Designing a Resilient Electric System: A Multi-objective Evaluation Considering Economic, Technological and Political Dimensions

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The Crossroads of Mexico’s Power Policy

- Mexico's National Electric System (SEN) at the forefront of public debate.
  - Central question: How involved should the state be in the electrical sector?
- Enrique Peña Nieto’s mandate saw reforms that boosted private sector roles.
- Andrés Manuel López Obrador's administration emphasizes state enterprise control, especially the Federal Electricity Commission.

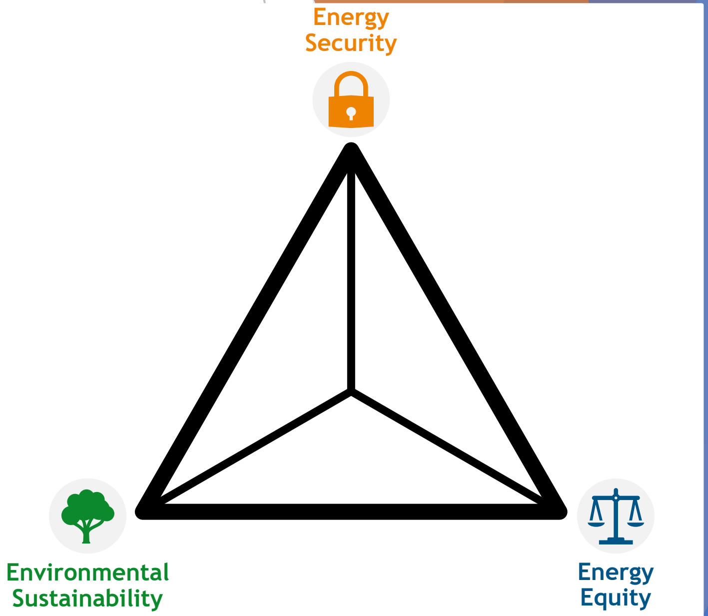
Reframing Mexico's Energy Dialogue

- Moving beyond public vs. private sector roles in energy management, this thesis shifts focus to how energy policies benefit the population.
  - Emphasizes secure, affordable, and clean energy as core metrics.
- Acknowledges Mexico's electric sector is influenced by economic, technological, and political uncertainties, not just linear growth.
  - Utilizes Robust Decision Making to assess policies from recent administrations against potential future scenarios.
- Aims to pinpoint system vulnerabilities under each policy and seeks to enrich public debate and guide the crafting of energy policies.
  - Goal: A superior National Electric System for all Mexicans.

How Do We Measure the Performance of Electric Systems?

WORLD ENERGY COUNCIL

- **Energy Security**
  - Energy sufficiency, continuity and flexibility.
  - Reliability of energy infrastructure.
- **Energy Equity:**
  - Accesibility.
  - Affordability.
- **Environmental Sustainability:**
  - Mitigation of environmental damage, and
  - Impacts of climate change.



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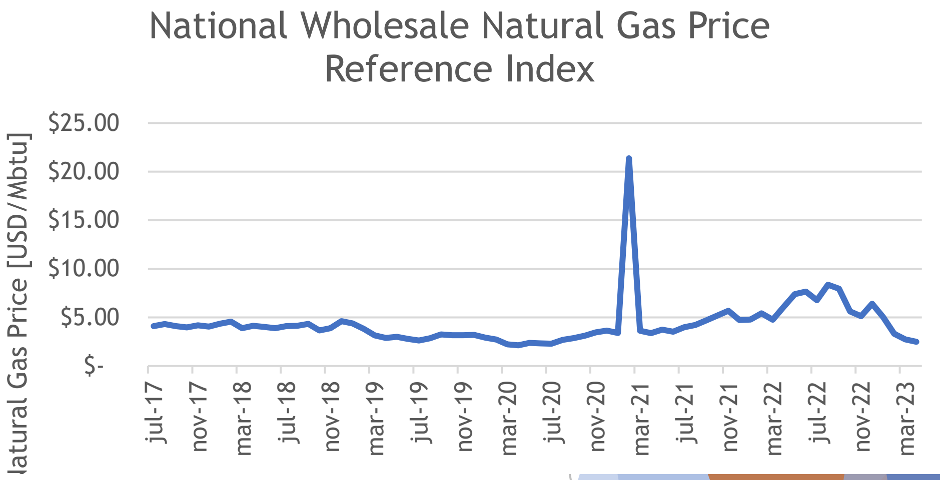
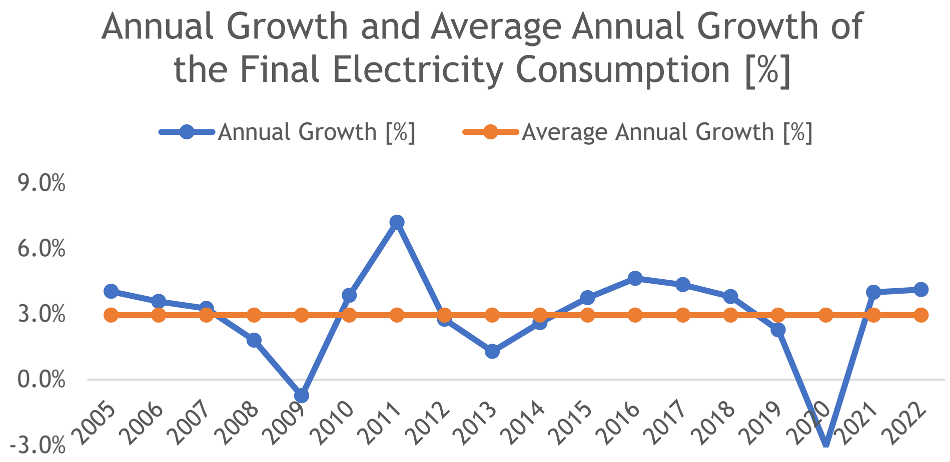
- **Energy Security:**
  - Uninterrupted energy supply at an affordable price.
    - Long-term: Investments for economic development & environmental needs.
    - Short-term: Ability to react promptly to sudden changes in supply-demand.

Some useful facts about the National Electric System…

- Demand averages a 3% annual growth.
- Natural gas price volatility is linked to external uncertainties
  - History indicates potential rises up to 10 USD/MBtu in certain conditions.
- Mexican Federal Carbon Tax since 2014 taxes fossil fuels production and import at $55.83 MXN/t$CO_2$ under the IEPS Law.





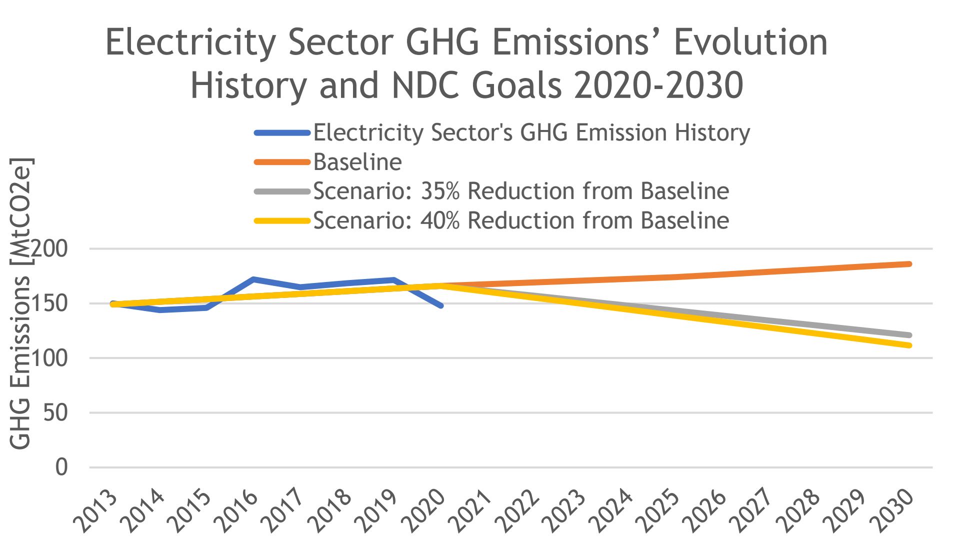
Tax Rate by Fuel in 2022

Fuel	Unit	2022 Tax [MXN]
Propane	Liter	₵8.2987
Butane	Liter	₵10.7394
Gasoline	Liter	₵14.5560
Jet Fuel and other kerosenes	Liter	₵17.3851
Diesel	Liter	₵17.6624
Residual Fuel Oil	Liter	₵18.8496
Petroleum Coke	Metric Ton	$21.8784
Coking Coal	Metric Ton	$51.2901
Mineral Coal	Metric Ton	$36.6201
Other Fossil Fuels	Carbon Metric Ton	$55.8277

Note. Source: Own Elaboration with data from the Secretaría de Hacienda y Crédito Público.

Some useful facts about the National Electric System…

- Nationally Determined Contributions (NDCs) indicate that GHG emissions from the electricity sector by 2030 should be limited to 121 MtCO2e given the 35% reduction goal or 112 MtCO2e given the 40% reduction goal. In 2019, GHG emissions were around 171 MtCO2e.



Robust Decision Making for Navigating Uncertainty

- Robust Decision Making (RDM) informs decision making processes in contexts of deep uncertainty.
- RDM diverges from “agree-on-assumptions" methods, instead employing an "agree-on-decisions" approach.
- It utilizes computational models to stress test proposed actions or policies across multiple plausible futures.
- This helps characterize each policy’s vulnerabilities and identifies suitable responses to improve policy robustness.
- Visualization tools aid in recognizing key policy features and necessary conditions for success.

The XLRM Matrix: A tool for Decision Framing in RDM

- RDM utilizes the XLRM matrix framework for structured decision-making.
  - "X" refers to the exogenous uncertainties.
  - "L" refers to the levers or policies to be evaluated.
  - "R" refers to the relationships within the system, which are defined in the system's model.
  - "M" refers to the metrics in terms of which the performance of each policy is to be compared.

X	L
• Annual Electricity Demand Growth. This includes the following stressors: ○ Economic Activity ○ Electrification ○ Energy Efficiency & Distributed Generation • Natural Gas Prices • Carbon Taxes	• Programa Indicativo para la Instalación y Retiro de Centrales Eléctricas (PIIRCE) 2023 (Baseline Policy) • PIIRCE 2018 • Optimized Reference Policy
R	**M**
• LEAP Model: National Electric System	• Reserve Margin • Costs of Production • Direct GHG Emissions

Performance Metrics for Quantifying Energy Policy Outcomes

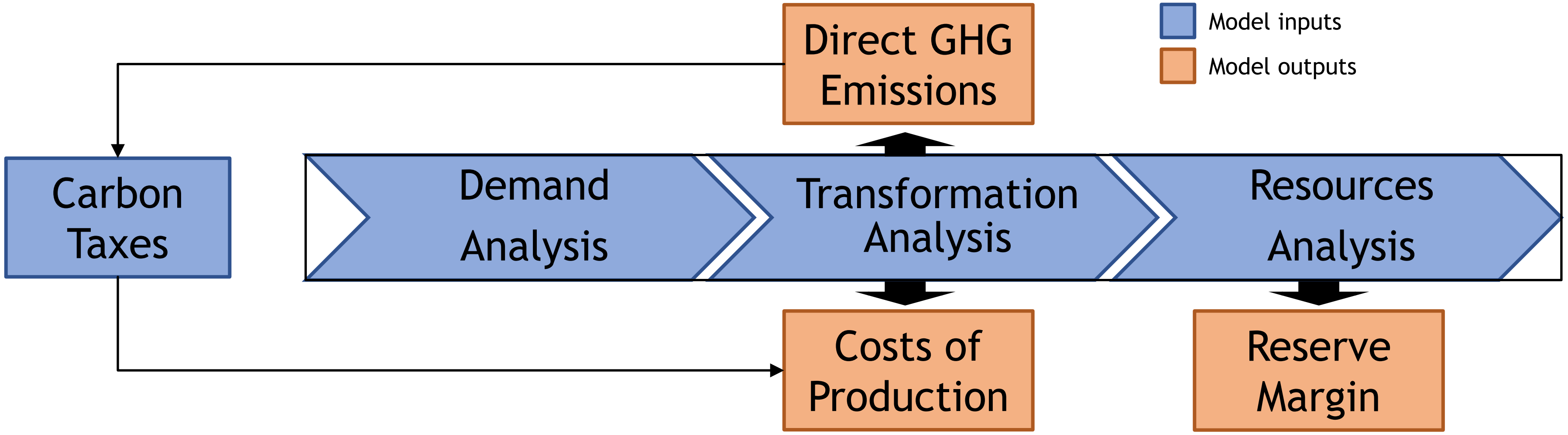
- **Reserve Margin, related to Energy Security:** Indicator of spare capacity for system reliability.
  - Success measured against a minimum reserve margin of 21.4% throughout the study period.
- **Costs of Production, related to Energy Equity:** Includes Fuel, O&M, Capital, and Environmental Externality Costs.
  - Success measured by comparing the Net Present Value (NPV) against the median NPV of all scenarios.
- **Direct GHG Emissions, related to Environmental Sustainability:** Tracks CO_2, CH_4, and N_2O emissions from energy generation.
  - Success linked to meeting Mexico's NDCs in the electricity sector by 2030.

LEAP and NEMO: Tools for Energy Policy Modelling

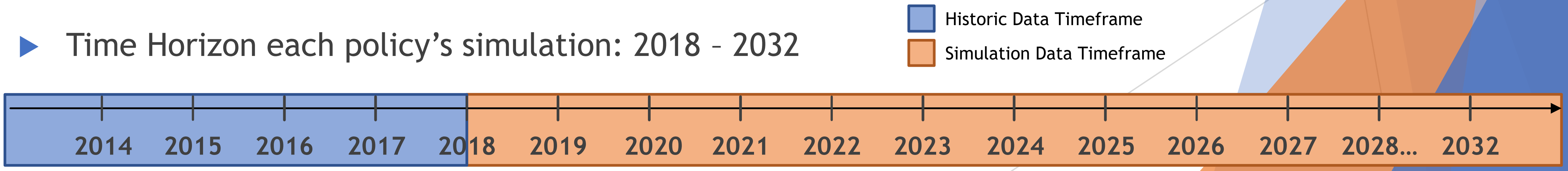
- The Low Emissions Analysis Platform (LEP) by SEI models the entire energy industry value chain and its social costs.
- For the study's timeframe of 2018-2032, LEAP was the primary modeling tool.
- The Optimized Reference Policy was modeled using SEI's Julia-based Next Energy Modeling system for Optimization (NEMO), integrated with LEAP for GUI and least-cost optimization.

How were the Energy Policies Modelled?

- Model Structure:



- Historic Data, common for all policies: 2014 – 2017
- Time Horizon each policy's simulation: 2018 – 2032



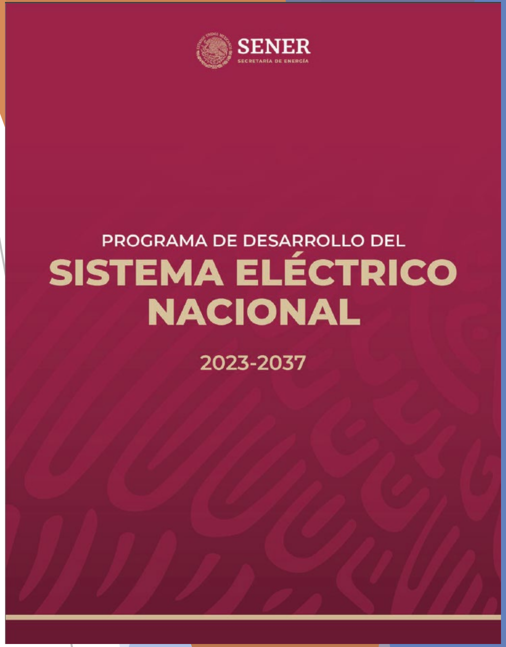
How were the Energy Policies Modelled?

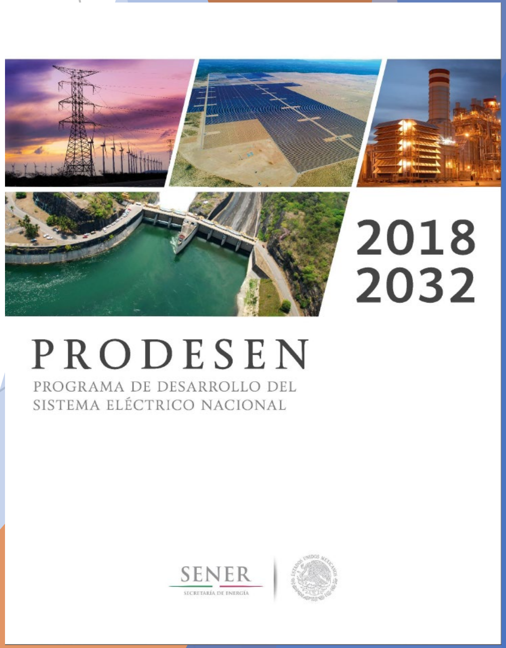
Transformation Analysis’s Input Parameters

- **Processes’ Parameters**
  - Basic Parameters
    - Lifetime
    - First Simulation Year
    - Process Efficiency
  - Cost-Related Parameters
    - Interest Rate
    - Capital Costs
    - O&M Costs
  - Dispatch-Related Parameters
    - Dispatch Rule
    - Maximum Availability
  - Capacity-Related Parameters
    - Exogenous Capacity
    - Capacity Credit
- **Product Parameters**
  - Deficit/ Surplus Rule
  - Target Imports/ Exports
- **Fuel Parameters**
  - Fuel Shares
  - Unitary Costs
  - Environmental Loadings
- **Module Parameters**
  - Planning Reserve Margin
  - Peak Load Ratio

Policy Pathways in Mexico’s Electricity Sector

- **PIIRCE 2023 Policy:**
  - Planning of capacity additions and retirements for 2023 – 2032.
  - Includes historic capacity evolution from 2018 to 2023.
- **PIIRCE 2018 Policy:**
  - Planning of capacity additions and retirements for 2018 – 2032.
- **Optimized Reference Policy:**
  - Not predefined by government planning but derived from optimization model results.
  - Uses NEMO software for least-cost policy under baseline uncertainty conditions.



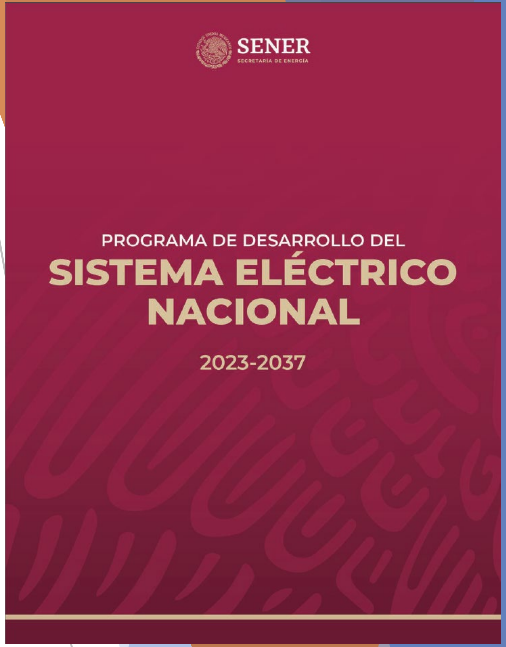


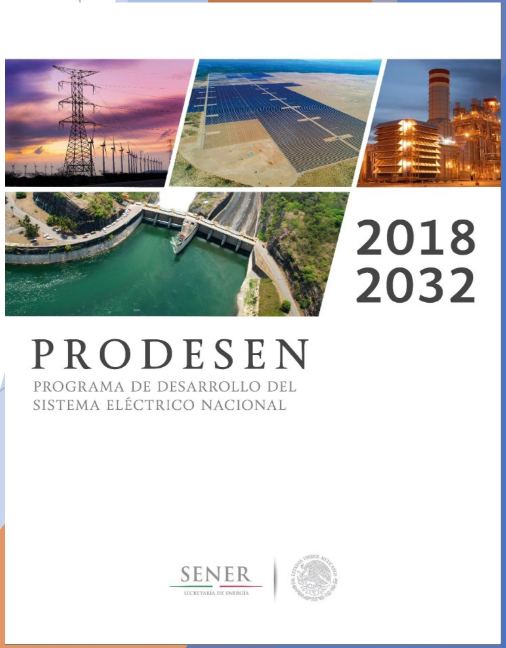
Policy Pathways in Mexico's Electricity Sector

TABLA 4.5.6. EVOLUCIÓN DE LA CAPACIDAD INSTALADA POR TIPO DE TECNOLOGÍA 2018-2032
(Megawatt)

Tecnología	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Convencional	**54,492**	**58,244**	**56,066**	**56,231**	**57,471**	**58,842**	**59,928**	**61,254**	**63,423**	**64,448**	**66,182**	**67,037**	**67,849**	**69,649**	**71,804**
Ciclo combinado	30,125	33,726	34,281	35,155	36,870	40,586	41,243	42,569	44,708	45,776	47,510	49,765	50,577	52,377	54,532
Termoeléctrica convencional	11,712	11,712	8,296	7,476	7,156	5,120	5,120	5,120	5,120	5,120	5,120	5,120	5,120	5,120	5,120
Carboeléctrica	5,378	5,507	5,507	5,507	5,507	5,507	5,507	5,507	5,507	5,507	5,507	4,107	4,107	4,107	4,107
Turbogás	5,062	5,062	5,746	5,746	5,663	5,311	5,311	5,311	5,341	5,298	5,298	5,298	5,298	5,298	5,298
Combustión Interna	1,635	1,657	1,657	1,768	1,695	1,738	1,706	1,706	1,706	1,706	1,706	1,706	1,706	1,706	1,706
Lecho fluidizado	580	580	580	580	580	580	1,041	1,041	1,041	1,041	1,041	1,041	1,041	1,041	1,041
Limpia	**25,007**	**29,193**	**31,903**	**34,587**	**37,397**	**39,253**	**42,282**	**43,823**	**45,089**	**46,961**	**48,303**	**51,147**	**54,106**	**56,682**	**58,487**
Renovable	20,453	24,638	27,348	29,992	32,561	34,048	36,808	38,349	39,059	40,552	41,770	42,591	44,190	45,406	47,211
Hidroeléctrica	12,642	12,671	12,671	12,671	12,671	12,671	13,135	13,198	13,198	13,244	13,676	13,747	14,393	14,393	14,856
Eólica	4,875	6,591	8,128	8,862	11,231	12,417	14,414	15,530	15,750	16,600	16,903	17,303	17,656	18,267	19,017
Geotérmica	951	936	906	891	891	891	891	917	1,067	1,317	1,450	1,450	1,550	1,655	1,708
Solar Fotovoltaica	1,971	4,426	5,630	7,555	7,755	8,055	8,355	8,691	9,031	9,377	9,727	10,077	10,577	11,077	11,617
Termosolar	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14
Otras	4,554	4,555	4,555	4,595	4,836	5,206	5,474	5,474	6,030	6,410	6,533	8,556	9,916	11,276	11,276
Nucleoeléctrica	1,608	1,608	1,608	1,608	1,608	1,608	1,608	1,608	1,608	1,608	1,608	2,968	4,329	5,689	5,689
Bioenergía	1,010	1,010	1,010	1,050	1,291	1,577	1,725	1,725	1,823	1,823	1,947	1,947	1,947	1,947	1,947
Cogeneración eficiente	1,930	1,931	1,931	1,931	1,931	2,014	2,134	2,134	2,592	2,972	2,972	3,634	3,634	3,634	3,634
Frenos regenerativos	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Total [1/]	**79,499**	**87,436**	**87,969**	**90,818**	**94,868**	**98,095**	**102,210**	**105,077**	**108,512**	**111,409**	**114,486**	**118,184**	**121,955**	**126,331**	**130,292**

Nota: El total incluye la adición y retiro de capacidad, no se incluye Importación, Generación Distribuida y FIRCO.[1/] Los Totales pueden no coincidir por redondeo. Fuente: Elaborado por la SENER.





Experimental Design for Simulating Uncertainty

Experimental Design

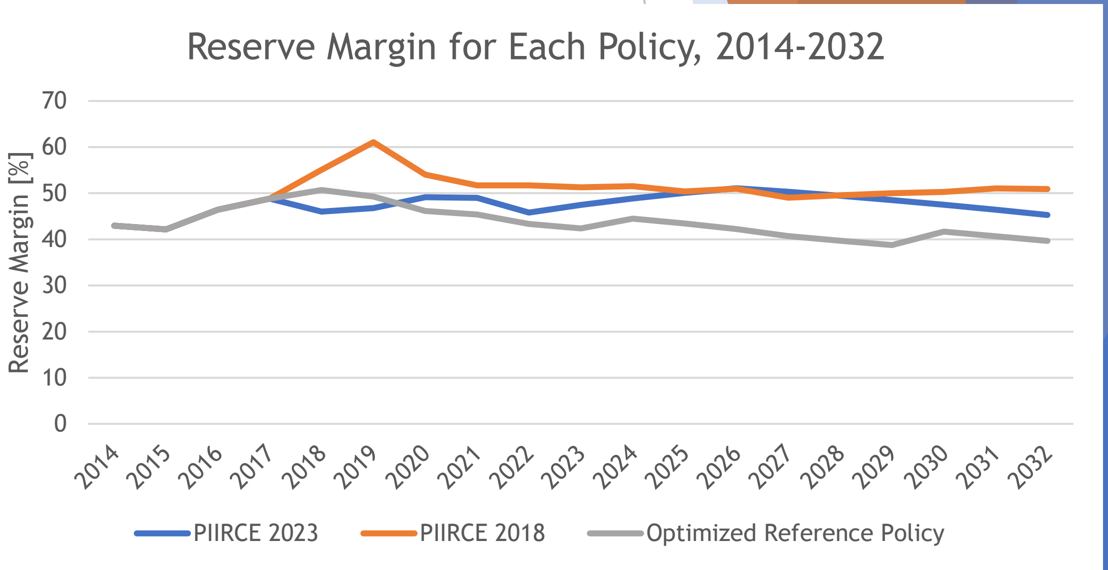
Uncertainty	Description	Experiment	Constant	Min Limit	Max Limit
Demand	Annual Growth of the Electricity Demand, in percentaje.	Baseline	3.00		
		Exploratory Analysis		1.50	4.50
Natural Gas Price	Final Price of Natural Gas in 2032 in USD/MBtu. The Price for previous years Will be interpolated within the model.	Baseline	4.25		
		Exploratory Analysis		1.00	10.00
Carbon Tax	Carbon Taxes, in UMAs/tCO2e.	Baseline	0.39		
		Exploratory Analysis		0.39	17.35

Note. Source: Own Elaboration.

- **Baseline Experiment:** 1 run for each Policy. Total: 3 runs.
- **Exploratory Analysis:** 508 runs for each Policy. Total: 1524 runs.

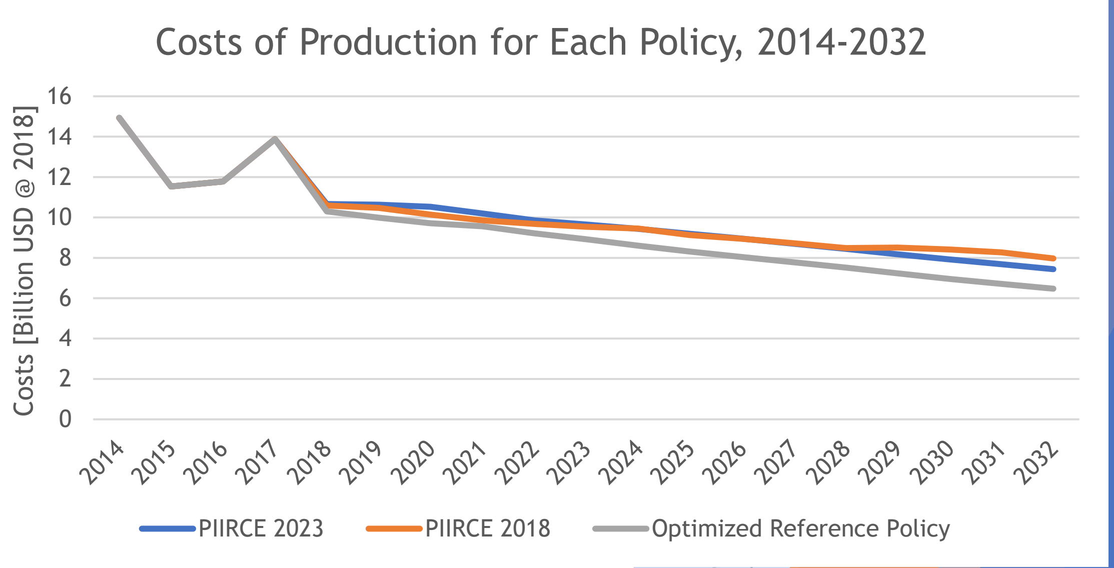
Reserve Margin for Each Policy under Baseline Conditions

- PIIRCE 2023 meets reserve margin goals, but a downward trend is identified from 2026 onwards.
- PIIRCE 2018 maintains a reserve margin above 50% for practically all the evaluated period.
- The Optimized Reference Policy achieves its cost-minimization objective but at the expense of a lower average reserve margin.
- Future developments might consider stricter reserve margins to increase the system's resilience amidst uncertain stress factors.



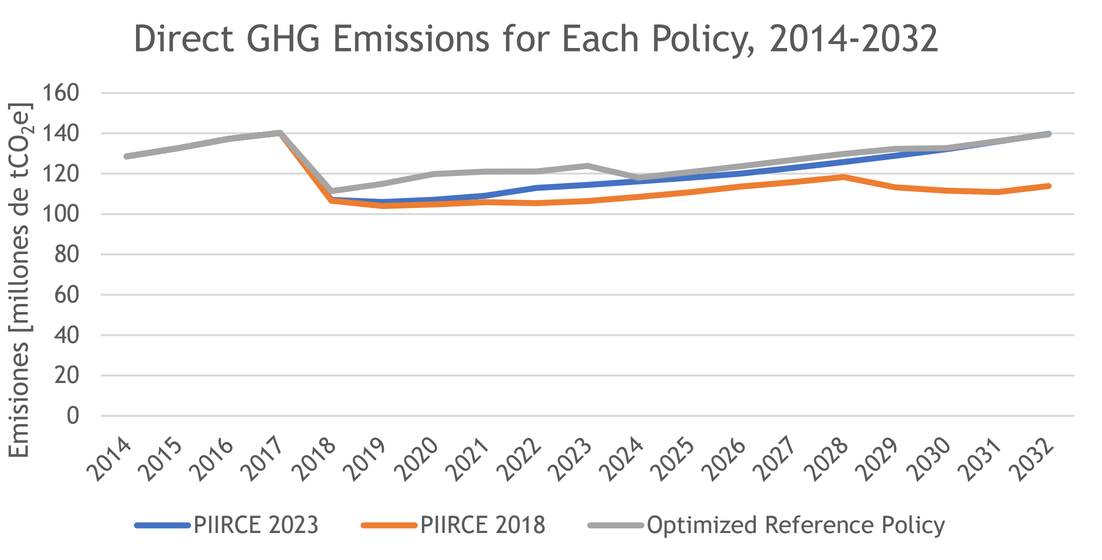
Costs of Production for Each Policy under Baseline Conditions

- PIIRCE 2023 delivers similar costs of production to PIIRCE 2018 but underperforms in other metrics.
- The Optimized Reference Policy provides the lowest costs of production.
- Future studies may include more stringent constraints in the optimization model, like tighter reserve margins, emission limits or mandates for minimum or maximum technology incorporation.



Direct GHG Emissions for Each Policy under Baseline Conditions

- PIIRCE 2023 does not achieve GHG emissions targets due to its high reliance on natural gas combined cycle generation technologies.
- PIIRCE 2018 outperforms other policies in achieving emission goals, aligning with international commitments.
- The Optimized Reference Policy fails to meet GHG emission reduction targets.



Vulnerability Boxes: Summary Table for the Exploratory Analysis

Vulnerability Conditions for the Three Performance Metrics

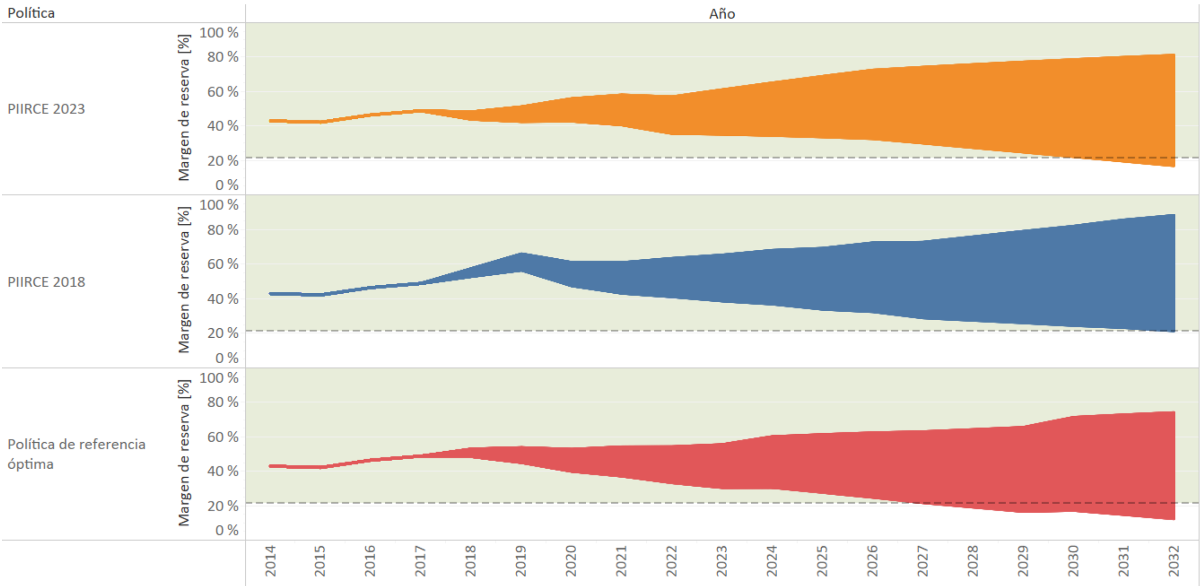
Policy	Box	Density	Coverage	Stressors' Ranges
PIIRCE 2023	Box 1	0.9963	0.6561	Demand >= 2.9 %
	Box 2	0.9000	0.2854	Carbon Tax >= 6.7 UMAs/tCO2e Natural Gas Price >= 2.3 USD/MBtu
PIIRCE 2018	Box 1	0.8900	0.7417	Carbon Tax >= 6.6 UMAs/tCO2e Natural Gas Price >= 2.1 USD/MBtu
	Box 2	0.9640	0.1607	Demand >= 3.6 %
Optimized Reference Policy	Box 1	1.0000	0.7308	Demand >= 2.8 %
	Box 2	0.9480	0.1337	Carbon Tax >= 9.6 UMAs/tCO2e Natural Gas Price >= 3.6 USD/MBtu
	Box 3	1.0000	0.0897	Demand >= 2.5 % Natural Gas Price >= 3.2 USD/MBtu

Note. Source: Own Elaboration

Reserve Margin and Direct GHG Emissions for Each Policy under Uncertain Conditions

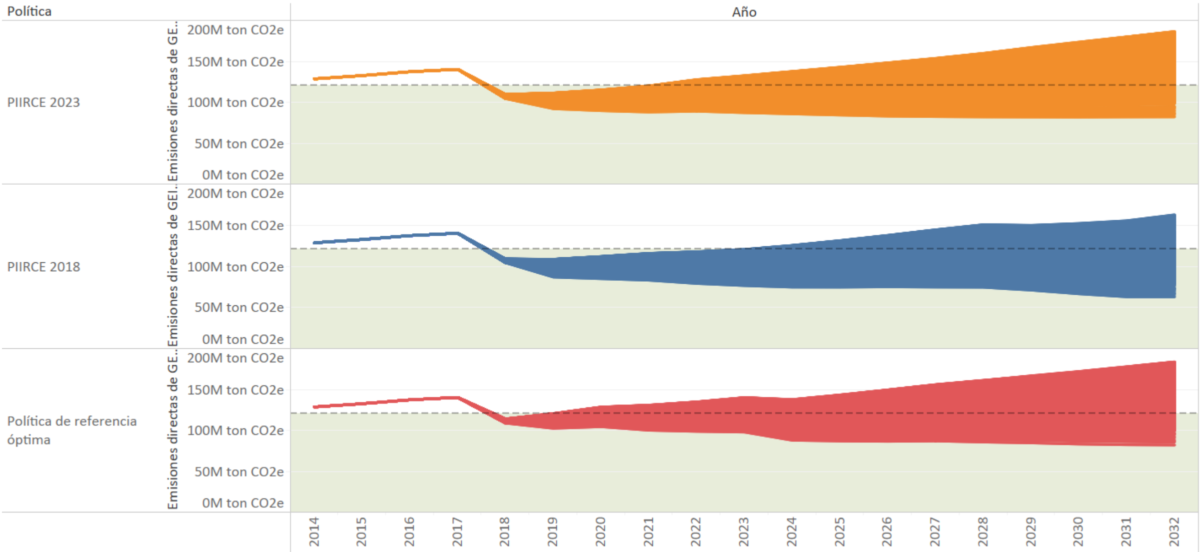
- Reserve Margin consistently meets benchmarks across nearly all scenarios for each policy analyzed.
- Direct GHG Emissions are projected to rise at most futures by 2030, with PIIRCE 2018 showing the most effective reduction compared to other policies.

Margen de reserva determinado por el análisis exploratorio y calculado a partir de la implementación de cada política, 2014-2032



La tendencia de Margen de reserva para Año desglosada por Política. El color muestra detalles acerca de Política. Se muestran detalles para Run Id.

Emisiones directas de GEI determinadas por el análisis exploratorio y calculadas a partir de la implementación de cada política, 2014-2032

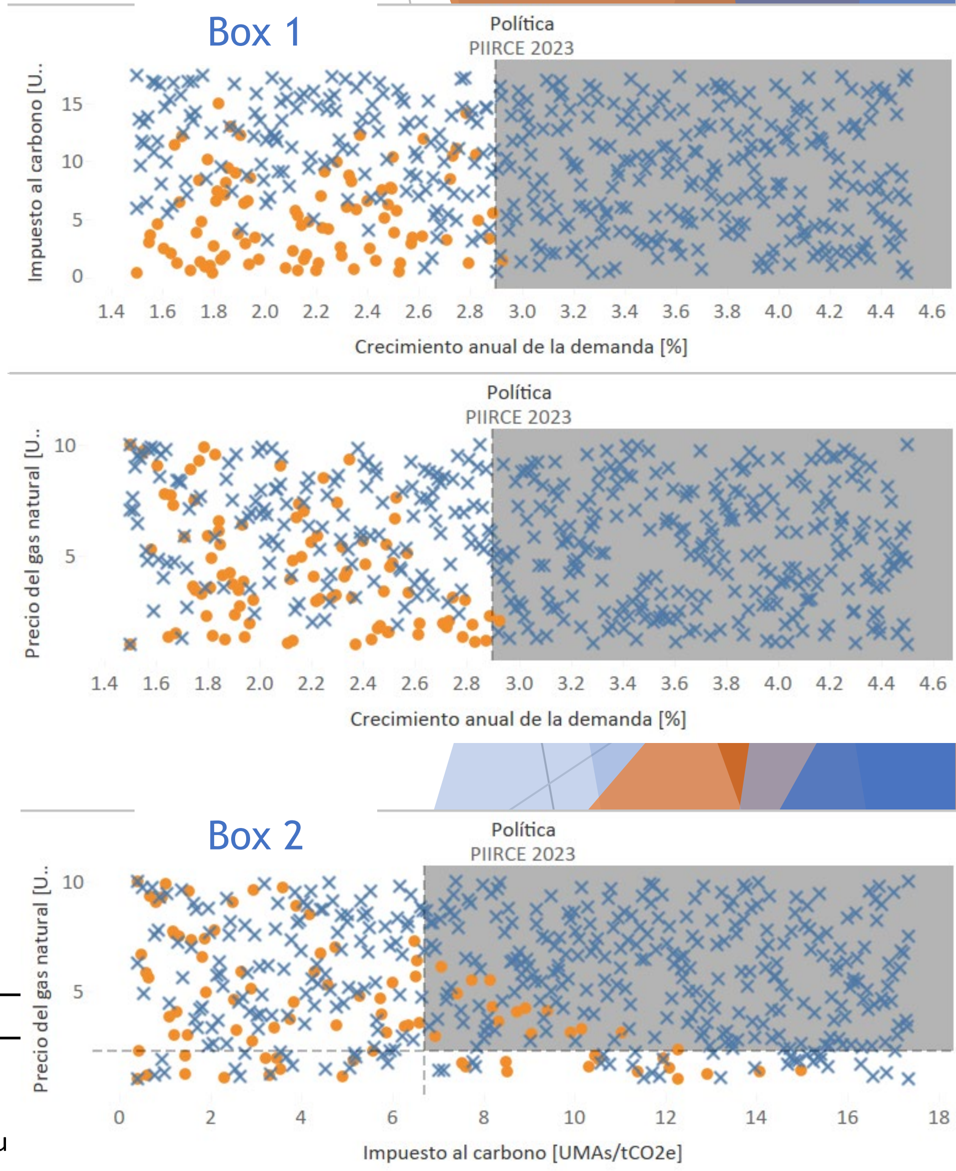


La tendencia de Emisiones directas de GEI para Año desglosada por Política. El color muestra detalles acerca de Política. Se muestran detalles para Run Id.

All Performance Metrics are met.
X At least one of the Performance Metrics is not met.

Vulnerability Conditions for PIIRCE 2023 Policy

- PIIRCE 2023 identified with two key vulnerability boxes, 94% system vulnerabilities combined.
- Primary vulnerability box (66% coverage, ~100% density) highlights risk of not meeting GHG emissions targets with >2.9% annual demand growth.
  - Policy robustness questioned with historical SEN demand growth around 3% annually.
- Secondary vulnerability box links carbon tax >6.7 UMAs/tCO2e and natural gas price >$2.3 USD/MBtu to potential cost metric failures.
  - Querétaro's carbon tax rate of 5.6 UMAs/tCO2e implies a 6.7 UMAs/tCO2e rate is possible; low gas price threshold of $2.3 USD/MBtu is likely to be surpassed.
  - Economic implications of these vulnerabilities are significant, despite their current improbability.

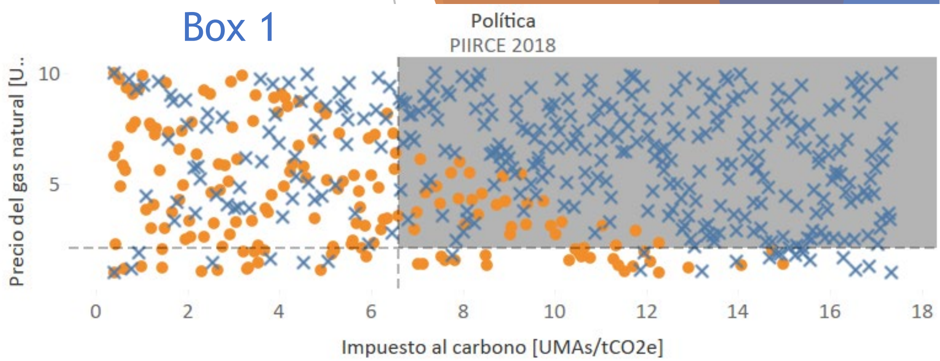


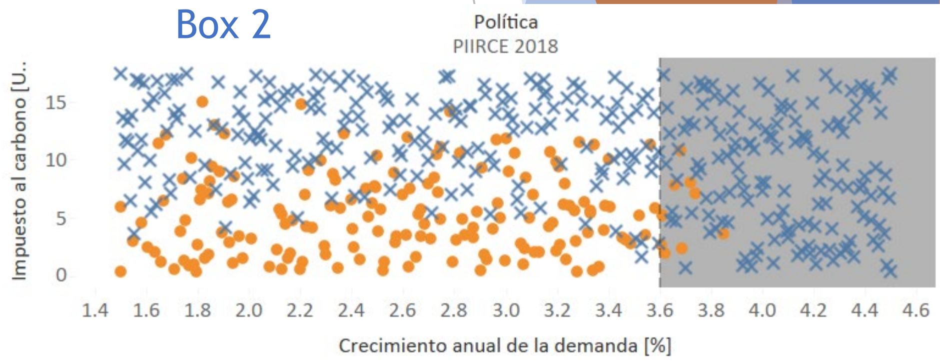
Policy	Box	Density	Coverage	Stressors' Ranges
PIIRCE 2023	Box 1	0.9963	0.6561	Demand >= 2.9 %
	Box 2	0.9000	0.2854	Carbon Tax >= 6.7 UMAs/tCO2e Natural Gas Price >= 2.3 USD/MBtu

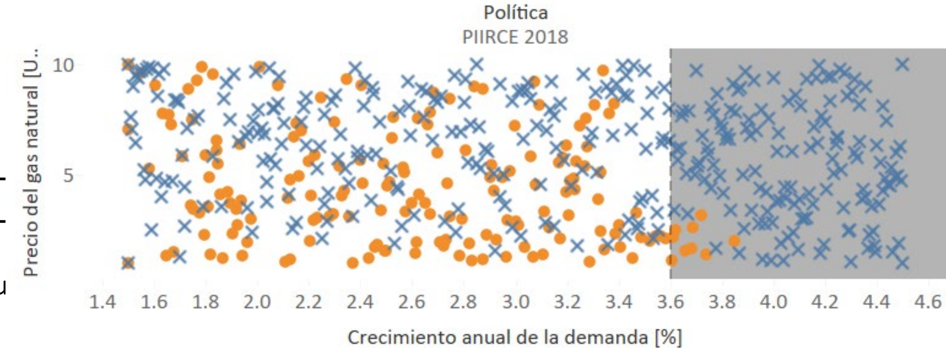
All Performance Metrics are met.
X At least one of the Performance Metrics is not met.

Vulnerability Conditions for PIIRCE 2018 Policy

- PIIRCE 2018 has two key vulnerability boxes, covering ~90% of the system's vulnerabilities.
- The primary box is particularly significant having 89% density and 74% coverage.
  - Similar to PIIRCE 2023, the first vulnerability box for PIIRCE 2018 signals potential failure in performance metrics if carbon tax exceeds 6.6 UMAs/tCO2e and natural gas prices rise above 2.1 USD/MBtu.
- The secondary vulnerability box represents 16% coverage with 96% density, less significant than the primary but still notable.
  - Suggests annual electricity demand growth exceeding 3.6% could compromise performance metrics, though such high growth is less likely, reinforcing PIIRCE 2018's robustness over PIIRCE 2023.



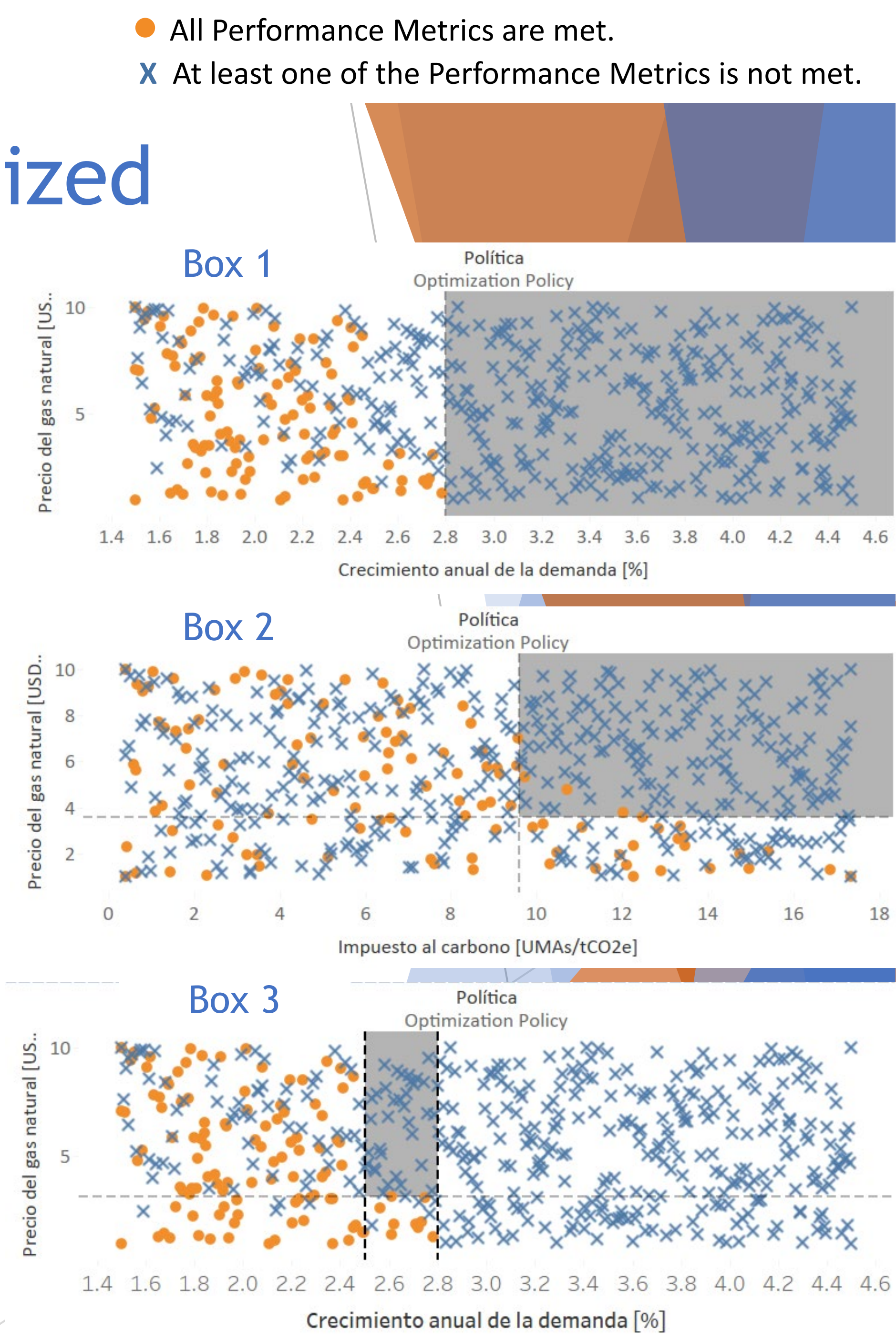




Policy	Box	Density	Coverage	Stressors' Ranges
PIIRCE 2018	Box 1	0.8900	0.7417	Carbon Tax >= 6.6 UMAs/tCO2e Natural Gas Price >= 2.1 USD/MBtu
	Box 2	0.9640	0.1607	Demand >= 3.6 %

Vulnerability Conditions for the Optimized Reference Policy

- The optimized reference policy has three vulnerability boxes, capturing 95% of system vulnerabilities.
  - Box 1 is similar to PIIRCE 2023's Box 1, with ≥2.8% annual electricity demand growth likely causing a breach in performance metrics, demonstrating sensitivity to even modest demand increases.
  - Box 2 indicates a carbon tax >9.6 UMAs/tCO2e and natural gas >3.6 USD/MBtu could risk not meeting metrics, particularly costs of production, but is considered an unlikely scenario within the current evaluation period.
  - Box 3, unique to this policy, suggests ≥2.5% demand growth with natural gas >3.2 USD/MBtu would likely result in not achieving targets, particularly impacting costs of production or emissions, with historical data showing a high probability of this situation due to usual demand growth and gas prices.



Policy	Box	Density	Coverage	Stressors' Ranges
	Box 1	1.0000	0.7308	Demand >= 2.8 %
Optimized Reference Policy	Box 2	0.9480	0.1337	Carbon Tax >= 9.6 UMAs/tCO2e Natural Gas Price >= 3.6 USD/MBtu
	Box 3	1.0000	0.0897	Demand >= 2.5 % Natural Gas Price >= 3.2 USD/MBtu

How to Identify a Robust Energy Policy?

- PIIRCE 2018 is identified as the most robust policy in the study. Elements that make this policy stand out are:
  - It has a **7% higher generation capacity** than PIIRCE 2023, enhancing system reliability and reducing the reliance on inefficient power plants.
  - The policy promotes a **diverse energy portfolio**, including combined cycle, solar, wind, nuclear, hydroelectric, and cogeneration.
  - It features a **significant inclusion of clean energy sources**, adhering to Mexican clean energy standards and minimizing greenhouse gas emissions.
- PIIRCE 2018 does not incorporate battery storage systems due to the early stages of this technology at that time, but their potential benefits should be further evaluated.

Key Takeaways for Future-Proof Energy Policies

- While the PIIRCE 2018 policy demonstrated greater resilience in the face of uncertainties, notably due to its enhanced capacity and energy mix, it has been superseded by the PIIRCE 2023 policy. The current policy's implementation raises concerns due to its potential vulnerabilities and less diverse energy portfolio, which could lead to challenges in meeting future demand and sustainability targets effectively.
- Electricity demand growth has been identified as a significant variable, influencing key performance metrics. The evolving dynamics of demand, influenced by trends such as electrification and nearshoring, underline the necessity for ongoing assessment in energy policy formulation.
- This thesis advocates for a shift in public dialogue towards optimizing the National Electric System for the greater good. Future discussions on energy management focus on evidence-based strategies that prioritize national well-being and development.
- Finally, this study proposes that the robustness of an energy policy is better measured by its ability to adapt to fluctuating conditions and maintain a reliable, affordable, and environmentally responsible energy supply.

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