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Decarbonization in the European steel industry: Strategies, risks, and commitments

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ABSTRACT

This paper investigates the challenge of decarbonizing the steel industry, a pillar of the global economy but also a major carbon emitter. Analyzing current decarbonization strategies, their effectiveness, and the role of corporate commitment and risk management offers insights needed to identify development paths in the current environment characterized by pressure driven by stringent environmental standards and fierce competition. An empirical approach, including a survey model and simulation, is used to answer prominent research questions. Aspects such as the influence of environmental and governance criteria, specific initiatives that can be undertaken, the importance of corporate commitment, and the integration of risk management into strategic planning are examined. Simulations suggest that the probability of meeting the 2030 goals range from 65.08 to 75.98 percent and the delta between low and high commitment ranges from 4.917 to 4.133 percent according to the share of renewables in the energy mix decarbonization. The influence of the energy mix is also included in the analysis. The research highlights the need for greater coordination and commitment across the industry to improve decarbonization efforts. It emphasizes the critical role of government policies and market dynamics in shaping industry actions toward achieving decarbonization goals. The findings contribute to understanding decarbonization processes, offering insights and guidance for the steel sector's transition to a low-carbon economy.

Introduction

Limiting global warming to 1.5° will require significant reductions in greenhouse gas emissions (GHG) in the short term. According to IPCC estimates, GHG should decrease by 43 % by 2030 and 60 % by 2035 compared to 2019. A prominent role can be played by the steel industry, a key pillar of the global economy, that is simultaneously a major carbon emitter. Decarbonization in this sector is a challenge and crucial opportunity to align with international environmental goals (Rübbelke et al., 2022).

The industry has adopted a facet of decarbonization strategies aimed at reducing greenhouse gas emissions, including significant investments in energy efficiency (Pardo and Moya, 2013), increasing self-generation of renewable energy along with electrification of industrial processes (Lopez et al., 2023), testing emerging cleaner technologies (Öhman et al., 2022), and monitoring and participating in carbon offsetting projects (Cheng et al., 2023). The transition to cleaner steel production is nevertheless hampered by several challenges, including internal factors such as financial constraints, the required know-how, competencies, and commitment to design strategies (Johnson et al., 2023), and external factors such as the energy mix (Hassan et al., 2024) and global climate agreements.

Previous literature has identified drivers of and barriers to the decarbonization of the steel industry. Drivers embracing technological solutions such as carbon capture and storage (CCUS), electrification, and fuel switching have been identified as prominent (Luh et al., 2020; Toktarova et al., 2020). In addition to technological changes, broader sociotechnical transitions, including changes in user behavior, culture, policy, industry strategies, and infrastructure, are essential for the transition to deep decarbonization (Wesseling et al., 2017). The literature emphasizes the role of policy options, sociotechnical systems, and behavioral energy efficiency in driving decarbonization efforts (Kim et al., 2022; Ponce de Leon Barido et al., 2018). Symmetrically, barriers to decarbonization include the lack of understanding of effective strategies for future deep decarbonization in the steel industry, potential implications of carbon pricing (Beccarello and Di Foggia, 2023), and economic biases such as the overestimation of technology mitigation potential and underestimation of costs (Åhman et al., 2016; Wen et al.,

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2023).

Unprecedented challenges have emerged prompted by the Environmental Social and Governance criteria (ESG), 2050 decarbonization targets (Vieira et al., 2021), global competitive pressure, and environmental policies based on carbon pricing market-based mechanisms such as the European Emission Trading System (ETS) (Presno et al., 2021), the carbon border adjustment mechanism (CBAM) (Rossetto, 2023), and market and regulatory compliance associated with decarbonization (Bashir et al., 2024; Kumar et al., 2024).

Consequently, in today's business environment, a research gap on how to forge efficient strategies and avoid strategic drifts has gained momentum. This article fills this gap by empirically examining effective strategies through a holistic approach that considers decarbonization strategies and managing associated risks, e.g. exogenous such as evolution of national policies, managerial, market, regulatory, or technical ones, providing a comprehensive analysis that can effectively guide decisions.

This paper explores critical research questions related to the effective implementation of decarbonization strategies. The first is the current state of the art regarding ESG criteria and decarbonization commitment (RQ1). The hypothesis is that while the industry progresses, it does so heterogeneously, suggesting that better coordination could yield shared benefits. Next, the paper delves into the specific initiatives that firms can adopt to effectively enhance their decarbonization strategies (RQ2). Here, the hypothesis is that common patterns exist within the industry and can be leveraged to improve the efficacy of decarbonization strategies in diverse firms. Another critical aspect is the role of commitment in the decarbonization process (RQ3). It is hypothesized that measurable commitment, adequate training, and vision are crucial for successfully implementing decarbonization strategies, potentially reducing outcome uncertainty. This study also focuses on how firms can optimize their decarbonization strategies by applying identified cross-industry levers to increase the expected outcome (RQ4) because incorporating risk assessment for each decarbonization initiative enhances the strategies' effectiveness and reduces the uncertainty of outcomes. Finally, the market and regulatory compliance risks associated with decarbonization strategies (RQ5) are explored. The hypothesis is that applying appropriate risk management decision tools can significantly influence the implementation of strategies, leading to improved strategic planning and limiting the risk of strategic drift.

A methodological approach divided into four main phases was adopted, starting by analyzing the available information and data collected through interviews to assess the ESG situation. The survey follows the definition of KPIs and is based on European objectives and the guidelines of the national steel industry to measure progress in sustainability. The third phase involves analyzing the risk management that can influence decarbonization strategies. Finally, considering the identified risks, this study implements an algorithm-based simulation to support strategic decisions. This approach combines qualitative and quantitative analyses to guide organizations toward sustainable choices.

This study analyzed the interaction effect between corporate commitment and the national political context on the decarbonization process in the steel sector. The results indicate a direct correlation between the level of corporate commitment to decarbonization and the expected outcome, together with a reduced impact on uncertainty. firmsThis analysis highlights the importance of synergy between government policies and corporate actions, highlighting how a collaborative and integrated approach is fundamental for an effective and low-risk transition to a low-carbon economy.

The remainder of this article is organized as follows: the literature review focuses on decarbonizing the steel industry, exploring the strategies adopted, the associated risks, and the key factors driving this process. A description of the methodology follows. Next, the results are presented along with a simulation developed to analyze a broad spectrum of risks associated with these decarbonization processes to identify and reduce them. The conclusions follow. This analysis aims to provide a comprehensive and practical framework that can assist steel firms in transitioning toward more sustainable practices, balancing economic needs with environmental and social responsibilities.

Literature review

The steel industry plays a significant role in global carbon emissions (Rynikiewicz, 2008). The industry's impact on carbon emissions is evident in regions with substantial steel production, energy consumption, and carbon emissions (He et al., 2020). Consequently, the environmental sustainability of the steel industry is a growing concern (Goyal et al., 2018; Goyal and Routroy, 2021), and unsurprisingly, efforts to reduce carbon emissions in the steel industry have been investigated, highlighting the potential for emission reductions by 2030 (Kuramochi, 2016). Similarly, research indicates that emissions have entered a peak period, making it necessary to meet the 2030 agenda goals (Wang et al., 2023). Decarbonization drivers have been studied in Europe, considering the European Green Deal and decarbonization targets (Di Foggia and Beccarello, 2024) and Government policies have been recognized as crucial factors in promoting the use of clean energy and stimulating sustainability in the steel industry (Goyal and Routroy, 2021).

The environmental impact of this industry also involves high resource consumption and the generation of industrial byproducts (Long et al., 2016; Nguyen et al., 2021). The role of scrap recycling in reducing emissions in steel plants suggests a commitment to the industry's focus on emission reduction strategies (Sahoo et al., 2019) considering the benefits of steel scrap recycling in achieving a circular economy and reducing carbon emissions (Broadbent, 2016).

Low-carbon technologies and integrated renewable energy have been explored to address these challenges, reduce emissions, and improve energy efficiency (Liu et al., 2021). In addition, the application of green technologies has been identified as a means by which the steel industry can adapt to environmental requirements and gain a competitive advantage (Wang et al., 2022).

Decarbonizing the steel industry is critical to addressing climate change, given the significant impact of steelmaking on global carbon emissions (Tian et al., 2018). Deep decarbonization is essential for meeting the 2050 emission targets because it requires an accelerated transition in energy-intensive processing industries (Wesseling et al., 2017). To achieve climate neutrality, the industry must develop new business models and make maximum contributions to industrial decarbonization (Axelson et al., 2021). In addition, global steel scrap flows and their recycling can significantly contribute to the decarbonization efforts of the global steel industry (Cai et al., 2023).

Technoeconomic and environmental assessments of decarbonized fossil-intensive industrial processes and the phasing out of blast furnaces are deemed essential for achieving global climate goals (Cormos et al., 2020; Vogl et al., 2021). Electrification has been identified as a crucial strategy for minimizing carbon emissions in the steel industry (Kleinekorte et al., 2022; Lechtenböhmer et al., 2016), and low-emission steelmaking technologies are critical for achieving the expected level of emission reduction to effectively address climate change (Jahanshahi et al., 2016).

The global demand for green steel is critical for transitioning to sustainable, low-carbon industrial practices. Several factors contribute to the forecast of green steel demand by 2050. The transition to deep decarbonization is essential for meeting emission targets, and the steel industry is expected to play a significant role in this transition (Wesseling et al., 2017).

Steel demand is expected to double by 2050, with the steel industry generating a substantial portion of global emissions (Cullen et al., 2012). To address this, the industry is expected to transform, with the potential to contribute to decarbonization goals through industrial carbon capture and storage (Tian et al., 2018). The forecast of global steel demand in 2050 is influenced by several factors, including the transition to a circular economy and the role of stocks in the steel cycle (Pauliuk et al., 2011).

The transition to green steel production involves higher costs due to the adoption of alternative production technologies. For example, it has been estimated that green steel production could be 20–30 % more expensive than conventional steel production because of the higher costs of alternative production technologies (Muslemani et al., 2021).

The integration of renewable energy sources to obtain green hydrogen significantly determines green steel production costs (Cavaliere et al., 2021). In addition, reducing blast furnaces to meet global climate goals is a complex consideration that can affect production costs (Vogl et al., 2021).

The literature has highlighted the impacts of cost increases in the steel sector on costs and prices further up the product chain, underscoring the interconnected nature of cost implications within the sector (Rootzén and Johnsson, 2016). Various factors, including environmental awareness and political support, influence the market acceptance of green steel products. Studies have highlighted the importance of creating markets for green steel products and the challenges associated with decarbonizing steel production (Muslemani et al., 2021). Green product adoption is critical for environmental sustainability, and the marketing literature emphasizes the importance of green product adoption in promoting sustainable practices (Wan and Ha, 2021). In addition, a study on consumer adoption of green products has emphasized the role of cultural values and consumer awareness as enablers of green product adoption (Nath et al., 2013).

Market creation policies can support the global diffusion of low-emission primary steel production, highlighting the role of policy in shaping the market reception of green steel products (Vogl et al., 2020). The economic and environmental impacts of a technological shift toward hydrogen-based solutions for steel production have been studied, shedding light on the potential implications for market reception and adoption of green steel production technologies (Conte et al., 2022). The impact of green product knowledge on green purchase intentions was explored, emphasizing the role of consumer awareness in driving green product adoption (Haider et al., 2020). Finally, environmental legitimacy through green product adoption and its effect on brand value have been studied, indicating the potential impact of green product adoption on market reception (Hashem, 2021).

Another corpus of literature refers to the impact of emissions trading schemes and CBAM on the European steel industry, given that the impact on firms (Martin et al., 2016) covered by the system is recognized. The potential for carbon leakage has been a concern for energy-intensive industries (Acar et al., 2021), and concerns have been raised about the effectiveness of the European emission trading system (in addressing carbon leakage and its impact on the competitiveness of the European steel industry (Monjon and Quirion, 2011). The CBAM intends to address carbon leakage by imposing a carbon price on imported goods from specific sectors, including steel,. This mechanism creates a level playing field for European and foreign producers (Bravo Gallegos et al., 2022). However, the impact of CBAM on international trade and its role in addressing carbon leakage have also been discussed (Huang et al., 2022) even if the literature is still limited. The introduction of the mechanism is expected to have significant implications for international trade relations and the steel industry's economic performance (Korpar et al., 2022). In addition, the potential impact of CBAM on the economic performance of the steel industry has been the subject of analysis, with a focus on its implications for international trade and economic competitiveness (Ulanov and Skorobogatko, 2022), considering various design options for reforming the ETS and addressing carbon leakage (Ismer et al., 2020). Its implications for established business models in the European steel industry have also been the subject of analysis, focusing on its potential to disrupt existing trade relationships and economic sustainability (Chupina, 2022).

It is evident that the feasibility of investing in renewable energy plants increases and may reduce problems arising from the adoption of renewable energy sources in steel production, which may have significant cost implications for final demand (Khalid et al., 2021; Wall et al., 2021).Integrating renewable energy into production processes has been associated with efforts to reduce energy costs and carbon emissions, highlighting the potential economic benefits of renewable energy adoption (Materi et al., 2021). However, the adoption of renewable energy technologies varies widely by product type, indicating the complexity of cost implications in different applications (Anderson and Moncaster, 2023). In addition, the economic feasibility of floating offshore renewable energy facilities has been evaluated, emphasizing the financial considerations associated with renewable energy projects (Castro-Santos and Filgueira-Vizoso, 2019).

The potential for reducing carbon emissions by integrating renewable energy and hydrogen into the production process has also been analyzed, indicating the importance of renewable energy adoption in addressing environmental concerns and production costs (Otto et al., 2017). In addition, the role of renewable energy in reducing energy costs and carbon emissions through energy flexibility in production systems has been highlighted, emphasizing the potential for cost savings and environmental benefits (Materi et al., 2021).

A prominent topic in decarbonization strategies is the scope of related measures. Scope 1 emissions from the steel industry contribute significantly to its carbon footprint [68]. In addition, Scope 2 emissions from the steel industry, particularly from electricity and heat use, are crucial to understanding the indirect environmental impact of these emissions (Alves de Novaes Gomes et al., 2022). Although not analyzed in this article, the role of Scope 3 emissions is also worth noting (Hertwich and Wood, 2018).

Finally, the role of carbon credits and offset systems in the steel industry is worth introducing. These mechanisms allow industries to offset carbon emissions by investing in projects that reduce or remove carbon emissions (Quader et al., 2015). In addition, another study (Rootzén and Johnsson, 2016) explored the costs of reducing carbon emissions from the steel industry, examining the downstream impacts of carbon pricing and investments made in carbon reduction in the steel industry and emphasizing the importance of carbon offsetting. as part of the industry's decarbonization efforts.

Contextual background

This paper should be contextualized in the European context, particularly on two macro trends functional to achieving climate neutrality by 2050 (Vieira et al., 2021). First, it is essential to consider the evolution of the European Union Emissions Trading System (ETS), the primary policy tool used to reduce carbon emissions, which the CBAM has recently complemented to counteract the phenomenon of carbon leakage in sectors most exposed to global competition (Bellora and Fontagné, 2023). The CBAM will gradually replace free allowances until they are eliminated. Starting in 2026, when the CBAM becomes fully operational, the free allowances will be reduced, as shown in Table 1.

Scope

This study focuses on electric arc furnace (EAF) technology even though steel can be principally made via the last furnace–basic oxygen furnace (BF-BOF) and the EAF routes. Fig. 1 contains a European perspective in the pie sub chart. In contrast, the histogram shows a breakdown of EAF technology by country.

This paper is better suited to the EAF case because of the role of electricity consumption in such technology.

National energy and climate plans (NECP) targets

In the simulation and regression analysis, 17 European countries were included, excluding Luxembourg, because of a lack of updated data. Given the determinants of innovation in energy-intensive industries, the role of energy policies in influencing decision-making has

Table 1
Trend of free allowances within the European ETS.

	2026	2027	2028	2029	2030	2031	2032	2033	2034
Free allowances	97.5	95	90	77.5	50.5	39	26.5	14	0

Data in percentage.

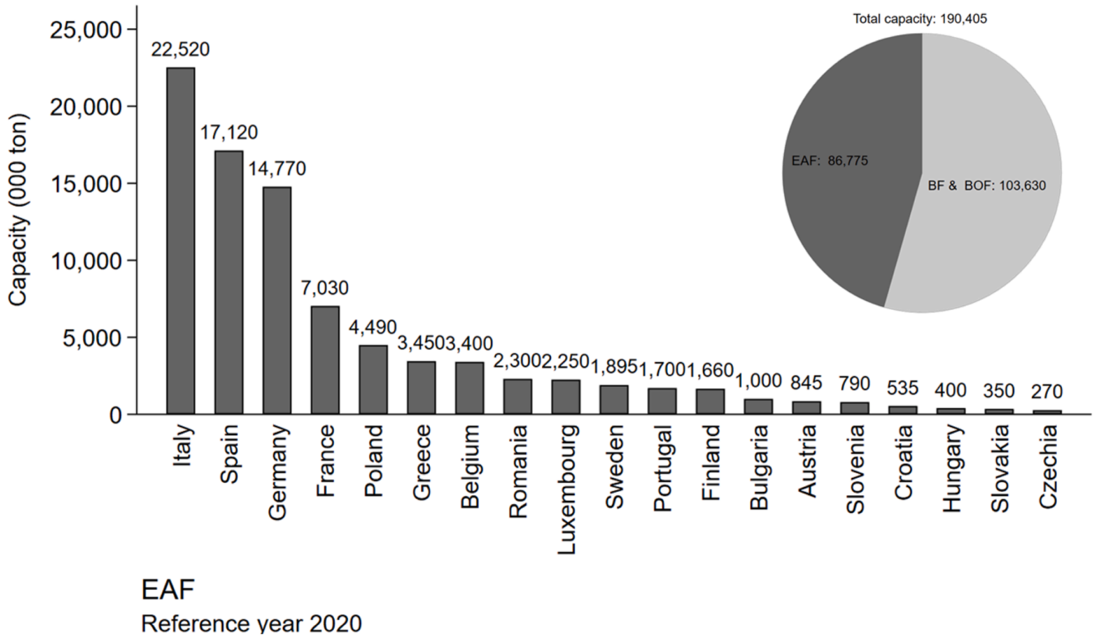

Fig. 1. Steel production capacity (EAF).

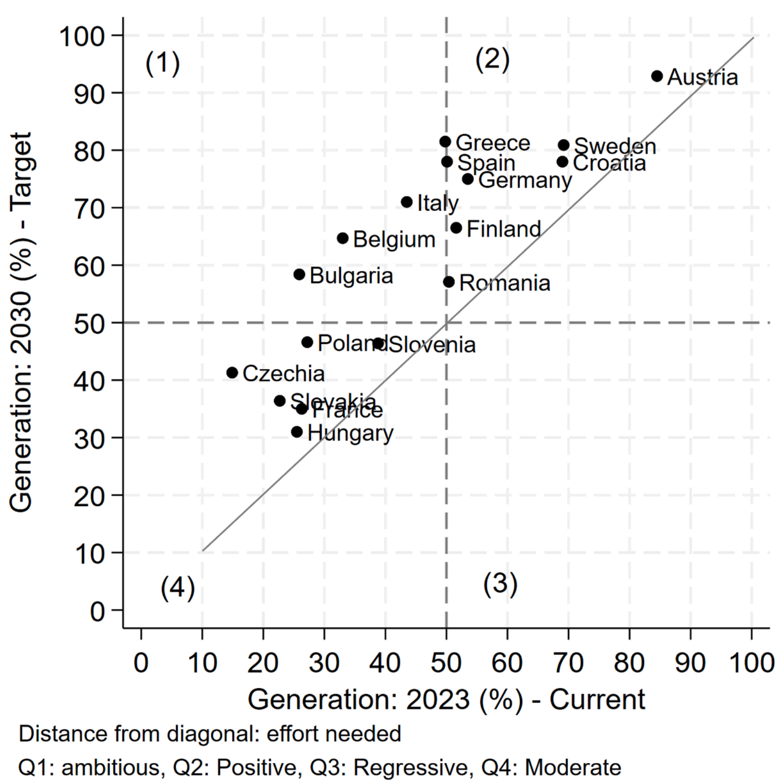

Fig. 2. Renewable energy generation: current figure vs. NECP targets.

gained momentum (Song and Oh, 2015) because the penetration of renewables is a prominent tool for boosting economic growth and protecting the environment (Zhang and Kong, 2022). The importance of considering internal and external factors when steering a timely decarbonization strategy is notable (Hafner et al., 2022). This study uses the renewable energy generation 2030 targets as a proxy for the impact of a policy-making variable on decarbonization efforts. Fig. 2 resumes this variable and details how it can range according to the country-by-country targets of the NECPs.

Table 2 contains main descriptive statistics of the variable used to measure the impact of different variables on meeting decarbonization targets in the European countries considered. Such variables were selected according to previous literature.

Table 2 contains key statistics on the factors that impact the achievement of renewable targets.

An analysis of 11 steel firms' business plans and interviews was also conducted.

Methodology

The methodological approach adopted is divided into four phases. First, an in-depth analysis of nonfinancial reporting and other information sources was conducted, including data collection through structured questionnaire-based interviews. This step was crucial for evaluating the environmental, social, and governance (ESG) situation of the organizations involved in the study. Second, the key performance indicators (KPIs) were defined on the basis of the European objectives and the guidelines proposed by the National Steel Industry Association. This approach allowed us to establish clear and measurable parameters for evaluating progress in sustainability. The third phase concerned the analysis of the risk management and strategies that could influence the outcome of the decarbonization strategies. This aspect is fundamental to understanding how organizations can mitigate the potential negative impacts that emerge when implementing their sustainability strategies. Finally, a simulation model aimed at supporting strategic decision-making was implemented to make it possible to evaluate different scenarios, considering the various risks identified.

To predict the propensity of countries to reach NECP targets, an analysis was also implemented, as in Eq. (7). The article integrates qualitative and quantitative analyses, aiming to provide a comprehensive and pragmatic framework for achieving sustainability objectives in complex industrial contexts.

Research questions and hypotheses

RQ1. What is the current state of the art regarding ESG criteria and decarbonization commitment? Hypotheses: The industry is making steps forward, but heterogeneity and better coordination will bring shared benefits. A survey approach involving an ESG assessment based on nonfinancial disclosures, industrial plans, and interviews with representatives from 11 firms was employed. RQ2. What specific initiatives can firms adopt to effectively enhance their decarbonization strategies? Hypothesis: Common characteristics exist across industries that can be leveraged to improve the efficacy of decarbonization strategies in diverse firms. Therefore, the effectiveness of decarbonization strategies depends on an integrated approach that combines technological innovations, resource management, and stakeholder engagement. The research method involved the analysis and synthesis of assessments to identify levers and KPIs, drawing from the analyzed cases and published targets of industry associations. RQ3: What is the role of firms' commitment and human resource involvement in decarbonization? Hypothesis: Adequate training and active involvement of internal staff are essential for successfully implementing decarbonization strategies, thereby reducing dependence on external consultancy.firms RQ4. How can firms optimize their decarbonization strategies by applying the identified levers to increase the expected outcome? Hypothesis: Incorporating risk assessment for each decarbonization initiative increases the effectiveness of the strategies and decreases the uncertainty of the outcomes. To answer this RQ, a simulation was designed and tested to model the optimization of decarbonization strategies through identified initiatives and the evaluation of associated risks. RQ5: What are the central market and regulatory compliance risks associated with the decarbonization strategy? Hypothesis: Appropriate risk management decision tools can significantly influence the implementation of decarbonization strategies and improve strategy planning. Both analysises were employed to identify the drivers of renewable energy development in Europe, considering these as exogenous factors in decarbonization strategies and, therefore, in the simulation proposed in this paper.

Scope and phases

ESG assessment

ESG assessment is an essential component in designing an effective decarbonization strategy. This detailed evaluation was based on the analysis of a series of documents and the administration of questionnaires. This methodological approach, aimed at capturing and analyzing meaningful data from different sources, is illustrated and detailed in Fig. 3.

The main objective of this analysis was threefold: first, to provide crucial data for defining an industrial decarbonization strategy; second, to generate proposals and suggestions aimed at influencing political decisions at the institutional level; and third, to offer guidance and advice relevant to the financial world, particularly the capital market.

Cleaner production

The research outlined a cleaner production strategy following the ESG assessment described in the previous section. In this landscape, setting decarbonization targets is an imposing challenge and an essential requirement for maintaining competitiveness in the steel sector. The

Table 2
Descriptive statistics.

Var	Label	Source	Formula	min	mean	sd	max
	Distance to the target	NECPs	RE_2030 - Rey	−5.82	20.719	15.642	87.8
gri	km of grid/km2	EDSO	Network length/Km2	0.369	3.143	3.022	16.738
res	Renewable in 20,212	Eurostat	RE%	1.3	26.317	19.167	74.71
fos	Share of fossil	Eurostat	Fossil%	1.49	47.468	25.044	99.5
hid	Share of Hydro-E	Eurostat	Hydro%	0	14.606	17.164	67.04
ebu	HPs - ambient heat cap GWh	Eurostat	Ambient heat cap GWh	0.613	3.682	3.91	4.626
eve	EVs/km distribution grid	Various	EVs/Network km	0	0.074	0.241	3.488
pop	Populatio m	Eurostat	Population m	0.418	16.474	21.743	83.23
mkt	Firms > 5 % of E gen	Eurostat	% utilities > 5 % of generation	25.48	68.184	17.442	100
pri	Price signal eprice*wind_so	Ember	Price *% of RE	0	3.013	3.232	4.116
cin	Carbon emission pct	Eurostat	Carbon emission/pop	3.7	7.085	3.043	22.17

Table 2 contains the key statistics on the variables. Source: based on Di Foggia and Beccarello (2024).

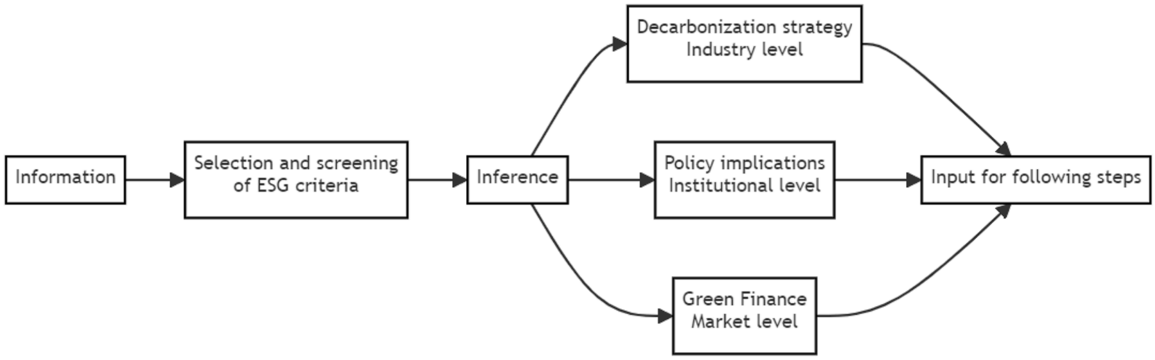

Fig. 3. ESG Assessment steps.

method adopted to articulate the decarbonization strategy was based on a set of strategic and methodical actions. First, a structured approach was adopted to crystallize decarbonization goals, followed by meetings with industry experts to enrich the analysis with up-to-date technical knowledge and strategic visions. This included an assessment of targets Firmsand consideration of market-imposed decarbonization expectations from customers and the financial sectorfirms. This is set to become an essential criterion for ensuring market competitiveness. Finally, KPIs were generated, as shown in Fig. 4. A reduction in emissions has been highlighted as a priority KPI for reducing the amount of carbon emitted per ton of steel produced. This indicator measures the effectiveness of the decarbonization measures implemented. In addition, energy intensity is used to assess and optimize the energy used for production output, aiming for greater energy efficiency. Increasing the use of renewable energy is another essential KPI in the energy domain that encourages a shift to low-carbon energy sources. Carbon credit offsets are recognized as complementary measures.. Regarding materials and resource management, residuals in circular processes promote the transition to a circular economy by minimizing residuals and increasing the use of recycled materials in production processes. Finally, specific water consumption emphasizes the importance of using water more efficiently, reducing consumption per production unit and thus supporting water conservation.

These KPIs provide a solid basis for steel firms to assess their current operations, define strategies for improvement, align with sustainability goals, and respond effectively to regulatory and market pressures.

Identifying strategic levers is essential for transforming decarbonization and green production goals from ambitions to tangible realities. Fig. 5 summarizes levers that, if implemented, can enable the steel industry to take concrete steps toward reducing its environmental impact. These enabling factors are categorized by scope, outlining the specific actions referred to in Scopes 1 and 2. Although Scope 3 represents a significant component of the value chain, this research focuses exclusively on Scope 1 and 2.

For Scope 1, the use of green fuels, adoption of electrification measures, increased energy efficiency, and implementation of CCUS technologies are considered. These actions are directly controllable by the company and immediately impact the reduction of emissions from its production activities. Under Scope 2, self-generation of energy from renewable sources and the purchase of green power purchase agreements (PPAs) or guarantees of origin are measures that help reduce indirect emissions associated with electricity consumption. In addition, decarbonization of the national energy mix is a crucial lever that, although more elusive to firms' direct control, influences their sustainability profile.

Market and regulatory compliance risk analysis

This description provides a detailed view of how the model works, emphasizing the relationships between variables and the importance of corporate commitment to risk management and decarbonization strategy. Initially, simulation assumptions are included to define exogenous contexts that are not dependent on the decarbonization strategy. Several national energy mix scenarios and the probability of achieving the decarbonization targets in 2030 and 2050 are stated in the NECPs, which have been recently updated. In Eq. (1) $emix_{min}$ referes to renewable energy share in electricity generation, wheras in Eq. (2) vimax stands for maximum impact of each risk factor taken into consideration. In Eq. (3) reduction is a factor capturing the role of exogenous factor on corporate strategy. In Eq. (4) the inversion relation between commitment and risk is formalized. Similarly, in Eq. (5) the role of energy efficiency in defined to capture its impact on other variables. Results are defined according to Eq. (6).

In Eq. (1), the minimum value of the energy mix corresponds to the country's current percentage of renewable energy α, while the maximum is determined by the country's NECP commitment, i.e., β to 2030. This target is an intermediate step toward decarbonization in 2050. Next, a value that formalizes the model can be referred to as random because it is generated between these limits. This step captures the variable that considers the target country's performance in achieving the goals. This is an essential step because it allows for changing the lower and upper bounds and enables better international benchmarking. This variable can be set at a level compatible with each NECP, as indicated in Eq. (1).

$$emix_{min} = \alpha, < emix < emix_{max} = \beta \quad (1)$$

Next, corporate commitment, represented by commitment, is set. These values can vary on a scale (e.g., a Likert scale), with minimum and maximum values indicating the level of commitment. For a commitment

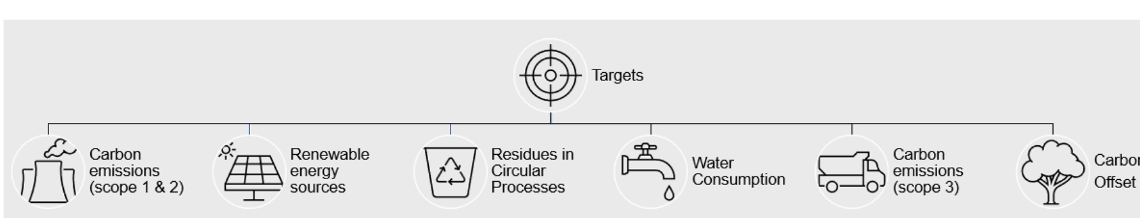

Fig. 4. Identified environmental KPIs.

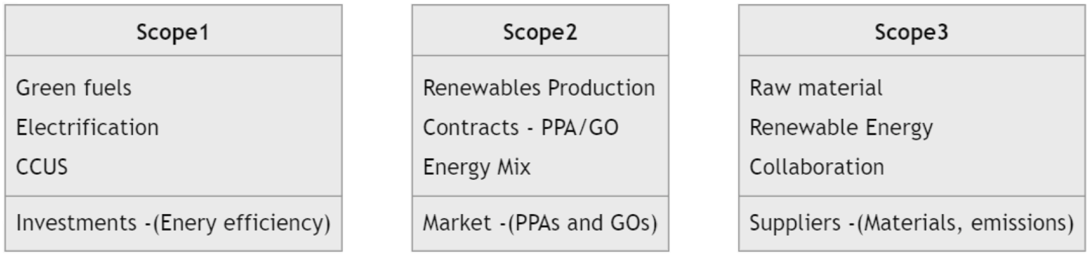

Fig. 5. Strategic levers.

to be credible, it must be verifiable through information included in nonfinancial statements and communication channels to stakeholders. Risk variables are generated on the basis of the analysis of the risk management strategy, and the value of some of them is impacted by the values assumed by the commitment variables. The maximum value of each risk variable depends on the number of factors identified in Eq. (2):

$$v_{i_{max}} = \frac{100 - emix}{n} \tag{2}$$

The energy mix is assumed to affect some risk variables through a negative correlation. For example, some variables decrease proportionally as the percentage of renewable energy in the energy mix increases in addition to α in the way proxied by Eq. (3):

$$\text{reduction} = \max(0, (emix - \alpha) \times \delta) \tag{3}$$

The equation states that risk reduction is directly proportional to the decarbonization of the energy system. The formula calculates the reduction by multiplying the difference between the overall decarbonization level and α, which is the lower limit of the percentage of renewables in the energy mix, by the factor δ, a scaling factor that determines the intensity of the reduction. In this paper, we focus on the role of staff training and the decarbonization strategy. The model modifies several risk variables according to the level of corporate commitment, as formalized in Eq. (4). This modification is represented by an inverse function, indicating that as the level of commitment increases, the risk associated with specific variables decreases. The relationship can be expressed using the following generic formula:

$$Risk = \frac{1}{f(Com)} \tag{4}$$

where $f(Com)$ is a function that reflects firm commitment. This relationship represents the principle that greater commitment on the part of the company to train staff or adopt decarbonization strategies leads to reduced risks associated with these issues. The specific function $f(Com)$ can be customized to the needs and characteristics of the company, thus providing flexibility in the application of the model.

The relationships between energy efficiency and other risk factors are given in Eq. (5). If the energy efficiency is below a set threshold, it impacts other risks, such as the purchase of carbon credits and carbon capture. This logic is based on the idea that high energy efficiency can reduce the need to depend on external strategies such as purchasing carbon credits or investing in carbon capture and storage technologies, thereby reducing the risks associated with these initiatives. The threshold and amount of risk reduction can be adjusted according to the specific needs and realities of the model you are building. This simplification illustrates how relationships between variables could be established in such a model. In reality, these relationships might be complex and require more detailed analysis to determine the appropriate values to use. When the energy efficiency is below a certain threshold, the impact variables are also reduced by the same amount for each unit of reduction. This can be mathematically expressed in Eq. (5).

$$\text{Reduction}_{vars} = \max(0, \text{level} - eff) \tag{5}$$

This formulation creates a direct, proportional correlation: the greater the discrepancy between the current energy efficiency and the threshold is, the greater the reduction in related variables. Then, the total risk impact and the expected outcome of the decarbonization strategy are calculated. The expected outcome is greater between the current or projected energy mix and the remaining measure of success after considering the total risk impact. In essence, this formula balances current or planned energy decarbonization against potential risks, choosing the value that indicates the greatest success. In summary, this equation evaluates the expected outcome of the decarbonization strategy by considering both the level of energy decarbonization and the overall impact of the risks associated with the strategy. Eq. (6) provides a quantitative estimate of the feasibility and effectiveness of a company's decarbonization strategy.

$$Output = \max(emix, 100 - \text{sum of risks}) \tag{6}$$

Finally, the results are visualized, providing insights into the potential success of the company's decarbonization strategy. The model offers the possibility of customization by adapting it to specific needs. These specific needs are subjective and depend mainly on the company's strategic positioning. This study also presents a panel regression model formalized in Eq. (7) designed to examine the dynamics and multiple influences in the context of NECP targets.

$$y_{it} = \beta_0 + \beta_1 x_{1it} + \beta_2 x_{2it} + \ldots + \beta_n x_{nit} + u_{it} \tag{7}$$

It is essential to emphasize that achieving the NECP targets is treated as an exogenous variable. While the variables relating to commitment and other elements can be considered endogenous and interdependent, the NECP targets are influenced by a broader and more complex set of determinants that go beyond the direct field of application of the market and regulatory risk analysis model.

Results

The main results are reported as inherent in the ESG assessment to answer RQ1 and the strategic levers identified in Table 4 regarding RQ2. The results for RQ3 analyze the role of commitment as per RQ3, and for RQ4, the combination of corporate commitment and energy policy is analyzed, as highlighted in Tables 5 and 6. Finally, the simulation model of RQ5 emphasizes the complexity of decarbonization, highlighting the importance of risk management in strategic planning.

Table 3 presents a consolidated summary of the environmental aspects of a broad ESG assessment. The analysis encapsulates various firms and provides a concise overview of standard environmental practices, challenges, and areas for improvement. The first two columns outline the main environmental factors examined during the assessment and the aggregate results, highlighting areas where firms have been successful and gaps that needed to be filled to be ESG compliant according to the strategies. The "Strategies" column introduces actionable recommendations tailored to practitioners, outlining pathways toward better environmental management. Accordingly, the "public policy" column suggests targeted government interventions to incentivize industrial decarbonization. Finally, the "Finance" column provides strategic clues

Table 3
ESG assessment–focus on (E).

Scope evaluated	ESG assessment	Strategies	Public policy	Finance
Environmental Management	Standardization, procedures, certified systems, reporting, and performance monitoring.	Reporting systems to monitor environmental performance and integrate them with existing certifications.	Environmental certification incentives	Environmental Certification Financing.
Pollution	Individual factories, group-wide coordination, common policy lack, and environmental impact reduction.	Standard policies for reducing environmental impact, incentivize by sustainability responsibility programs.	Decarbonization R&D Funding.	Pollution reduction investment funds.
Energy Management	Energy management, energy-intensive firms, lack of specific policy, renewable energy exploration.	Energy management policies that emphasize renewable energy use and reduce energy consumption.	Renewable integration grants and bonuses	Energy efficiency and renewable incentives
Climate Change	Climate change strategy, risks, and quantitative targets	Strategies to address climate change, including quantitative targets and specific action plans.	Emission reduction facilities.	Climate goals investment products.
Emissions	GHG emissions calculation, lack of targets, and action plan absence.	Clear and quantifiable targets for reducing emissions with dedicated action plans.	Carbon credit incentive programs.	Emissions Reduction bonds.
Water resources	Water impact policy absence and closed-loop water reuse.	Policies for the sustainable management of water resources by promoting conservation and reuse practices.	Water conservation and reuse funding.	Water conservation and reuse funding.
Biodiversity	Biodiversity impact reduction lacks soil protection procedures.	Policies to minimize impacts on biodiversity, including specific actions to protect soil and local ecosystems.	Biodiversity and Soil Protection Support.	Biodiversity protection financial support.
Raw Materials	Raw material use reduction, environmental impact, circular economy.	Circular economy projects by adopting procurement and raw material use practices that reduce environmental impact.	Circular economy and material sustainability incentives.	Circular economy investments.
Waste Management.	Plant-level management and common policy absence.	Policies for waste management and recycling, promoting material reduction and reuse.	maste Management and recycling funding.	Waste management technology funding.
Decarbonization strategy	2030 and 2050 commitments, loosely defined, heterogeneous base years.	Specific decarbonization strategies with clear targets and deadlines.	Low-Carbon technology adoption incentives.	Low-carbon transition financial products.

Source: The authors.

for financial institutions to support green investments.

Recognizing the critical interplay between industry actions, government regulations, and financial mechanisms, we have also included forward-looking strategies, public policy recommendations, and financial proposals. These are designed to complement and enhance the results of ESG assessments, offering valuable insights and actionable directions. This approach highlights the existing efforts and gaps in environmental management and proposes a trajectory for sustainable development in line with global environmental goals. The additional suggestions strengthen industry practices, inform decision making, and guide investment decisions, thus contributing significant value to the discourse on environmental management.

Table 4 summarizes key findings from the assessment of decarbonization initiatives, outlining both the drivers and risks associated with each initiative and the scope of these actions and challenges and the commitments that firms can make to mitigate risks and strengthen the success of their environmental strategies.

These data provide a snapshot of the current landscape of decarbonization efforts and serve as a critical component in the development of simulation algorithms. The information gathered here will inform and refine predictive models that help predict the outcomes of various decarbonization pathways. Initiatives range from adopting green fuels to carbon capture technologies, while risks highlight real-world challenges faced by firms, such as market volatility and regulatory hurdles. The commitment column suggests proactive measures for continuous improvement and strategic alignment with broader environmental goals.

Fig. 6 can be used for static assessment of the current business situation and simulations based on modifiable variables, for example, to explore scenarios in different countries with different energy mixes.

Fig. 7 provides significant insights into the relationship between an industry's level of commitment toward decarbonization and the outcome of its strategies. In particular, higher commitment is generally associated with a greater expected outcome in implementing decarbonization strategies. In addition, a high level of commitment is associated with a decrease in the standard deviation of outcomes. This suggests reducing uncertainty by adopting more consistent and effective decarbonization strategies. Examining the values associated with the achievement of NECP targets in different countries, it is observed that in contexts where national decarbonization targets are more ambitious and close to being achieved, firms tend to be more effective in terms of their emission reduction path. In conclusion, these results highlight how firms' approach and commitment to pursuing decarbonization strategies are crucial factors in the success of such initiatives. The increased likelihood of success with high corporate commitment demonstrates the importance of well-defined corporate strategies consistent with long-term sustainability goals.

Furthermore, specific considerations can be drawn at the country level, as shown in Fig. 8.

It is worth delving into how the political environment and corporate commitment interact to influence the transition toward decarbonization in the steel sector, highlighting the dynamics between the variation in the expected outcome and risk of decarbonization strategies and offering an interpretation of potential future developments. Table 5 reports the expected outcome of decarbonization strategies according to the level of corporate commitment and the implementation of renewable targets, which reflect the achievement of specific percentages of renewables, as indicated in the NECPs.

A gradual increase in the expected outcome as the percentage of achievement of the NECP objectives increases is shown in Table 6. Therefore, a context approaching renewable energy goals is correlated with more effective decarbonization strategies, which is consistent with common wisdom. Therefore, a country's energy context plays a significant role in influencing the likelihood of business success. Furthermore, in every NECP target achievement scenario, a more significant industry commitment corresponds to a greater expected outcome. However, the delta decreases as the percentage of NECP target meetings increases (ranging from 4.917 to 4.133 when going from 0 % to 100 %).

Consequently, as energy integration increases, the additional effect of high corporate commitment on the likelihood of success becomes less pronounced. Therefore, in an already favorable context, due to sustainable energy policies, the impact of further corporate commitment to decarbonization is less discernible due to increasing marginal costs, although it remains significant. Regarding the associated risk, Table 6 shows that the standard deviation decreases as the probability of meeting the NECP target increases. Thus, the greater the orientation of

Table 4
Levers.

Initiative	Risk	Type	Actions
Decarbonizing the energy mix	Delayed decarbonization policies	Exogenous	Constantly monitor the country's carbon intensity level.
Training and analysis of the energy and market scenario	Lack of skills and a prospective vision	Management	Staff training and collaboration with universities and research institutes.
Clear decarbonization strategy	Scarce alignment	Management	Define a decarbonization strategy by involving internal staff
Carbon credits	Reputation and compliance	Management	Prefer energy efficiency interventions and renewable self-production
Green fuels: hydrogen	Hydrogen supply delay	Market	Demand aggregation as contractual leverage.
PPA purchase and guarantees of origin	Limited offer	Market	Increase supplier portfolio and long-term agreements.
PPA purchase and guarantees of origin	Volatility of wholesale prices	Market	Choose flexible PPA structures
Self-production of energy from renewable sources	Uncertainty in Plant Development Costs	Regulatory	Include specific clauses in construction contracts
Self-production of energy from renewable sources	Bureaucracy and long approval times	Regulatory	Start the permitting process ahead of the project timeline.
Energy efficiency	Low incentives to hedge risk	Regulatory	Monitoring energy efficiency projects
CCUS	Technology immature	Technical	Evaluate alternative technologies.
Green fuels: hydrogen	Complexity of using hydrogen in the production process	Technical	Collect information about tests conducted by others
Self-production of energy from renewable sources	Delayed plant construction time	Technical	Include penalties in contracts.

Source: The authors.

energy systems toward renewables is, the lower the uncertainty of decarbonization outcomes. In each scenario, the standard deviation is lower when the commitment is high. Hence, firms with a solid commitment to decarbonization are more likely to succeed and show less variability in outcomes, suggesting more consistent and predictable outcomes and increasing the feasibility of investments. Indeed, the delta tends to decrease as the achievement of the NECP objective increases. Therefore, in contexts where the government actively promotes the energy transition, high-commitment firms benefit from an environment already predisposed toward renewables, reducing the variability of their decarbonization outcomes.

The analysis reveals that the success of decarbonization strategies is influenced by both the national political context and the specific commitment of firms. Where government policies favor renewables, the expected outcome of corporate initiative increases, and a strong commitment from firms can further intensify this effect. However, in contexts where national decarbonization objectives are already in an advanced state of achievement, the differentiated impact of high corporate commitment tends to decrease, indicating that close synergy between state-level sustainability policies and corporate actions is crucial for minimizing uncertainty and consolidating progress toward decarbonization. A collaborative approach involving the government and industry is critical for an effective and low-risk transition to a low-carbon economy.

Following the information contained in Table 2 and the theoretical background supporting the selected variables, Eq. (7) becomes Eq. (8), i.e., a panel model whose results are summarized in Table 7. The results of the formula used for the regression are represented where y_it is the gap for country i at time t and u_it is the error term.

$$y_{it} = \propto + \beta_1 gri + \beta_2 res + \beta_3 fos + \beta_4 hid + \beta_5 ebu + \beta_6 eve + \beta_7 pop + \beta_8 mkt + \beta_9 pri + \beta_{10} cin + u_{it} \tag{8}$$

Table 7 shows two versions of the same model: (1) refers to all European countries, whereas (2) captures the effect of the sample on the achievement of NECP targets.

Table 7 contains some information regarding the determinants that can drive or slow the meeting of NECP targets. Fossil sources have been confirmed to be influential in slowing down the path toward the energy objectives of a country, with a pronounced effect. At the same time, an increase in the percentage of renewables increases the marginal cost of further development. It is important to clarify that these observations refer not to the general development of renewables but specifically to the target set in the NECPs. In addition, the market concentration suggests that greater competition in the electrical sector could slow decarbonization. Transport electrification has a significant effect. Consistently, the density of the distribution network has a significant influence, confirming this hypothesis.. These data confirm the importance of investments in enhancing and extending the electrical distribution network. Finally, the price signal variable corresponds to the intake of wholesale price incentives for renewable energy producers, even if this is not statistically significant.

Discussion

This article provides a significant contribution from both a theoretical and practical point of view, proposing more targeted and effective solutions for the sector's decarbonization focusing on internal and external factors impact; specifically firms commitment in decarbonization strategies. The success probability delta between low and high commitment ranges from 4.917 to 4.133 percent according to the level of energy mix decarbonization.

This article shares some similarities with previous studies. For example, Kim et al. (2022) evaluated current and emerging practices for decarbonization and identified 86 potentially transformative technologies. Similarly, Mallett and Pal (2022) underline that the adoption of technologies that reduce carbon emissions is an important path to decarbonization and that collaboration and government efforts can catalyze such innovations. According to Löfgren and Rootzén (2021), efforts to enhance coordination are crucial for accelerating decarbonization, indicating that implementing policy measures to reduce such barriers is a primary focus. Focusing on energy efficiency, Di Foggia et al. (2022) also referred to support policies as an essential aspect of decarbonization.

The analysis revealed that firms have planned or initiated projects, but the targets are sometimes not defined explicitly. Although several positive forward-looking pieces of information emerged from the surveys, we argue that additional efforts should be made to advance decarbonization. Similar conclusions were drawn by Villafranca Casas et al. (2024), who, based on a survey of steel producers, found that approximately 14 out of the 30 targets did not provide an emission reduction plan. The findings of this study are crucial for evaluating the transition toward sustainability in the steel sector. They highlighted that strong corporate commitment and effective demand analysis (Nath et al., 2013) are crucial for success.

The findings significantly impact firms' strategic and operational approaches, driving greater awareness and preparedness to address

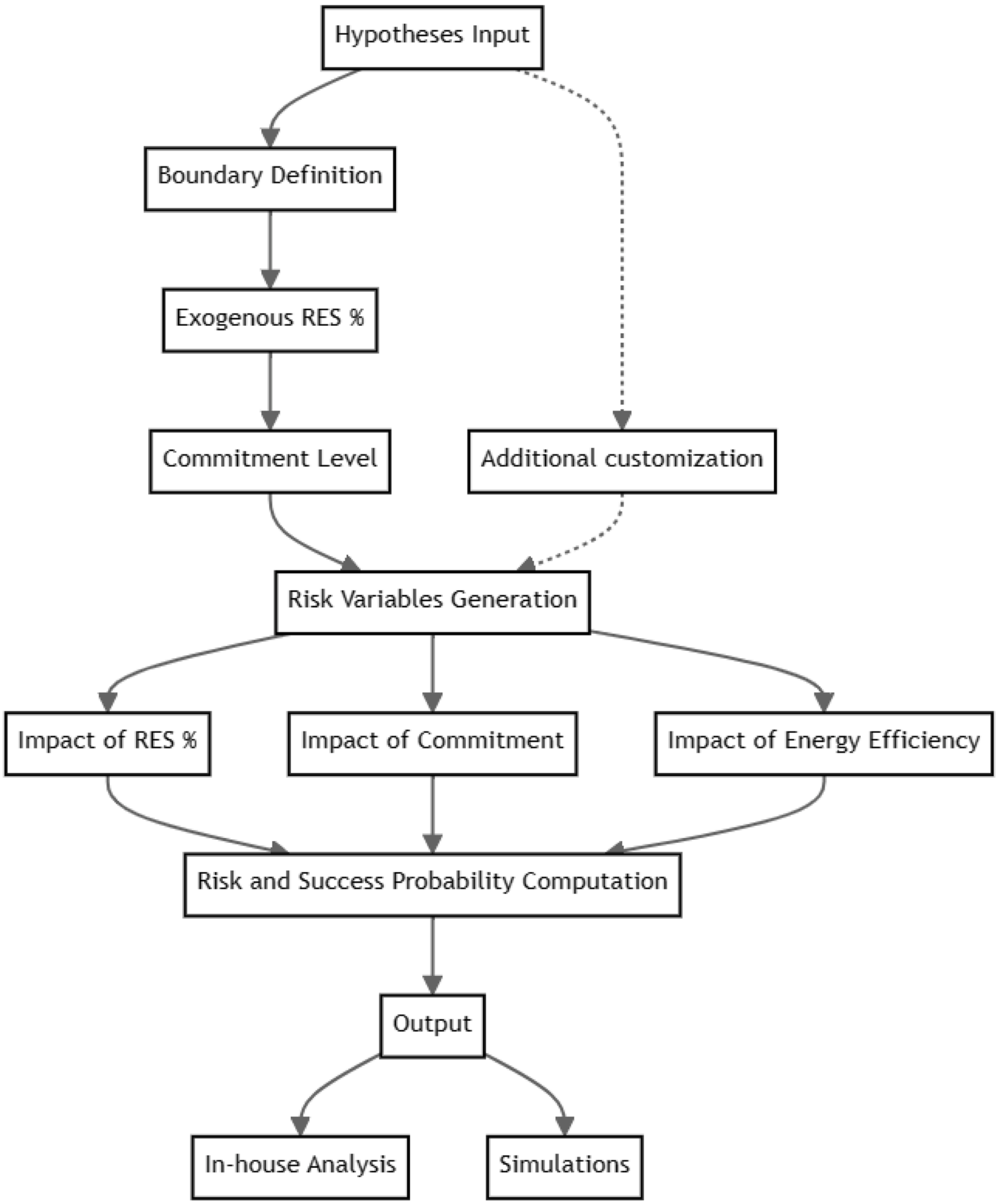

Fig. 6. Simulation model.

environmental challenges. Therefore, this research contributes to a better understanding of decarbonization processes and offers essential guidelines for the sector. The findings provide insights into the RQs posed. For RQ1, the findings confirm the initial hypothesis of heterogeneous progress in the industry. As detailed in Table 3, the analysis revealed a disparity in the commitment and execution of decarbonization efforts across different firms. While some have shown serious commitment and made notable investments in renewables and energy efficiency, a lack of uniformity and coordination remains a prominent issue. For RQ2, as summarized in Table 4, several levers were identified, such as the decarbonization of the energy mix, which firms can employ to bolster their environmental strategies. Concerning RQ3, the findings supported the hypothesis that internal staff training and involvement are critical. The study showed that competencies, knowledge, and firm managerial vision, coupled with clearly defined and measurable strategies, significantly enhance the success of decarbonization strategies and reduce their risks. This emphasizes the importance of cultivating an informed and engaged workforce to achieve environmental goals. For RQ4, the results confirm the role of both commitment and energy policy, as shown in Tables 5 and 6. Switching to RQ5, the simulation reinforces the hypothesis that understanding and managing these risks is crucial for strategic planning. The model's ability to integrate various factors, including those beyond a company's control, such as the NECP targets, illustrates the complex interplay between industry actions, government regulations, and market dynamics in shaping decarbonization strategies.

Consistent with expectations, the decarbonization outcome is impacted by public policy and the evolution of the energy mix (Åhman et al., 2016), which are external factors outside of direct corporate control. That said, some managerial implications are as follows: in-depth analysis and understanding of the energy scenario and market require a corporate green vision (Holappa, 2020; Jha and Arora, 2013) to avoid strategic drift. Managing carbon credits involves risks associated with

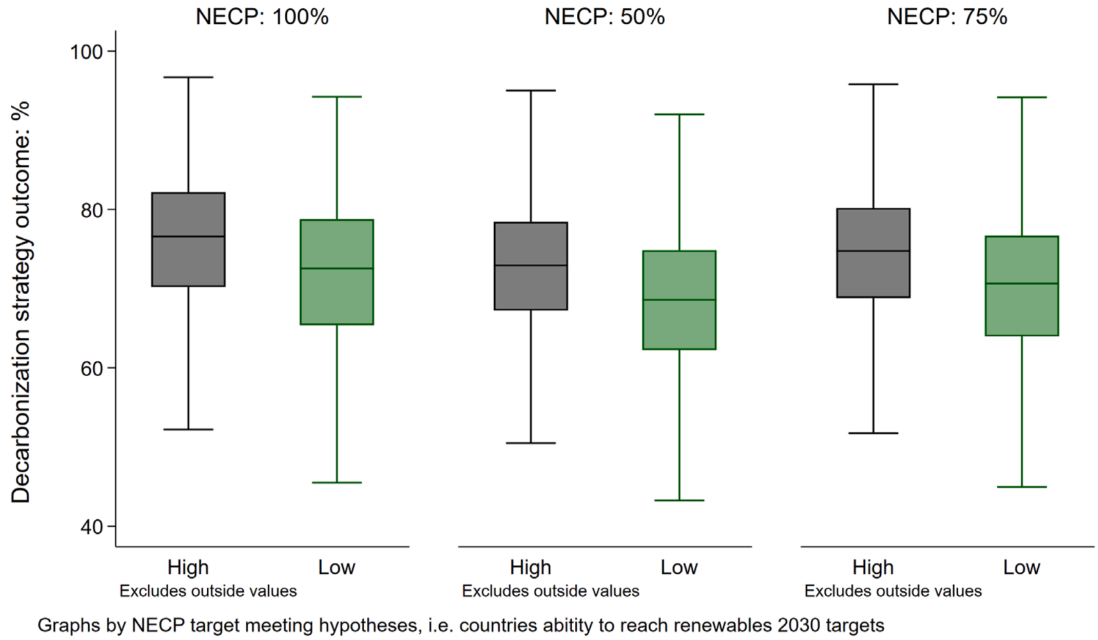

Fig. 7. EU-wide output sensitivity.

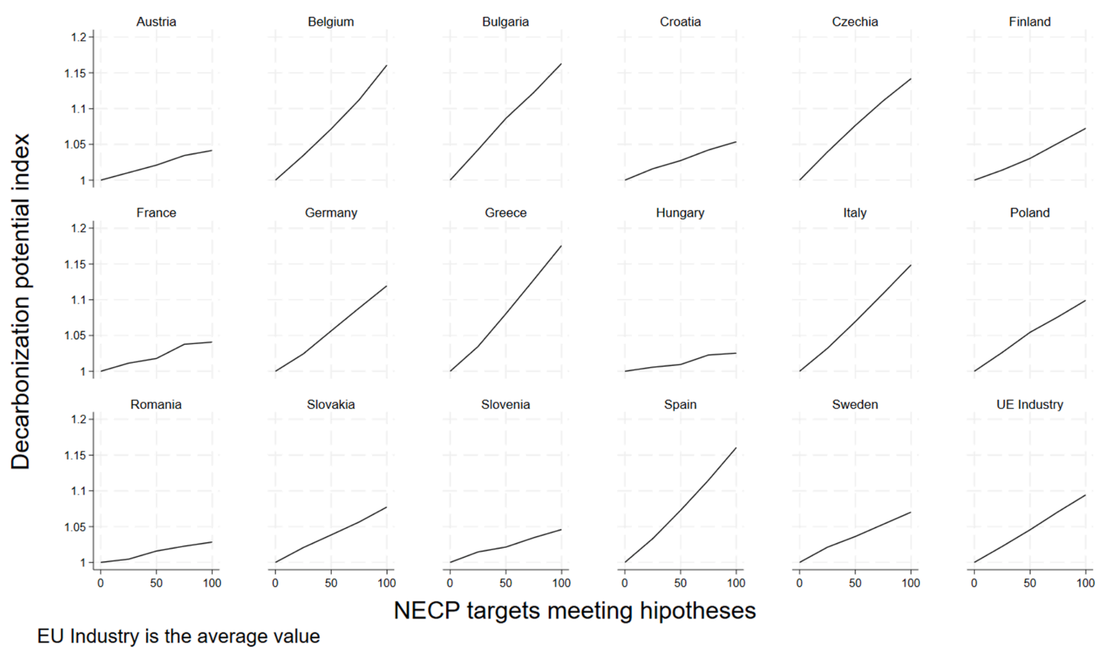

Fig. 8. Country-level potential index.

Table 5
Sensibility of the strategy output.

NECP meeting	Low commitment	High commitment	Delta
Low: 0 %	65.084	70.001	4.917
Medium-low: 25 %	66.722	71.376	4.654
Medium: 50 %	68.450	72.789	4.339
Medium-high75 %	70.205	74.421	4.215
High: 100 %	71.850	75.983	4.133

Source: the authors.

Table 6
Sensibility of strategy risk.

NECP meeting	Low commitment	High commitment	Delta
0 %	9.300	8.342	−0.957
Medium-low: 25 %	9.036	8.144	−0.892
Medium: 50 %	8.897	8.035	−0.862
Medium-high75 %	8.943	7.995	−0.948
High: 100 %	9.038	8.137	−0.901

Source: the authors. Standard deviation of the expected result of decarbonization strategies.

corporate reputation and regulatory compliance, implying the need to adhere to strict ethical and regulatory standards (Abadie et al., 2024; Blum and Lövbrand, 2019). Green fuels, such as hydrogen, face the risk of supply delays, a market variable that underscores dependence on external supply chains. However, according to Andrade et al. (2024),

Table 7
Regression analysis.

Variables	(1) Distance to targets	(2) Distance to targets
gri	−1.372*** (0.495)	−1.447*** (0.503)
res	0.700*** (0.101)	0.702*** (0.0980)
fos	0.796*** (0.0251)	0.790*** (0.0254)
hid	−0.265***(0.0431)	−0.271***(0.0436)
ebu	−0.00022*** (6.30e-05)	−0.00021*** (6.38e-05)
eve	−2.621*** (0.814)	−2.698*** (0.828)
pop	0.201** (0.0853)	0.216** (0.0909)
mkt	0.137*** (0.0263)	0.139*** (0.0267)
pri	−0.00022** (9.86e-05)	−0.00027** (1.00e-04)
cin	0.597*** (0.184)	0.623*** (0.186)
sample		−1.505 (4.102)
Constant	−42.67*** (4.660)	−41.83*** (5.112)
Observations	297	297
Number of ID country	27	27
R2	0.9632	0.9629
Wald chi2	5568.43	5399.52

Source: The authors based on Di Foggia and Beccarello (2024).

using biomass in the steel industry may reduce the marginal cost of steel. Purchasing PPAs and guarantees of origin are limited by availability and price volatility, which are market factors that can affect energy strategy and financial stability. Self-generation of renewables faces uncertain development costs, bureaucracy, and regulatory factors that can impose significant delays.

The limitations of this study deserve attention. Focusing only on steel mills using the EAF process may not fully represent the variety of challenges encountered in other types of steel production. Furthermore, the use of subjective simulation criteria can influence the objectivity and replicability of the results. Finally, uncertainties regarding the objectives of the NECPs add a further level of variability and potential imprecision in applying the study results. These limitations highlight the need for more extensive and diverse research to comprehensively address decarbonization in the steel sector. The policy implications of the findings are broad, underscoring the need for policies that promote collaboration between the public and private sectors for decarbonization. This includes adopting financial and regulatory incentives to encourage the use of low environmental impact technologies, supporting technological innovation, and implementing measures to reduce emissions. Furthermore, the study highlights the importance of adequate financial strategies to support these initiatives, emphasizing the need for joint and coordinated efforts to effectively address sustainability challenges in the steel sector.

Conclusion

Limiting global warming to 1.5° will require significant reductions in greenhouse gas emissions by 43 % by 2030 compared to 2019. This study has analyzed decarbonization strategies highlighting the importance of corporate commitment and risk management.

This study makes a significant contribution to the literature on decarbonization by introducing a sophisticated method for risk analysis and highlighting the importance of corporate commitment and government–industry collaboration.

The steel industry is progressing in its commitment to decarbonization, albeit heterogeneously across countries and industries. This lack of uniformity underscores the need for greater coordination to enhance environmental management across industries. This article provides a significant contribution for the sector's decarbonization. The probability of meeting the 2030 goals range from 65.08 to 75.98 percent and the delta between low and high commitment ranges from 4.917 to 4.133 percent according to the share of renewables in the energy mix. Also, European countries positioning with reference to 2030 targets has been discussed providing evidence on the difference between the current level of renewable energy generation against the 2030 declared targets. Furthermore, the findings reveal that specific initiatives, such as the decarbonization of the energy mix, are pivotal for enhancing decarbonization strategies in steel firms. The role of internal staff training and involvement is crucial in the successful implementation of these strategies. The findings support the idea that firm commitment, knowledge, and a clear vision from management significantly improve the outcomes of decarbonization efforts and reduce risks. Finally, the study introduces a comprehensive simulation model that provides managers with a tool to assess the impact of business commitment on outcomes, understand market and regulatory compliance risks, and benchmark industry standards. As detailed in our findings, this model illustrates the complex interplay between industry actions, government regulations, and financial mechanisms, emphasizing the importance of risk management in decarbonization strategic planning. Future research should broaden the geographical scope to further explore the interaction between environmental, economic, and political variables in the context of decarbonization.

Data availability

If you prefer the database dor regression analysis is available at this link I created https://doi.org/10.5281/zenodo.13318259.

CRediT authorship contribution statement

Giacomo Di Foggia: Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Massimo Beccarello:** Writing – review & editing, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2024.100988.

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