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On the Economic Uncertainty and Crisis Resiliency of Decarbonization Solutions for the Aluminium Industry

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ABSTRACT

The aluminium industry emits approximately 1.1 billion tonnes of CO_2-eq annually, contributing about 2% of global industrial emissions. Decarbonization pathways aim to achieve net-zero emissions by 2050, but this requires making decisions today for technologies having lifetimes of 20 – 25 years, based on uncertain economic assumptions, particularly given the volatility of energy prices. Traditional price forecasting models often fail to anticipate major disruptions, such as the 2022 energy crisis. This work applies Monte-Carlo Analysis (MCA) to evaluate the financial stability of decarbonization pathways under energy crisis scenarios and report on the resilience of the alternative solutions. In the modelled secondary aluminium production facility, direct electrification is assumed for lower temperature furnaces of annealing heat treatments or preheating, while the study defines the decarbonization options based on the melter furnace technology, a key bottleneck in terms of load and viable technological alternatives with roof temperatures exceeding 1,000°C. In this study, four decarbonization pathways characterized by unique melting furnace solutions are analyzed, namely: an oxyfuel scenario using natural gas with carbon capture, a biomass-based approach relying on syngas, a hydrogen-based solution utilizing onsite electrolysis, and a plasma-based system with torches for melting. These options are compared to a natural gas baseline. Differences in electrification levels and reliance on imported energy sources result in varied economic resilience under price shocks that can occur during different times of the plant's life. Results obtained for a set of initial price levels at moderate or crisis energy price profiles revealed a more resilient oxyfuel scenario, followed by biomass utilization, and finally the all-electric scenarios utilizing either hydrogen or plasma. For instance, the oxyfuel option demonstrates a 54% probability of negative incremental Net Present Value (iNPV) with reference to the base case under both crisis and moderate price profiles. Conversely, the biomass scenario was found to have a 95-98% likelihood of economic loss under similar conditions while the all-electric solutions were at 100% likelihood of loss regardless of the initial price or profile. This is because electricity prices start at a higher baseline than combustible fuels and spike dramatically during crisis events. This analysis highlights the importance of considering energy price volatility and the need for diversified energy sources when developing decarbonization strategies for the aluminium industry.

Keywords: Aluminium, Decarbonization, Energy Prices, Crisis Modelling, Monte-Carlo Analysis.

INTRODUCTION

Increasing global warming effects have urged heavy industries to actively reduce greenhouse gas (GHG) emissions, targeting net zero by 2050. The aluminium sector emits approximately 1.1 billion tonnes of GHG annually, representing 2% of global industrial emissions [1]. The primary energy source for aluminium remelting furnaces is fossil natural gas; while rolling processes consume electricity whose embodied emissions depend on geographical location. Decarbonization strategies for aluminium include biomass gasification, power-to-gas, direct electrification of furnaces, and carbon capture. While most of these technologies have lifetimes of 20 – 25 years, decisions on their installment must be made during the early stages of design. Prices and future availability of utilities depend on many economic and geopolitical inter-related aspects. Another influencing value is the cost of continuing to emit GHG which could directly translate to an imposed carbon tax [2] or a defined social cost of negatively impacting the environment [3]. Hence, future uncertainty in energy prices must be accounted for in today's decisions.

Price forecasting models, while useful, are often inaccurate, failing to account for significant events like the 2022 energy crisis [4–6]. Historical data shows that predictions can significantly underestimate or overestimate actual prices due to unpredictable market factors. This is because the market is not only a function of demand and supply but is also dependent upon numerous geopolitical factors which are simply unpredictable in the long term. Nonetheless, prices are a major influencing factor on decision-makers' choices towards industry decarbonization, which necessitates the development of a systematic methodology to deal with such uncertainty.

Monte-Carlo analysis (MCA) is a stochastic mathematical technique for global sensitivity and risk or uncertainty evaluations. It is mainly used to quantify the simultaneous impact of various parameters on a performance indicator using hundreds of thousands of model inputs. One study used MCA to explore decarbonization strategies in the steel industry [7]. The authors used MCA to examine the effects of factors such as hydrogen prices, the investment costs of reduction furnaces, and associated emissions on the adoption of hydrogen in steel production. Their analysis identified hydrogen price as the most critical factor. Similarly, another study evaluated the impact of natural gas price uncertainty on the economic feasibility of offshore power hubs with carbon capture systems for Floating Production, Storage, and Offloading facilities (FPSOs). By generating stochastic price profiles, the researchers calculated incremental net present values (iNPVs) for various configurations and found that profitability was highly sensitive to operational delays, as longer delays increased the likelihood of losses due to opportunity costs and depreciation [8]. Similarly, MCA could be used in evaluating the economic stability of different decarbonization configurations developed for the aluminium industry. In this regard, this work adopts stochastic and deterministic methodologies to more accurately model the effect of energy price uncertainty, especially during times of economic crisis, on potential decarbonization pathways for secondary aluminium production. The work integrates Process Systems Engineering (PSE) methodologies by combining mixed-integer linear programming (MILP) with MCA to evaluate uncertainty in industrial energy systems. The developed framework provides a systematic approach for assessing economic risk in decarbonization pathways, offering a decision-support tool based on PSE principles for process optimization under uncertainty.

METHODS

The methodology developed in this work starts by modeling a typical secondary aluminium production plant and a set of energy conversion systems associated with different decarbonization pathways within the OSMOSE platform [9]. Herewith, a MILP optimization approach is applied to generate a list of optimal system configurations under specified economic scenarios using a defined set of current energy price levels. Finally, MCA is performed to estimate the probability of each solution incurring higher costs than the base case over a 25-year lifetime, incorporating random price fluctuations and crisis-like price profiles. This hybrid deterministic-stochastic approach aligns with PSE methodologies, enabling more robust decision-making in the face of industrial uncertainties.

First, a typical secondary aluminium production process is modeled based on Novelis' production facility in Sierre, Switzerland, consisting of a cast house, and a rolling mill for subsequent treatment and coil rolling [10]. The process begins with preheating pure aluminium ingots to around 250°C in the preheater, to prevent explosion risks during melting, this step accounts for approximately 5% of the plant's total natural gas consumption. In the melter, where around 49% of the facility's natural gas is consumed, pure and scrap aluminium are melted at approximately 660°C and then superheated to 700°C. The holder furnace, which uses 4% of the plant's natural gas, acts as a buffer for the direct chill casting (DCC) process, where the aluminium solidifies gradually by dissipating heat into a water sink. The cast ingots undergo surface treatment before being sent to the pusher furnace for annealing, which consumes 25% of the plant's natural gas, followed by hot and cold rolling processes. Finally, the coils are subjected to further heat and chemical treatment in the annealing continuous line (ACL), which accounts for 17% of the natural gas consumption. While conventional facilities rely on fossil natural gas to fuel these furnaces, several decarbonization alternatives can be explored, utilizing diverse energy sources. This work evaluates several of these alternatives. A simplified schematic of the potential decarbonization options is presented in **Figure 1**. The energy conversion technologies and furnaces were modeled in detail using software tools such as Aspen Plus®, supplemented by data from industrial system audits and commercial technology specifications. All optimized scenarios, except the base case, employ fixed electrification solutions for the preheating, annealing, and holding furnaces. Thus, the optimization focuses on the melter furnace, identified as the technological bottleneck in decarbonizing secondary aluminium production. The following scenarios define the range of solutions explored:

1. **Base Case:** This represents the current baseline operation of the plant, where all furnaces rely on fossil natural gas combustion.
2. **Oxyfuel CCS:** Implements an oxyfuel combustion system for the melter furnace, where natural gas is burned in oxyfuel burners, followed by post-combustion carbon capture and sequestration through transportation and injection. Oxygen for the process is supplied by an on-site air separation unit (ASU).
3. **Bio-Syngas:** Utilizes oxyfuel combustion of bio-syngas, a mixture of CO, H_2, and CO_2 gases, produced via on-site biomass gasification for the melter furnace. Oxygen is supplied using an on-site ASU.
4. **Hydrogen:** Employs air combustion of hydrogen in the melter furnace, with hydrogen generated on-site using a proton exchange membrane (PEM) electrolyzer.
5. **Plasma:** Adopts an electric aluminium melting solution using plasma torches for the melter furnace, with nitrogen plasma gas supplied via an on-site ASU.

This structured approach ensures that each decarbonization pathway addresses the specific challenges posed by the melter furnace while considering diverse energy resources and technologies.

Furthermore, MCA is applied to assess the economic feasibility of these defined decarbonization pathways for aluminium production compared to the natural gas-based baseline (Base Case). Two modes of price evolution are modeled: moderate price trends, representing natural market fluctuations, and crisis scenarios, simulating sudden price spikes followed by gradual recovery. An example of the generated price profiles is illustrated in Figure 2 (moderate trends) and Figure 3 (crisis scenarios).

Table 1: Initial energy prices and crisis mode multipliers

Resource	Initial Price	Peak multiplier
Natural gas	0.04 (€/kWh)	7
Electricity	0.10 (€/kWh)	3
Biomass	0.06 (€/kWh)	3
CO_2 tax	100 (€/tCO_2)	N/A

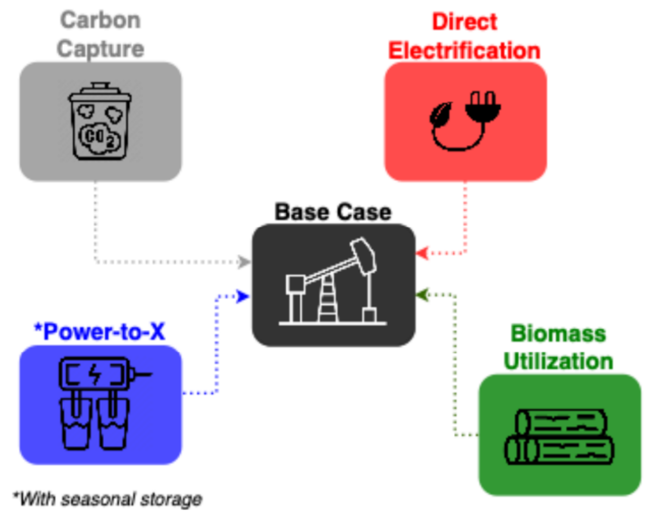

Figure 1. Simplified schematic of aluminium decarbonization scenarios investigated in this work.

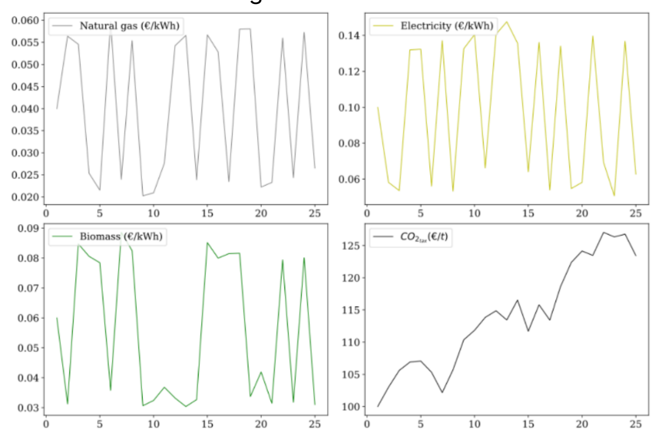

Figure 2. MCA sample of a set of stochastic energy price profiles over a lifetime of 25 years.

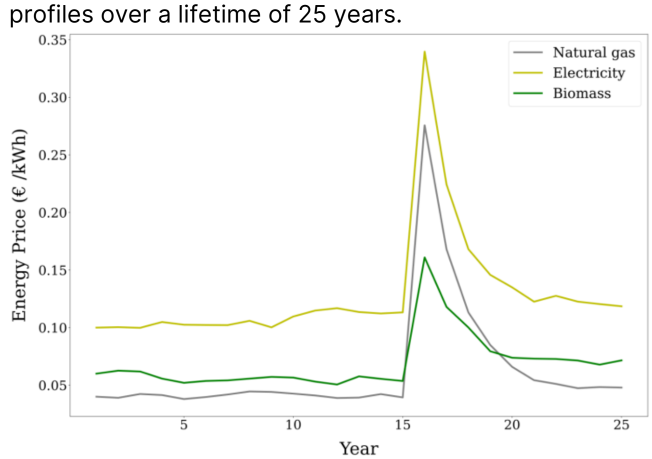

Figure 3. MCA sample of a set of energy price shock profiles over a lifetime of 25 years.

Initial Price Trends and Profiles

The simulation begins by defining initial energy and commodity prices for key resources, as shown in Table 1.

Next, price evolution is modeled as follows:

1. **Moderate Price Trends:** Prices fluctuate annually based on a normal distribution with a 5% standard deviation around the previous year's price. These profiles represent natural market dynamics without major disruptions and are shown in Figure 2.
2. **Crisis Scenarios:** A random crisis year is selected between years 2 and 20. During this year, prices experience sudden spikes, defined by resource-specific peak multipliers. Prices then gradually stabilize post-crisis at levels 20% higher than the initial price. An example of these crisis-induced profiles is illustrated in Figure 3.

The price profiles in this study are generated using pseudo-random numbers sampled from statistical distributions implemented by Python's NumPy random number generator. The following equations provide more insight into how the profiles are generated:

- **Moderate Trends:**

$$P_y = P_{y-1} \cdot (1 \pm random\ variation) \quad (1)$$

In this case, the random variation is sampled from the range defined by `varin=(0.3, 0.5)`, representing deviations of 30% to 50% of the initial or previous year's price. This range ensures variability while maintaining realistic fluctuations in the moderate trend profiles. Additionally, for each resource price profile, a trend probability parameter (P_{trend}) determines the likelihood of following a predefined trend. In the current simulation, $P_{trend} = 0.5$, meaning there is a 50% probability that the price will follow the specified trend ("up," "down," or "none"). The remaining 50% of the time, prices deviate randomly, ensuring variability in the generated profiles.

- **Crisis Mode:**

○ Pre-crisis:

$$P_y = P_{y-1} \cdot Normal\ (1, 0.05) \quad (2)$$

Smaller fluctuations in prices before the crisis are modeled using random multipliers sampled from a normal distribution $Normal\ (1, 0.05)$, which ensures prices fluctuate around the previous year's value with a mean of 1 and a standard deviation of 0.05, reflecting natural market variability.

○ Crisis year:

$$P_y = P_{y-1} \cdot Peak\ multiplier \quad (3)$$

During the crisis year, prices experience sharp spikes, modeled using predefined peak multipliers (e.g., 7 for natural gas, 3 for electricity, and 2 for biomass).

○ Post-crisis:

$$P_y = P_{y-1} - (P_{y-1} - P_{post-crisis}) \cdot Decline\ Rate \cdot Normal\ (1, 0.05) \quad (4)$$

After the crisis, prices gradually stabilize toward a defined post-crisis level, calculated as a fixed percentage above the initial price (e.g., 20% higher, as set in this simulation). The decline rate, set to 0.5, in this case, controls how quickly prices approach the post-crisis level.

Cost Calculation and NPV Evaluation

For both modes, the Base Case and decarbonization scenarios are evaluated as follows for the defined parameters listed in Table 2:

1. **Annual Cost Profiles:**
   - Resource costs (natural gas, electricity, etc.) are multiplied by respective consumption flows to calculate operational expenses (OPEX).
   - Capital expenditures (CAPEX) are distributed as 60% in the first year and 40% in the second year.
2. **Net Present Value (NPV):**
   - Total Expenditures ($TOTEX_y$) include CAPEX and OPEX for each year.
   - Discounted cash flows are calculated using:

$$NPV = \sum_{y=1}^{N} \frac{TOTEX_y}{(1+i)^y} \quad (5)$$

   where $i = 6\%$ is the discount rate.
3. **Incremental NPV (iNPV):**
   - $iNPV = NPV_{decarb} - NPV_{base\ case}$
   - The likelihood of loss ($iNPV < 0$) is calculated over 10,000 Monte Carlo iterations.

Table 2: Simulation settings for both moderate and crisis modes

Parameter	Value
Discount rate (i)	6%
Plant lifetime (N)	25 years
Annual Operating hours	8,760 h
Monte-Carlo iterations	10,000

By combining moderate and crisis price profiles, the approach quantifies the economic stability of decarbonization pathways, highlighting the influence of market volatility and extreme price shocks on incremental net present value. This dual-mode simulation provides a probabilistic framework for decision-making under uncertainty.

RESULTS

First, the performance of the defined decarbonization routes is assessed relative to the Base Case. **Figure 4** illustrates the energy load distribution and the equivalent carbon footprint (including scope 1 and 2 emissions) for the various alternatives. Among the scenarios, the

Bio-Syngas route achieves the lowest carbon footprint, at approximately -2.80 $kgCO_2/tAl$, due to the net-negative impact of sequestering biogenic carbon used in the melter furnace. The all-electric options result in a footprint of around 30 $kgCO_2/tAl$, primarily driven by the indirect emissions associated with the electricity grid. In contrast, the Oxyfuel CCS scenario has slightly higher emissions, at approximately 55 $kgCO_2/tAl$, which is attributed to both indirect electricity emissions and loss of some direct CO_2 during furnace operation prior to capture.

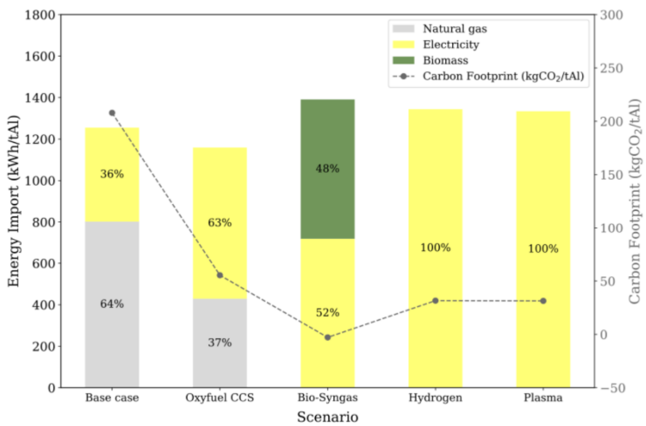

Figure 4. Energy load distribution and equivalent carbon footprint of aluminium decarbonization options.

Next, the iNPVs of the different scenarios are evaluated for both moderate and crisis price fluctuations over 10,000 Monte-Carlo samples and the resulting distributions are plotted in **Figure 5**. It is evident that moderate price fluctuations generally result in broader iNPV ranges than crisis price profiles while the average iNPV value for both modes is observed to be similar. The Oxyfuel CCS is the least economically volatile solution at a 54% likelihood of loss regardless or moderate or crisis modes, followed by the Bio-Syngas option at around 95-98% likelihood of loss. Both electrification solutions are significantly negative in terms of iNPVs with reference to the natural gas driven base case. With a 100% likelihood of loss quantifying the economic risk associated with complete electrification.

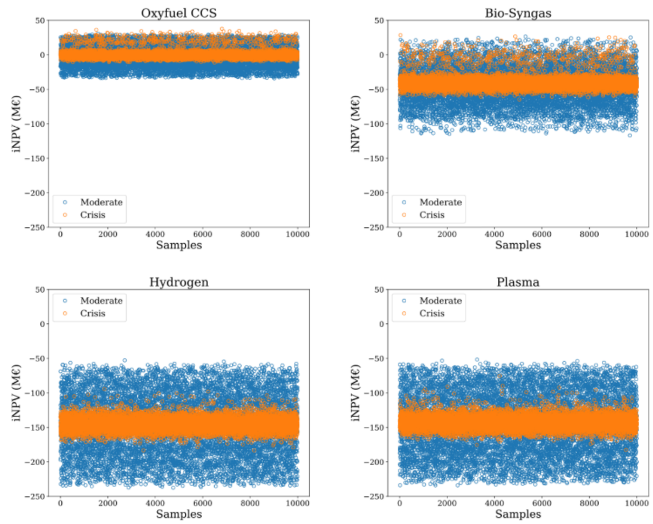

Figure 5. Resilience comparison of the decarbonization options in case of moderate or crisis price profiles.

To better understand the statistical distribution of iNPV results, **Figure 6** presents a box plot of iNPVs for the different decarbonization scenarios, highlighting the variability under moderate and crisis conditions. The boxes represent the interquartile range (IQR), while data points outside the whiskers, calculated as values smaller than Q1−1.5×IQR or larger than Q3+1.5×IQR, are considered outliers and plotted as dots. The outliers observed in the iNPV distributions, particularly under crisis scenarios, are closely linked to the timing of energy price spikes and their impact on operational costs. Both higher-than-average and lower-than-average outliers tend to occur when the crisis happens early in the project lifetime, specifically in Year 2. This timing coincides with a period where discounting effects are less pronounced, which intensifies the influence of energy price volatility on economic performance outcomes. The exact reasons for the dual behavior, positive and negative outliers, remain complex and may depend on several factors, including the severity of the spike, the recovery rate of energy prices, and other influential aspects. This result, however, highlights Year 2 as a critical period where energy price dynamics have an exaggerated impact on iNPV.

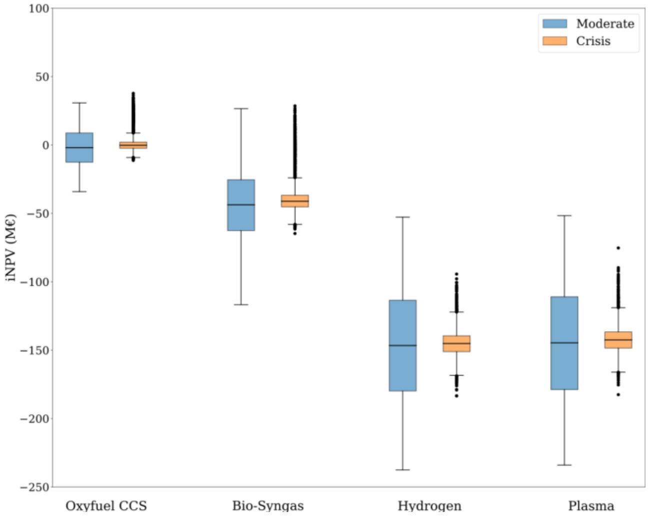

Figure 6. Box plot distribution of the likelihood of loss results for the decarbonization options.

Due to the apparent coupling of natural gas and electricity prices the economic risk for the Oxyfuel CCS solution seemed to remain constant at 54% for a fixed set of initial energy prices no matter the mode of energy price profiles (moderate or crisis). Hence, a sensitivity analysis over the likelihood of loss when varying initial prices of electricity and CO_2 tax was conducted following moderate price fluctuations. From **Figure 7**, it is seen that the breakeven initial CO_2 tax for this solution increases from around 170 €/tCO_2 for cheaper electricity (at an initial price of 0.1 €/kWh$_{EE}$) to 380 €/tCO_2 at double the initial electricity price following a directly proportional correlation.

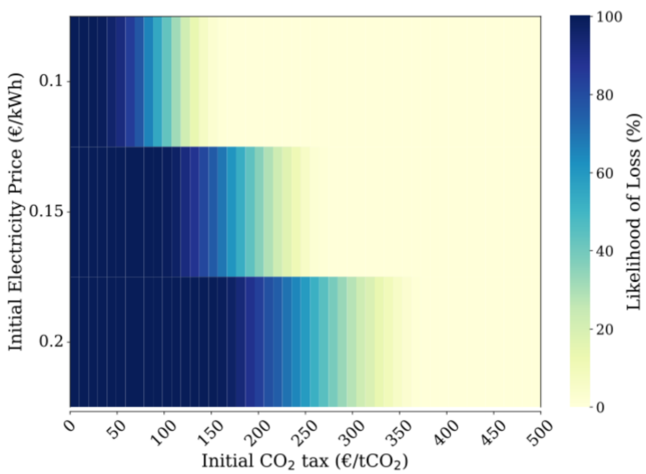

Figure 7. Economic risk of the Oxyfuel CCS configuration as a function of the initial values of CO_2 tax and electricity price.

CONCLUSION

This study highlights the critical role of economic uncertainty and energy price volatility in shaping the viability of decarbonization pathways for secondary aluminium production. By combining Monte Carlo Analysis with mixed-integer linear programming, the work leverages PSE tools to provide key insights into the resilience of various technological configurations under moderate and crisis scenarios. The findings emphasize that decarbonization strategies heavily reliant on electricity are particularly vulnerable to price shocks, leading to a 100% likelihood of economic loss compared to the natural gas baseline. In contrast, the Oxyfuel CCS scenario exhibits greater economic resilience, maintaining a constant 54% likelihood of loss across both modes of price evolution, suggesting its potential as a transitional pathway. However, these conclusions must be taken with caution as they are heavily influenced by the low initial natural gas price of 0.04 €/kWh, mainly due to fossil subsidies, which currently makes it a more economically favorable energy source. If renewable electricity becomes significantly cheaper in the future, the relative economic performance of electrification-based solutions could improve, shifting the results of this comparative evaluation. This work provides a probabilistic framework to guide policymakers and industry stakeholders in navigating market uncertainties and emphasizes the importance of preparing diversified and adaptive decarbonization strategies.

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