sum_{r=1}^{R}\left|1 - \frac{EG_{r,t}}{D_{r,t}}\right| \quad (10)$$

Where $CGGI$ is the generation-consumption balance indicator, R is the number of regions, $EG_{r,t}$ is the electricity produced (MWh) in region r in year t, and $D_{r,t}$ is the consumption (MWh) in region r in year t.

3.2.6. Average emission factor

To identify approximately what the equivalent amount of CO_2 emissions per unit of electricity is generated in a power system during a specific period, this indicator was proposed. By using this indicator, the linear relation between generation and emissions in one system or another is avoided. Hence, the average emission factor of the Mexican power system was calculated using Eq. (11).

$$SEF = \frac{1}{T}\sum_{t=1}^{T}\sum_{i=1}^{I}\frac{EF_i \cdot EG_{i,t}}{EG_t} \quad (11)$$

Where SEF is the average emission factor indicator ($kgCO_{2eq}$/MWh) of the Mexican power system during the study period, EF_i is the emission factor ($kgCO_{2eq}$/MWh) of technology i, and EG_t is the electricity produced (MWh) in the Mexican power system in year t.

3.2.7. INDCs goals met

This indicator evaluates how well each scenario accomplishes the INDCs proposed by Mexico [27] using the proposed Eq. (12). There are three possible ranges of values this indicator can show, zero, positive or negative. A zero value means the goals of INDCs were accomplished. A positive value, the goals were achieved with outstanding performance, and a negative value the goals were not met.

$$NDCM = \left[1 - \frac{\sum_{i=1}^{I} EF_i \cdot EG_{i,2030}}{GHGE_{2030}}\right] \cdot 100 \quad (12)$$

Where $NDCM$ is the indicator of compliance (%) of Mexico's INDCs by the power sector, $EG_{i,2030}$ is the electricity produced (MWh) by technology i in the year 2030, and $GHGE_{2030}$ is the 2030 goal of emissions (139000 million of $kgCO_{2eq}$) by the electricity generation sector in the Mexico's INDCs.

3.3. Models and data

The scenarios considered in this study contain only information about the annual installation and the retirement of power plants by region and by technology. However, it is necessary to acquire extra information to calculate most of the indicators described previously, such as the annual energy generation by technology or the regional energy generation. This extra information can be obtained by estimating the operation of the Mexican power system, since CENACE operates the power system using economic criteria we decided to use optimization software that simulates this situation to fill this gap. To get some of the input information of the indicators, an optimization software of the annual energy dispatch by region was used, which is described in section 3.3.1. Also, for the characterization of each scenario and to complete the input data of the indicators, information was taken from various official Mexican government documents, as described in section 3.3.2. Finally, section 3.3.3 shows the multi-criteria decision methodology used to evaluate each PRODESEN.

3.3.1. Power dispatch optimizer

The MC Optimizer [28] is an optimization software developed by academics of the National Autonomous University of Mexico (UNAM) in support of the activities of the Energy Planning Unit (UPE) to create and analyse expansion scenarios for the power sector, as well as dispatch and transmission. This optimizer is based on linear programming and developed in MATLAB and seeks to satisfy the power demand in future years at a minimum cost. The optimizer was used to determine the optimal dispatch of each scenario studied.

The objective function of the MC Optimizer is the following:

$$Min\ Z = \sum_{t=1}^{T}\sum_{r=1}^{R}\sum_{i=1}^{I} c_{i,r,t} \cdot x_{i,r,t} \tag{13}$$

Where Z is the dispatch cost of the Mexican power system in the study period, and $x_{i,r,t}$ is the decision variable which can be the energy dispatched or transmitted by technology i in region r in time step t.

Subject to the next constraints:

- Supply hourly demand by region:

$$\sum_{t=1}^{T}\sum_{r=1}^{R}\sum_{i=1}^{I} x_{i,r,t} = \sum_{t=1}^{T}\sum_{r=1}^{R} D_{r,t} \qquad \forall i \in I \tag{14}$$

- Maximum annual generation:

$$x_{i,r,t} \leq fd_{i,r,t} \cdot F_{i,r,t} \tag{15}$$

- Maximum annual added capacity:

$$x_{i,r,t} \leq fd_{i,r,t} \cdot MAPPA_{i,r,t} \tag{16}$$

- Maximum power grid capacity:

$$\sum_{t=1}^{T}\sum_{r=1}^{R}\sum_{i=1}^{I} x_{i,r,t} = MATCA \tag{17}$$

- Annual clean energy generation percentage:

$$\sum_{t=1}^{T}\sum_{r=1}^{R} x_{r,t} \geq CEGF \sum_{t=1}^{T}\sum_{r=1}^{R} x_{r,t} \tag{18}$$

- No negativity:

$$x_{r,t} \geq 0 \qquad \forall i \in I \tag{19}$$

Where $c_{i,r,t}$ is the cost of energy dispatch or transmission by technology i in region r in time step t, $fd_{i,r,t}$ is the availability factor of technology i in region r in time step t, $F_{i,r,t}$ is the capacity (MW) of technology i in region r in year t, $MAPPA_{i,r,t}$ is the maximum capacity addition of technology i in region r in year t, $MATCA$ is the maximum electricity transmission capacity (MWh) between regions, and $CEGF$ is the clean electricity generation fraction.

3.3.2. Input and output data

For the development of the scenarios, the following assumptions were made:

1. The average annual growth rate of demand in each scenario was 3%.
2. The regions of Baja California and Baja California Sur remain isolated.
3. The transmission capacity has an increase of 25% as of the year 2024 compared to the capacity of the year 2019.
4. The capacity of the Occidental-Oriental and Norte-Occidental transmission lines have an increase of 20% by the year 2029 compared to the capacity of the year 2024.
5. The capacity of the Noroeste-Occidental transmission line has an increase of 50% by the year 2029 compared to the capacity of the year 2024.
6. The hydro availability factor increases in peak load hours in the last two years of the period.

Assumptions one and two were made using the data obtained from [21] and [22]. The cost of unserved energy was taken from [29]. The rest of the assumptions were constructed by analyzing the information and graphs from [20] and the weekly wholesale market reports made by CENACE.

The construction of assumption four corresponds to the fact that CENACE takes as reference the year 2024 to complete some transmission lines which would support the new installed capacity in the period 2019-2024. The case of assumptions five, six, and seven are related to the need for meeting Mexico's INDCs which is reflected in the expected reduction of GHG from the power sector by 2029 and 2030.

The main characteristics of each scenario are listed in Table 2, while the data of the technologies used in the optimizer are shown in Table A2 and A3 in Appendix 1.2.

The main output data from the optimizer are the following:

- The hourly dispatch of electricity by region and technology.
- The hourly regional exchange of electricity by technology.
- Unserved energy

3.3.3. Decision-making analysis

The multi-criteria decision method called "Position Vector of Minimum Regret analysis" (PVMR) developed by Martin-del-Campo et al. [30] was used to evaluate the two scenarios considering all indicators aggregated in one global qualification. The idea is to find which scenario could improve sustainability the most by looking for the decision that could cause the minimum regret. This method has some relevant advantages in comparison with mini-max regret decision method because it allows to rank alternatives by finding a global score, making comparisons among alternatives by using all the criteria together. In the PVMR method it is possible to use relative weights for each criterion that it is not possible in the mini-max regret decision method based on pairwise comparison. The PVMR method is focused to make comparisons among more than two alternatives, however, in our case study we are comparing only two options, and the conventional normalization process creates extreme scores which do not adequately reflect the relative difference between two alternatives with similar scores. For this reason, we modified the step 2 of the PVMR method to overcome this situation. In the present case study, we have two alternatives k and seven indicators j. The method was adapted by following the next six steps:

Table 2: Input data of PRODESEN 2018-2032 and PRODESEN 2019-2033.

Characteristics	PRODESEN 2018-2032	PRODESEN 2019-2033
Capacity of the base year 2019 (MW)	79488	79272
Additional capacity 2019-2030 (MW)	53149	55292
Retirements of capacity 2019-2030 (MW)	10690	10690
Number of technologies	13	13
Clean energy restriction	free	free
Number of regions	9	9
Number of transmission lines	10	10

Step 1: A weight (W_j) was attributed to every indicator (j) satisfying the Eq. (20).

$$\sum_{j=1}^{7} W_j = 1 \tag{20}$$

Step 2: A linear normalization was carried out by dividing each value c_{kj} by the highest value when the goal is to maximize, Eq. (21) was applied. When the goal is to minimize each value c_{kj} is divided by the lowest and Eq. (22) was used. For the cases with negative values of c_{kj} Eq. (23) was used.

$$u_{kj} = \left| \frac{c_{kj}}{\max_j (c_{kj})} - 1 \right| \tag{21}$$

$$u_{kj} = \left| \frac{c_{kj}}{\min_j (c_{kj})} - 1 \right| \tag{22}$$

$$u_{kj} = \left| \frac{c_{kj} - \min_j (c_{kj})}{\max_j (c_{kj}) - \min_j (c_{kj})} - 1 \right| \tag{23}$$

Step 3: A score equal to 0 (zero) was assigned to the value c_{kj} of both alternatives k.

Step 4: Through step 2 the normalized values (u_{kj}) of both alternatives were obtained for each indicator j, and the ideal alternative was located in the coordinates (0,0,0,0,0,0,0) of the space solution.

Table 3: Indicators, and alternatives proposed.

Name of indicator (*j*)	PRODESEN 2018-2032 (*k=1*)	PRODESEN 2019-2033 (*k=2*)
1. Average capacity diversification (*j=1*)	u_{11}	u_{21}
2. Natural gas importation (*j=2*)	u_{12}	u_{22}
3. New clean power plants (*j=3*)	u_{13}	u_{23}
4. Total cost (*j=4*)	u_{14}	u_{24}
5. Generation-consumption regional balance (*j=5*)	u_{15}	u_{25}
6. Average emission factor (*j=6*)	u_{16}	u_{26}
7. INDCs goals met (*j=7*)	u_{17}	u_{27}

Step 5: The seven components (p_{kj}) of the vector (p_k), that represents the position of the alternative *k* in the seven-dimensional-space, were calculated for both alternatives using Eq. (24).

$$p_{kj} = u_{kj} \cdot W_j \tag{24}$$

Step 6: For both alternatives *k*, the modulus of the position vector was obtained by using Eq. (25) and (26). This modulus indicates the *regret* of have selected alternative *k*.

$$|p_1| = \sqrt{p_{11}^2 + p_{12}^2 + p_{13}^2 + p_{14}^2 + p_{15}^2 + p_{16}^2 + p_{17}^2} \tag{25}$$

$$|p_2| = \sqrt{p_{21}^2 + p_{22}^2 + p_{23}^2 + p_{24}^2 + p_{25}^2 + p_{26}^2 + p_{27}^2} \tag{26}$$

Table 3 contains the parameters used in Eq. (20) to Eq. (24) and remember that alternatives 1 and 2 are the scenarios of PRODESEN that are being qualified.

4. Results and discussion

This section is divided into two main parts. The first corresponds to the single value attribute function obtained through the mathematical equation of each indicator, and the second contains the scenario's ranking results generated by the application of the multicriteria decision method integrating all the indicators.

4.1. Results for every indicator

All information collected regarding to power plants, demand, regions and transmission grid were used into modelling the scenarios analysed, and by using the MC optimizer, optimal dispatch was obtained. The resulting data was used to calculate the magnitude of the position vector for each indicator and then for each scenario. According to the data collected, handing data and the output information of the optimal dispatch simulated with the MC Optimizer, a slightly variation in the results for each indicator were found and are described following:

4.1.1. Average capacity diversification

As shown in figure 4, the annual diversification of both scenarios significantly decreases since 2023, mainly due to the fact that the added capacity is mostly composed of only three technologies: combined cycle, solar, and wind, which causes the other ten technologies to show a reduction in their contribution to the capacity mix over time. The PRODESEN 2018-2032 is more diversified than PRODESEN 2019-2033 along the period with an exception for the year 2023. Moreover, by 2029 and 2030 the first scenario has nuclear added which increases diversification, especially by 2030. The retirement of capacities possibly played a role in obtaining these results since technologies such as conventional thermal share more than 50% during the first years of the period, causing a further decrease in the value of diversification.

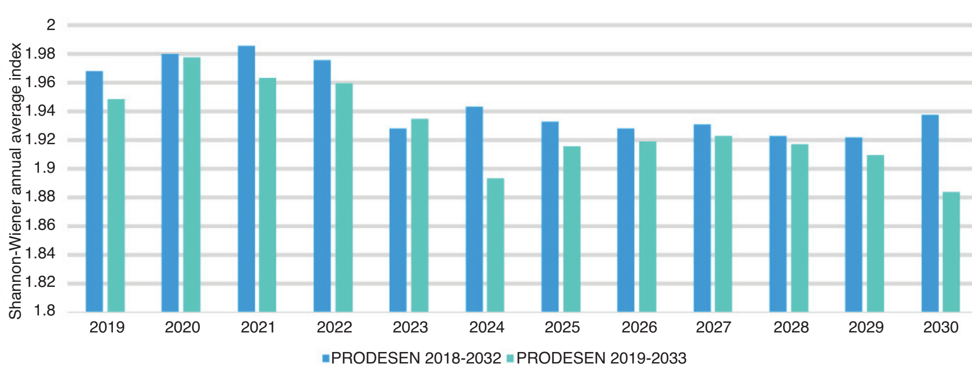

Figure 4: Shannon-Wiener annual average index.

4.1.2. Natural gas importation

As observed in Figure 5 the results have an evident increasing trend in the importation indicator. This is probably because there is an important dependence on combined cycle technology and that it also helps to manage the energy balance properly.

4.1.3. New clean power plant

Figure 6 depicts the difference in clean technology investments contemplated in both scenarios. One can observe that PRODESEN 2018-2032 has a better distribution of additions considering that renewables must be accompanied by their corresponding support in order to maintain the reliability of the power grid. Even when high percentages of investments are observed in the PRODESEN 2019-2033 by 2024 and 2026, the results do not favour it completely, since the average number of clean generating facilities in the PRODESEN 2018-2032 scenario is 60.70%, while in the PRODESEN 2019-2033 is 59.55%.

4.1.4. Total cost

The total cost is represented by each cost component (investment, Fixed O&M, Variable O&M, and fuel). This is detailed in Figures 7 and 8 for each scenario. There is a descending pattern of the total annual cost, due to the gradual reduction of the investments considered. However, the PRODESEN 2019-2033 scenario has a very different distribution of the cost of its facilities, since the first two years of the period consider a large number of facilities, while the rest of the years the investments are very low. On the contrary, the PRODESEN 2018-2032 keeps a more uniform distribution of its facilities throughout the period, which could be considered more realistic because not all technologies can be built in the same period and possible delays must be considered at the start of operation of the plants.

4.1.5. Generation-consumption regional balance

By looking at graphs on figures 9 and 10, a reduction in the regional generation-consumption balance can be detected by 2023. This is due to the fact that the transmission capacity between some regions in the year 2023 will have a considerable increase of the addition of intermittent technologies. This increase, in turn, allows those regions that had the greatest transmission capacity to avoid congestion, in such a way that regions with

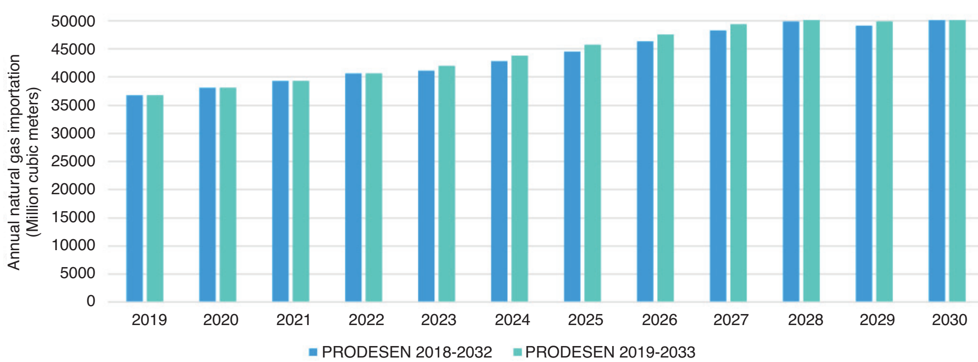

Figure 5: Natural gas annual consumption.

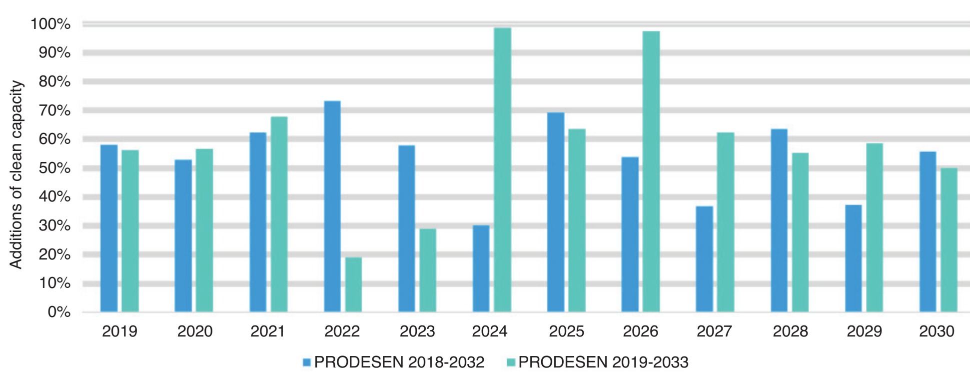

Figure 6: Percentage of additions of clean capacity.

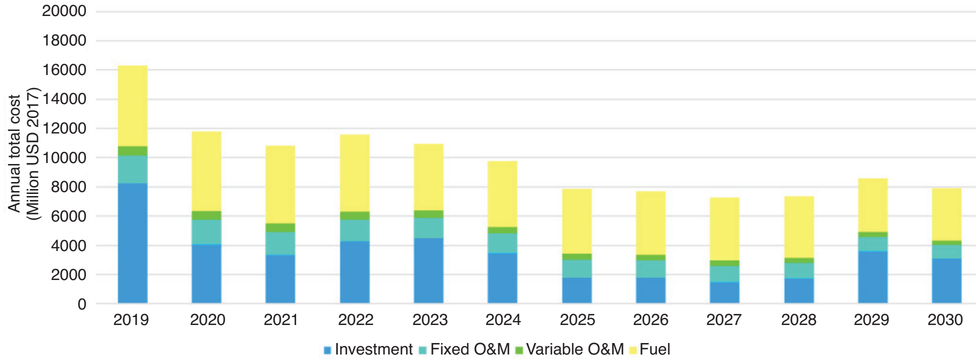

Figure 7: Annual total cost for scenario PRODESEN 2018-2032.

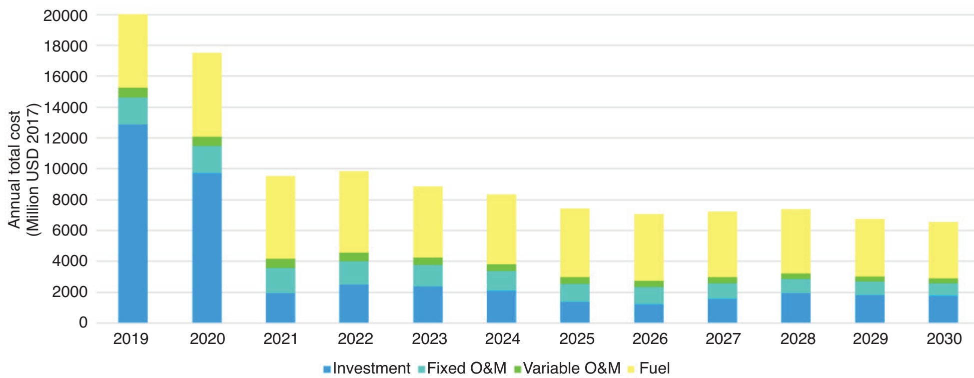

Figure 8: Annual total cost for scenario PRODESEN 2019-2033.

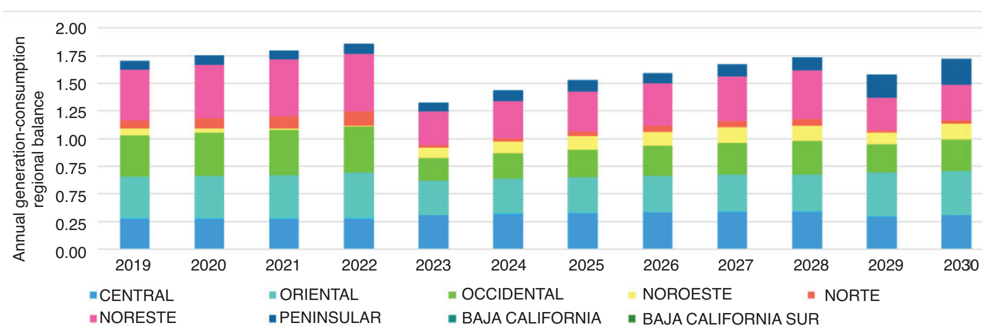

Figure 9: Generation-consumption regional balance of scenario PRODESEN 2018-2032.

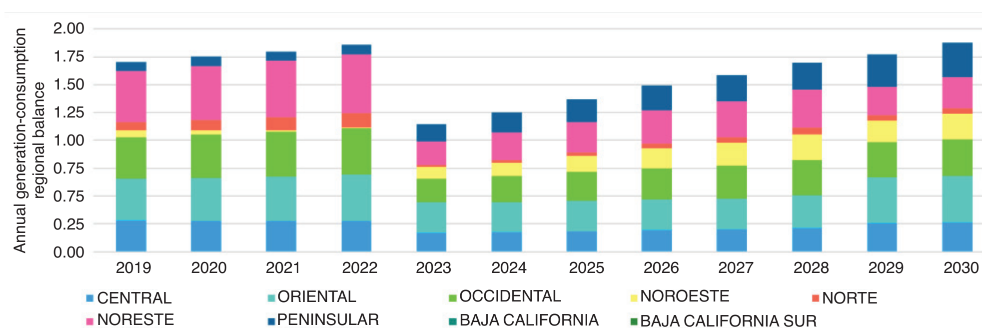

Figure 10: Generation-consumption regional balance of scenario PRODESEN 2019-2033.

deficits can import energy from other regions that had low export capacity. For this reason, the decrease in balance is mainly due to the Oriental and Noreste region.

4.1.6. Average emission factor

Figure 11 contains information regarding the results of the annual average emission factor. The pattern of the previous indicator is maintained possibly due to the increase in capacity of transmission lines that allows greater generation from lower-cost technologies, which are technologies with lower emissions per megawatt-hour generated. Additionally, the increase in the availability factor of hydroelectric plants, contributed to a further reduction in emissions in the last two years of the period.

4.1.7. INDCs goals met

The last indicator is focused on determining the scenario that would have the best performance in compliance with the INDCs by 2030 corresponding to the electricity sector. Figure 12 shows that the difference in emissions between the two scenarios is mainly due to the use of bio-energy technology, which is normally burned to generate electricity in Mexico, and as such produces a high number of emissions which come from combined cycle plants. Both scenarios met the goals. However, the total emissions of the first scenario were 128401 and the second one has a better score with 126155 million $kgCO_{2eq}$.

Table 4, compares an overview of all the indicators, where it confirms that results were very close.

4.2. Decision-making analysis results

For this study, the most relevant objective is that the three dimensions of sustainability have the same importance. As mentioned above, we selected three key indicators to assess the energy security dimension that have the same weight. Likewise, for the dimensions of energy equity and environmental sustainability, we selected two key indicators with exactly the same importance for the dimension analyzed. Table 5 contains the goal for each indicator, *max* for a maximum value and *min* for a minimum. The final weights for each indicator are also shown.

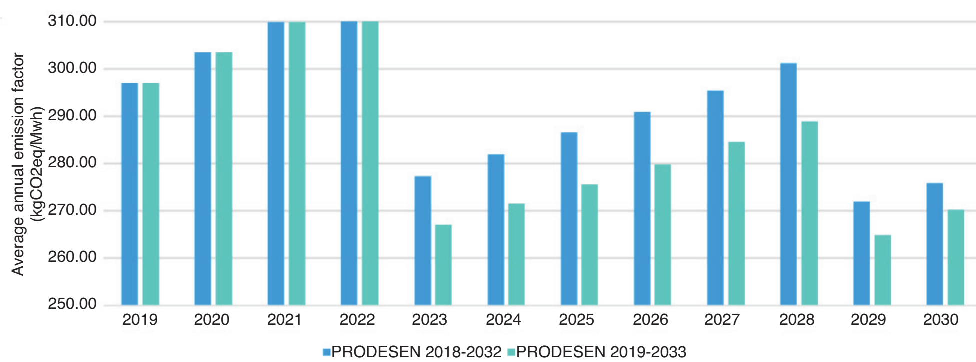

Figure 11: Average annual emission factor.

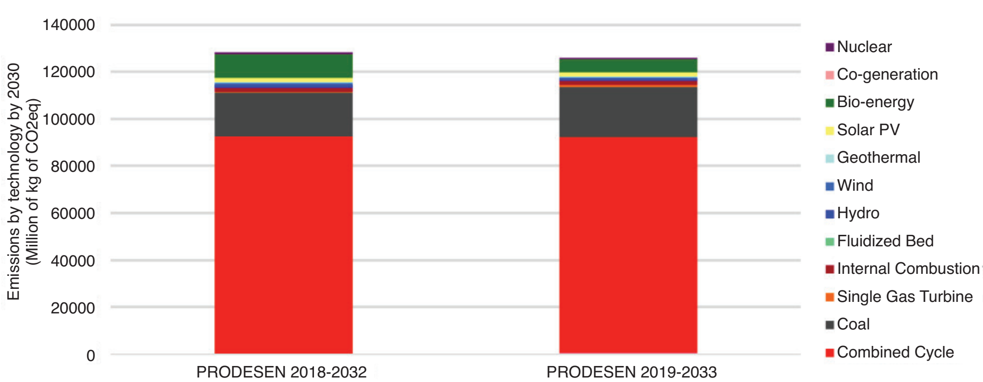

Figure 12: CO_{2eq} emissions by technology to 2030.

Table 4: Performance table.

Indicator (j)	Unit	PRODESEN 2018-2032 (c_{1j})	PRODESEN 2019-2033 (c_{2j})
1	Fraction	1.94	1.92
2	Million cubic meters	528205.99	536025.98
3	%	60.79	59.55
4	Million USD_{2017}	117980.06	117250.02
5	%	23.48	25.07
6	$kgCO_{2eq}$/MWh	292.35	285.79
7	%	7.63	9.24

Table 5: Normalized values for each indicator.

Indicators titles	Goal	PRODESEN 2018-2032 (u_{1j})	PRODESEN 2019-2033 (u_{2j})	Weight (W_j)
Average capacity diversification	Max	0	0.008977	1/9
Natural gas importation	Min	0	0.014804	1/9
New clean power plants	Max	0	0.020475	1/9
Total cost	Min	0.006260	0	1/6
Generation-consumption regional balance	Min	0	0.067530	1/6
Average emission factor	Min	0.022951	0	1/6
INDCs goals met	Max	0.174810	0	1/6

As a sensitivity analysis, a second set of weights was applied to compare the results. In this case, exactly the same weight was assigned to each indicator regardless of the dimension to which it belongs.

Applying Eq. (24), the component of the position vector of minimal regret for every indicator was calculated. Finally, Eq. (25) was applied for the scenario PRODESEN 2018-2032 obtaining 0.029403 and 0.025203 for the first and second set of weights. Similarly, Eq. (26) was applied to calculate the magnitudes of the regret for the scenario PRODESEN 2019-2033 obtaining 0.011642 and 0.010379 for the first and second set of weights. In both cases the last scenario results as the most sustainable.

5. Conclusions

In this investigation, the aim was to identify and develop indicators to assess the sustainability of the Mexican power system planning for two scenarios proposed by different government administrations by using the installation and retirement of capacity. This paper adopts the Energy Trilemma and the PVMR as a basis to identify, develop and evaluate sustainability indicators applied to the Mexican power system planning. An optimization software was used to determine the optimal energy dispatch by technology in each region studied, and the results showed that the PRODESEN 2019-2033 scenario is more sustainable than the PRODESEN 2018-2032 scenario. The first one performed better in three indicators: total cost, average emission factor, and INDCs goals met, while the second one got better results for four indicators: average capacity diversification, natural gas importation, new clean power plants, and generation-consumption regional energy balance. However, the gap between the results in the last indicator "INDCs goals met" made the difference in the final results. This situation could be discussed since both scenarios achieve, even exceed, the goals. In any case, we recommend a sensitivity analysis be performed to make a final decision.

The relevance of the optimization software is clearly supported by the current findings, for example, the increasing transmission capacity of the power grid improves the generation-consumption regional balance, and the changes in the availability factor of hydro cause a greater impact on the results of indicators especially on emissions and consequently, on the sustainability of the power system.

The results presented in this paper are subject to many uncertainties caused by input data as well as access to public information from the official documents, so the results could change if alternate input data is considered or other assumptions are made. However, this work contributes to the formulation of Mexico's country-specific sustainability indicators to be used as an integrated methodology to assess and compare the power infrastructure plans under the Trilemma Energy vision.

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Appendix 1

Appendix 1.1 Nomenclature

Table A1 includes the description of the sets included in the different equations.

Appendix 1.2 Input data for the optimization of the scenarios

Table A2 includes input data of technologies considered for this study, and Table A3 contains the forecasted fuel prices to calculate some indicators and to determine the optimal cost dispatch.

Table A1: Sets.

Index	Description
$g \in G$	The index for conventional generating units which use natural gas as fuel ($G \subseteq I$)
$i \in I$	The index for Generating units (conventional and renewable)
$j \in J$	The index for indicator of the MGRA methodology
$k \in K$	The index for alternative of the MGRA methodology
$n \in N$	The index for clean generating units
$r \in R$	The index for supply region
$t \in T$	The index for year studied

Table A2: Technology data used.

Technology	FD	IC	NPV	FO&M	VO&M	HR	EF
	Fraction	USD_{2017}/kW	Fraction	USD_{2017}/MW	USD_{2017}/MWh	GJ /MWh	$KgCO_{2eq}$/MWh
Thermal	0.80	2045	1.1281	35.83	3.0	9.353	680
Combined cycle	0.85	1013	1.1130	18.95	3.3	7.032	346
Coal	0.90	1425	1.1664	33.78	2.4	9.486	773
Single gas turbine	0.75	813	1.0428	5.08	4.8	9.635	509
Internal combustion	0.85	2877	1.1226	46.41	5.2	8.518	660
Fluidized bed	0.90	1456	1.1664	35.00	2.5	9.486	509
Hydro	ND	1931	1.1499	24.39	0.0	0.000	15
Wind	ND	1423	1.0748	38.11	0.0	0.000	21
Geothermic	0.95	1889	1.0907	105.06	0.1	20.556	38
Solar	ND	1120	1.0674	10.67	0.0	0.000	48
Bio-energy	0.80	2588	1.1664	35.00	2.5	9.486	740
Co-generation	0.80	882	1.1130	7.10	3.2	11.496	346
Nuclear	0.90	3988	1.2821	101.08	2.4	11.229	65

Table A3: Forecasted fuel prices (USD_{2017}/GJ) used.

Year	Thermal	Combined cycle	Coal	Single gas turbine	Internal combustion	Fluidized bed	Hydro	Wind	Geothermic	Solar	Bioenergy	Cogeneration	Nuclear
2019	6.99	4.14	2.54	4.14	12.76	2.54	0.00	0.00	0.00	0.00	0.00	4.14	0.53
2020	7.24	4.28	2.56	4.28	13.08	2.56	0.00	0.00	0.00	0.00	0.00	4.28	0.55
2021	7.50	4.42	2.58	4.42	13.40	2.58	0.00	0.00	0.00	0.00	0.00	4.42	0.56
2022	7.77	4.57	2.60	4.57	13.74	2.60	0.00	0.00	0.00	0.00	0.00	4.57	0.58
2023	8.05	4.73	2.62	4.73	14.08	2.62	0.00	0.00	0.00	0.00	0.00	4.73	0.59
2024	8.34	4.89	2.64	4.89	14.43	2.64	0.00	0.00	0.00	0.00	0.00	4.89	0.60
2025	8.64	5.06	2.66	5.06	14.79	2.66	0.00	0.00	0.00	0.00	0.00	5.06	0.62
2026	8.95	5.23	2.69	5.23	15.16	2.69	0.00	0.00	0.00	0.00	0.00	5.23	0.64
2027	9.27	5.41	2.71	5.41	15.54	2.71	0.00	0.00	0.00	0.00	0.00	5.41	0.65
2028	9.61	5.59	2.73	5.59	15.93	2.73	0.00	0.00	0.00	0.00	0.00	5.59	0.67
2029	9.95	5.78	2.75	5.78	16.33	2.75	0.00	0.00	0.00	0.00	0.00	5.78	0.68
2030	10.31	5.98	2.77	5.98	16.74	2.77	0.00	0.00	0.00	0.00	0.00	5.98	0.70

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