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LETTER

Green hydrogen in the iron and steel industry increases resilience against shocks in energy prices

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Abstract

Geopolitical tensions and conflicts can disrupt energy markets, threatening international energy supply security and imposing financial stress on energy-intensive industries reliant on imported fossil fuels. Exploring the challenges and opportunities associated with supply diversification is crucial for understanding the potential for hard-to-abate industry decarbonization under the risk of future energy price shocks. In this context, we investigate the role of green hydrogen as a viable and sustainable alternative to natural gas applications in iron and steel manufacturing. We first quantify how the integration of green hydrogen into the existing infrastructure can complement stringent climate action ambitions in reducing CO_2 emissions over the next five decades. We find that green hydrogen acts as a transitional technology, enabling a gradual shift towards electrification of heat supply while bridging the gap until low-carbon steel technologies become commercially feasible. Furthermore, we assess the benefits of timely green hydrogen investments in mitigating the economic repercussions of unforeseen natural gas price surges. Overall, this study underscores the potential of green hydrogen in decarbonizing the iron and steel industry while promoting energy independence, but it also highlights its contingency on sufficiently ambitious climate policies and adequate technological advancements.

1. Introduction

The pursuit of low-carbon technologies and sustainable alternatives to fossil fuels represents a critical challenge in today's energy-intensive economy. Achieving ambitious international climate goals significantly depends on the decarbonization of the iron and steel industry. This sector contributes to roughly 7% of global greenhouse gas emissions due to its extensive energy requirements and substantial dependence on fossil fuels [1, 2].

Scientific research into emission reduction strategies for iron and steel production has brought to light important technological hurdles associated with direct decarbonization. These challenges predominantly relate to the reduction processes and high-temperature heat generation, making the related industries known as 'hard-to-abate' [3].

In response to these challenges, green hydrogen has emerged as a viable solution for the indirect electrification of iron and steel production. The advent of clean hydrogen calls for substantial transformations in the structure of industrial fuel supply and associated costs, particularly for replacing coal and coke. This shift requires significant investments in technological advancements and infrastructure expansion. Current discussions on hydrogen adoption primarily focus on its technological maturity and market viability, with a wide range of studies conducted on cost analyses across different deployment strategies [3–8]. Assuming the best current green hydrogen prices of approximately $4 per kilogram, replacing coal in steelmaking could increase the cost of producing one ton of steel by about 30% [9].

An alternative perspective arises when considering the substitution of natural gas—the second-largest fossil fuel consumed in the primary steel industry—with hydrogen. Natural gas is extensively used in iron-making, which accounts for the majority of emissions in the steel production process. It serves as an additional energy source in blast furnace (BF) burners and as a reducing agent in direct reduced iron (DRI) plants. Furthermore, natural gas is employed in steel-making for temperature regulation in basic oxygen furnaces (BOF), for high-temperature generation in electric arc furnaces (EAF), and for additional thermal treatment processes [10].

Numerous studies have assessed the feasibility of adapting existing natural gas infrastructure for hydrogen supply. This adaptation typically does not require modification to process equipment for low to moderate hydrogen shares in the gas mix. Even for higher hydrogen shares, the necessary interventions are generally limited and involve low risk. Additionally, there are opportunities for synergistic development of grid infrastructures for hydrogen delivery to industrial hubs [11–14]. Although natural gas contributes less to greenhouse gas emissions in the steel sector compared to coal, research has highlighted its role as a transitional energy vector. Dual-fuel steel plants are increasingly being considered to replace obsolete mills at the end of their life cycles, aiming to reduce emissions and prepare for the anticipated greater availability and economic competitiveness of hydrogen in the future [15]. These considerations position natural gas as a critical element in the steel industry's strategy to meet increasingly stringent environmental targets.

Furthermore, compared to phasing out coal, the transition from natural gas to hydrogen is expected to result in a relatively modest increase in steel prices. Stricter carbon regulations could raise the costs of fossil-based alternatives, making the relative price increase from hydrogen replacement even less significant. With conservative estimates projecting that green hydrogen prices will fall to $2 per kilogram by 2030 [9], the potential rise in steel production costs could be mitigated by gains from avoided emissions, improved regulatory compliance, and enhanced market positioning. Consequently, substituting natural gas with hydrogen emerges as a practical and advantageous solution for pioneering the adoption of a clean fuel in the energy mix of iron and steel production.

Among the key economic considerations for adopting green hydrogen in iron and steel production is its potential to decouple energy supply from fossil fuel prices, which are heavily influenced by international trade dynamics and geopolitical events. Unlike coal, natural gas prices are highly volatile, creating greater operational risks for steel producers. This volatility is especially concerning because the supply chains of energy-intensive goods like steel are particularly vulnerable to energy price shocks [16].

Yet, previous studies have not comprehensively investigated the role of energy shocks—defined as sudden and substantial disruptions or fluctuations in the availability, supply, or cost of energy resources—and the financial consequences of failing to take preventative measures, particularly for steel producers in countries with high energy dependence. In such regions, today's heat production heavily relies on imported natural gas, making their economies vulnerable to the international fuel markets. The recurrent volatility in energy prices has underscored a widespread undervaluation of the benefits of energy diversification within policy frameworks [17].

This article offers an exhaustive analysis of green hydrogen's role as a clean alternative to natural gas applications in the global iron and steel manufacturing sector, leveraging the repurposing of existing infrastructure. The research explores the trade-off between replacing natural gas consumption and enhancing resilience to energy price fluctuations. Employing the World Induced Technical Change Hybrid (WITCH) model [18, 19], a well-established Integrated Assessment Model (IAM), we evaluate alternative pathways of hydrogen adoption within the iron and steel industry's fuel mix for heat production. This evaluation recognizes green hydrogen's dual benefits in reducing emissions and increasing energy security for the sector.

Our findings indicate that adopting low-carbon hydrogen can facilitate the transitional period towards full electrification in primary steel production, acting as a convenient bridge technology to decarbonize heat generation. Beyond environmental advantages, the shift towards hydrogen has a role in securing the energy infrastructure, diversifying the fuel portfolio and hedging against fossil fuel market disruptions.

2. Methods

2.1. Model overview

This study conducts an environmental and economic analysis using the WITCH model. This IAM combines a top-down representation of the economy with a bottom-up representation of the energy sector for each of 17 macro-regions in which the world is subdivided. Solutions optimize each region's intertemporal utility, based on per capita final good consumption, through different economic and energy investment and consumption decisions [18, 19]. Our analysis focuses on the energy sector, incorporating advancements and deployment of technologies for green hydrogen production and the extraction, trade, and consumption of natural gas.

Table 1. Scenario architecture. The remaining carbon budget quantifies the cumulative global CO_2 emissions from 2020 until 2100 [22] consistent with a given temperature target. The choice of shock magnitude values is based on historical data [23], and quantifies the relative gas price increase with respect to a counterfactual gas price happening in the given shock year.

Dimension	Description	Operationalization
Climate policy	Current pledges	No carbon budget constraint
	2 °C target	RCB[a] = 1150 $GtCO_2$
	1.5 °C target	RCB[a] = 650 $GtCO_2$
Shock period	Early shock	Shock in 2030
	Mid shock	Shock in 2040
	Late shock	Shock in 2050
Shock magnitude	Low shock	Price +50%
	Medium shock	Price +100%
	High shock	Price +300%

[a] RCB: Remaining Carbon Budget.

We design a scenario framework to examine the economic impact of energy shocks on primary steel production over a 50 year period from 2020 to 2070. Scenarios are defined by a combination of dimensions and presented in table 1, including the timing of shocks (*tshock*), which segments the study period into early (2030), mid (2040), and late (2050) phases.

The magnitude of shocks (*pshock*) is based on historical price spikes from geopolitical events, categorized into low (50% increase), medium (100% increase), and high (300% increase) levels relative to baseline prices. This approach draws from Federal Reserve analyses of oil price shocks in the 20th century; notably, the price doubling post-1978 and quadrupling after 1973 due to Middle-Eastern conflicts, including the Iranian Revolution and the OPEC embargo [20, 21].

Climate policy frameworks of scenarios are characterized by different carbon budget constraints: a 'business as usual' scenario adhering to current climate targets without a specific budget, a 2 °C target limited by an 1150 Gtons CO_2 budget to maintain temperature rises below 2 °C from pre-industrial levels, and a 1.5 °C target with a 650 Gtons CO_2 budget. A bisection algorithm translates these budgets into equivalent carbon taxes to achieve the desired climate objective [22].

The policy framework reflects the global level of climate action ambition; the period and magnitude of the shock account for the uncertainty in timing and severity of an energy crisis, potentially triggered by unpredictable geopolitical events.

2.2. Steel industry demand and production

For a detailed sectoral analysis, we develop a specific module for tracking the steel industry dynamics, disentangling this sector from the broader final goods production function of the model. We base our demand model on the steel intensity of use hypothesis, as described in equation (1), which correlates the intensity of use IU with the GDP per capita of each region $\frac{\mathrm{GDP}}{\mathrm{POP}}$, POP being population levels. This relationship is defined through regression coefficients α_i and regional adjustment Dc applied for calibration purposes [24–26], as explained in supplementary note 1.

$$\mathrm{IU}(t,n) = \alpha_0 + \alpha_1\left(\frac{\mathrm{GDP}(t,n)}{\mathrm{POP}(t,n)}\right) + \alpha_2\left(\frac{\mathrm{GDP}(t,n)}{\mathrm{POP}(t,n)}\right)^2 + \alpha_3 t + \sum_{C=1}^{n-1}\alpha_c D_c. \quad (1)$$

The projected global demand for crude steel is exogenous and considered inelastic to changes in steel prices, and therefore to any increase in fuel costs associated with clean hydrogen technologies. Focusing the analysis solely on substituting natural gas with hydrogen implies only a marginal green premium, which is the additional cost of choosing low-carbon alternatives over conventional technologies, due to the relatively minor role of natural gas as an energy source in iron and steel manufacturing compared to coal and coke [9].

We derive national production capacities from the most recent data provided by the Global Energy Monitor's Global Steel Plant Tracker project, calculating each region's share of total manufacturing based on current, under-construction, and planned facilities over a 50 year time horizon [27]. Regional production shares are then estimated using a linear annual distribution of each country's cumulative capacity relative to global steel production, which is explained in more detail in equations (S2)–(S5) of supplementary note 2. Given the inertia involved in the planning and construction of steel mills, these projections offer a realistic estimate of future output, reflecting anticipated developments in the sector over the coming decades.

2.3. Modelling of primary steelmaking technologies and energy supply

We simulate the operation of BF-BOF and DRI-EAF production routes, the two most common manufacturing processes for primary steel from iron ore [28], incorporating key technological and financial metrics from IEA industry reports [10, 29]. The model reflects differences across manufacturing routes in energy inputs and intensity, affecting the fuel requirements per tonne of steel. Material metabolism analysis provides estimates for heat and electricity demand for each technology [30].

The competition between natural gas and hydrogen as heat sources is assessed based on their relative cost per kWh, assuming negligible retrofitting and development costs compared to fuel costs due to strategic reassignment of industrial hubs operating with gas-hydrogen fuel blends [31, 32]. In the model, the energy costs incurred by steelmakers are the product of the quantity of each energy source used times its respective unit cost. The unit cost of natural gas is determined by the dynamics of global market supply and demand, with additional markups due to regional differentiation and the effect of a carbon price when present [19]). The unit cost of green hydrogen reflects the capital and operational expenses associated with its production. Investment costs are calibrated to align with data from the IEA Hydrogen Report [33] up to 2020. The evolution of electrolyzer unit investment costs is driven by endogenous technological change, decreasing as global cumulative capacity expands (see the WITCH Hydrogen section in the supplementary material of [34]). Operational costs include expenditures on green electricity, determined endogenously by supply and demand, as well as operation and maintenance, assumed to remain constant at 4% of capital expenditures. Given the endogenous nature of costs, the model enables the exploration of different long-term trajectories for hydrogen's commercial viability, consistent with different climate policy assumptions.

Across different climate scenarios, higher carbon prices make natural gas more expensive and green electricity relatively cheaper. This can shift the iron and steelmaking energy mix and influence related investment decisions. Endogenous technological learning further accelerates the replacement of natural gas with hydrogen.

To better understand the cost implications of different scenarios and to validate the underlying model's assumptions, we compute the levelized cost of hydrogen (LCOH). This metric represents the average cost of producing and using one kilogram of hydrogen. LCOH serves as a convenient measure for evaluating the economic viability of hydrogen across time periods, regions and scenarios, and facilitates the comparison with existing literature (supplementary note 4).

2.4. Integration of energy shocks

A plausible link between international tensions and volatility in oil and natural gas prices is established through historical observations. We account for the impact of sudden increases in gas prices $FUEL\_PRICE_{gas}$ on steelmakers' fuel costs $COST\_FUEL_{gas}$ by developing an equation that considers shock parameters (*tshock* and *pshock*) and trade balances (equation (2)). We calculate the impact of price surges on imported resources during a shock by analyzing the difference between total fuel consumption Q_FUEL_{gas} and exported fuel Q_OUT_{gas}. This approach highlights the asymmetric effects of energy crises, as detailed in supplementary note 3 (equations (S6)–(S8)). Regional adjustments to gas prices p_markup_{gas} remain unaffected, as they only reflect local infrastructural costs.

$$\begin{aligned} COST\_FUEL_{gas}(t,n) = {} & FUEL\_PRICE_{gas}(t,n) \\ & \times \left(1 + pshock_{gas}(t,n)_{t=tshock}\right) \\ & \times \left(Q\_FUEL_{gas}(t,n) \right. \\ & \left. - Q\_OUT_{gas}(t,n)\right) \\ & + p\_markup_{gas}(t,n) \\ & \times Q\_FUEL_{gas}(t,n) \qquad (2) \end{aligned}$$

2.5. Unpredictability of energy shocks

By default, regions optimize their decisions intertemporally with perfect foresight in an open-loop Nash equilibrium. To prevent agents from taking preventive action against the precise year and magnitude of the upcoming energy shock, we consider 'myopic' runs. In these runs, the solution is fixed to its non-shocked counterfactual until *tshock* - 1, with optimization occurring only from *tshock* onwards. This adjustment is needed to capture the unpredictable nature of future large-scale international disruptions. As a result, we assume no proactive changes to the energy mix or technological assets are made in anticipation of the shock, and energy diversification depends solely on national energy policies.

3. Results

3.1. Decarbonization potential of green hydrogen

Our analysis focuses on projections from 2020 to 2070 for global long-term optimization of the coupled climate-energy-economy system. The results show the dynamics of energy supply and demand, track CO_2 emissions from fossil fuel combustion, industrial processes, and land use, and support the exploration of alternative carbon pricing mechanisms set according to desired cumulative emissions targets (see table 1).

Here, we extend the iron and steel industry representation within the model, introducing the technological competition between BF-BOF and DRI-EAF production routes (supplementary figure 1), as well as global steel market consumption and supply trends. We calibrate the extended model using historical data from the World Steel Association (figure 1(a)). With most of the existing and planned iron and steel manufacturing capacity concentrated in Europe and Asia, the model projects that Eurasia will maintain its position as the primary hub for steelmaking over the next 50 years [35]. The uneven distribution of crude steel production, with China, Europe, Japan–South Korea, and India collectively representing more than 75% of total output, is analyzed through the lens of natural gas trade. Trade balance indicates energy

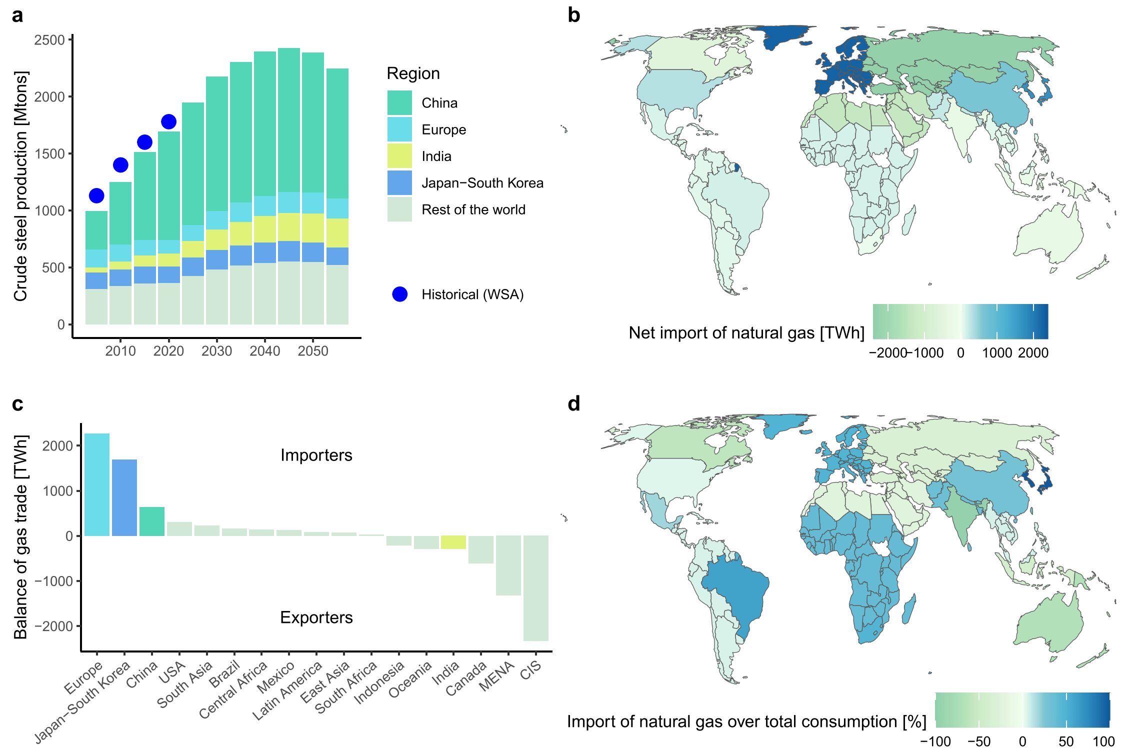


Figure 1. Shares of crude steel production among leading steel manufacturing countries and their dependence on imported natural gas. (a) Crude steel production in megatons over 50 years, with a focus on leading producers: China, Japan, South Korea, India, and Europe. Historical data in blue comes from the World Steel Association. (b) and (d). Energy dependency, represented as the net import of natural gas in terawatt-hours (TWh, (b)) and as the ratio of imported to total natural gas consumption (%, (d)) for each region. Countries in darker blue are net importers, whereas darker green denotes net exporters. (c) Regions ranked by natural gas imports, noting that three of the four largest steel industries (Europe, Japan–South Korea, and China) are among the top three.

dependence in the industry, given natural gas's critical role in steel manufacturing (refer to figures 1(b)–(d)). The largest net natural gas importers—China, Europe, and Japan–South Korea—depend heavily on external supplies for their domestic consumption. Their energy dependence, coupled with extensive crude steel production, makes these countries particularly vulnerable to gas market fluctuations and highlights opportunities for transitioning to alternative fuels.

We focus on the natural gas demand for ironmaking and steelmaking in energy-dependent countries (supplementary figure 2) and examine the competition between gas and hydrogen under varying climate policy stringency. Although current climate pledges may not sufficiently promote hydrogen adoption in industry, regions with ample renewable energy resources to produce green hydrogen are likely to respond swiftly to carbon pricing mechanisms (see figure 2). Furthermore, the model's estimations confirm the pivotal shift from the BF-BOF method of primary steelmaking to the DRI-EAF route [35], signaling increased electrification in the steel industry's energy mix. The growing share of DRI-EAF plants indicates a reduction in fossil fuel intensity, contributing alongside the integration of hydrogen as a crucial element in the sector's decarbonization pathway.

Among the primary steel producers, Europe is estimated to satisfy 79% of its steelmaking natural gas demand with hydrogen by 2040 under a 2 °C target and 88% under a 1.5 °C target. China—responsible for over half of the global crude steel production—shows a more gradual but eventually similar decarbonization. By 2050, hydrogen is projected to supply 89% of China's steelmaking natural gas demand under a 2 °C target and 92% under a 1.5 °C target (figure 2(a)). The increasing adoption of hydrogen in these regions and the transition from BF-BOF to DRI-EAF may lead to nearly complete substitution by 2060 in various climate scenarios, irrespective of the carbon budget.

However, Japan and South Korea exemplify countries where development is constrained by renewable energy availability, and even substantial policy interventions may result in delayed hydrogen adoption in the industry. The regional deployment of renewable energy capacity presented in supplementary figure 3 is therefore affirmed as an essential factor for scaling up the production of green hydrogen. This is further evidenced by the smaller relative decrease in LCOH in Japan and South Korea compared to Europe and China, due to slower technological learning.

Our projections for the levelized costs of hydrogen align with the expected ranges reported in the

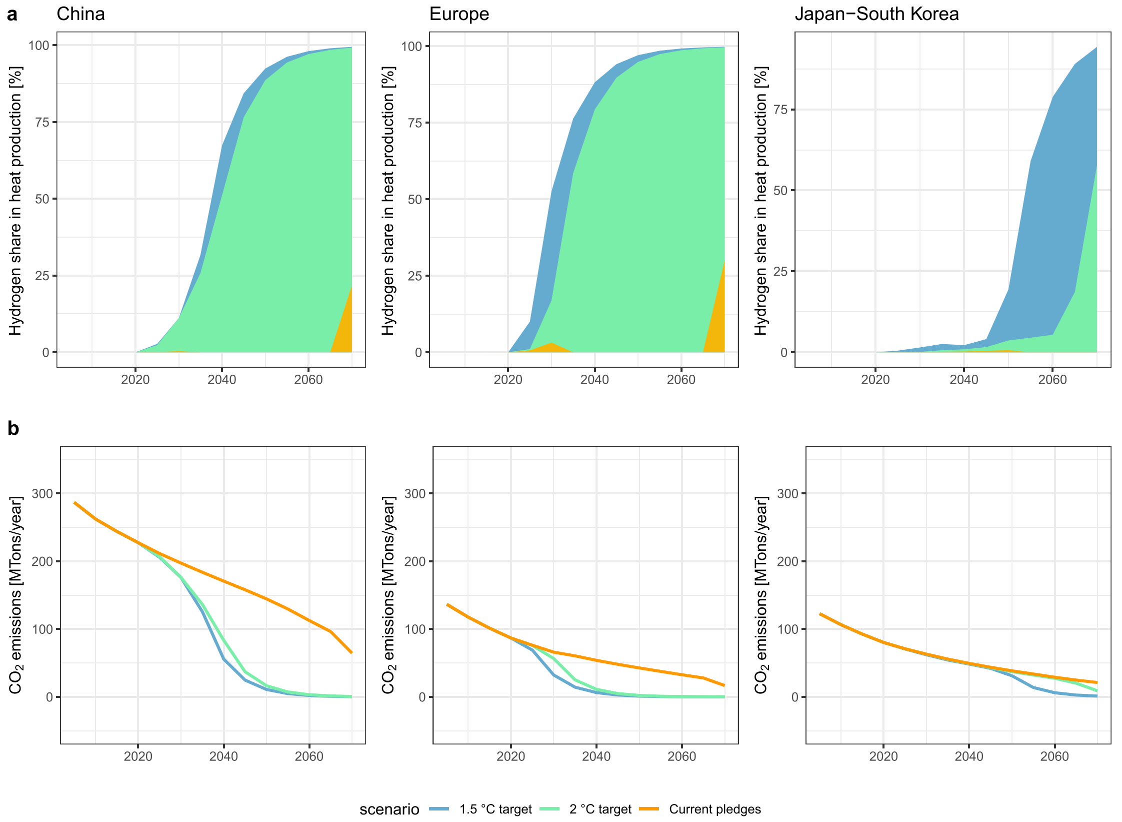


Figure 2. Trajectories of decarbonization in primary steelmaking natural gas consumption for China, Europe, and Japan–South Korea under various climate scenarios. (a) The proportion of hydrogen in the energy mix for the iron and steel industry's heat supply. (b) Yearly CO_2 emissions from heat generation through natural gas in crude steel production, measured in megatons.

literature and underscore the interplay between costs, time and and climate policy ambition. For short-term projections (2030), we estimate LCOH values between $2.8 and $4.8 per kilogram. The lower end of this range aligns with conservative literature estimates of $2 per kilogram for 2030, while the upper end is consistent with current estimates of $4 per kilogram. Long-term projections (2050) indicate a decline in LCOH, with values ranging from $1.7 to $3.4 per kilogram (supplementary table 2). Stricter climate targets are generally associated with higher LCOH values due to a greater need for accelerated investments in green hydrogen production and renewable energy deployment, especially in the short term. Nonetheless, over the long term, stricter climate targets lead to larger drops in LCOH, in most cases leading to values below those of current pledges, as technological change and economies of scale lower production costs. These trends reflect the trade-offs between short- and long-term costs of ambitious climate policies, as well as the synergistic impact of technological advancements and policy-driven investments in accelerating the transition to green hydrogen and renewable energy.

By 2050, under a 2 °C target, the shift in fuel supply is expected to yield cumulative emission reductions of 2048 megatons of CO_2 for China, 857 megatons for Europe, and 12 megatons for Japan–South Korea (figure 2(b)). Our analysis suggests that hydrogen could reduce global direct emissions from the steel industry by 4%, contributing to the 2050 target of 54% direct reduction from the sector for a decarbonization trajectory in line with the Paris Agreement [10].

This result has significant implications, as it considers only the introduction of green hydrogen as the first clean and cost-effective alternative for natural gas applications. The gradual adoption of hydrogen in the sector could serve as a bridging solution, facilitating sector integration and potentially generating spillover effects that could further reduce CO_2 emissions from coal consumption through H-DRI. Additionally, the implementation of other mitigation strategies, such as carbon capture, utilization, and storage, bioenergy, and electrification through molten oxide electrolysis, is expected to play a complementary long-term role in the iron and steel industry, contributing to the achievement of emission reduction targets.

3.2. Mitigation of economic risks from energy price shocks

Incorporating unexpected energy shocks in the scenarios above allows for an analysis of the economic disruptions faced by major steel producers when sudden increases in natural gas prices cause unforeseen fuel expenditures to energy-importing countries.

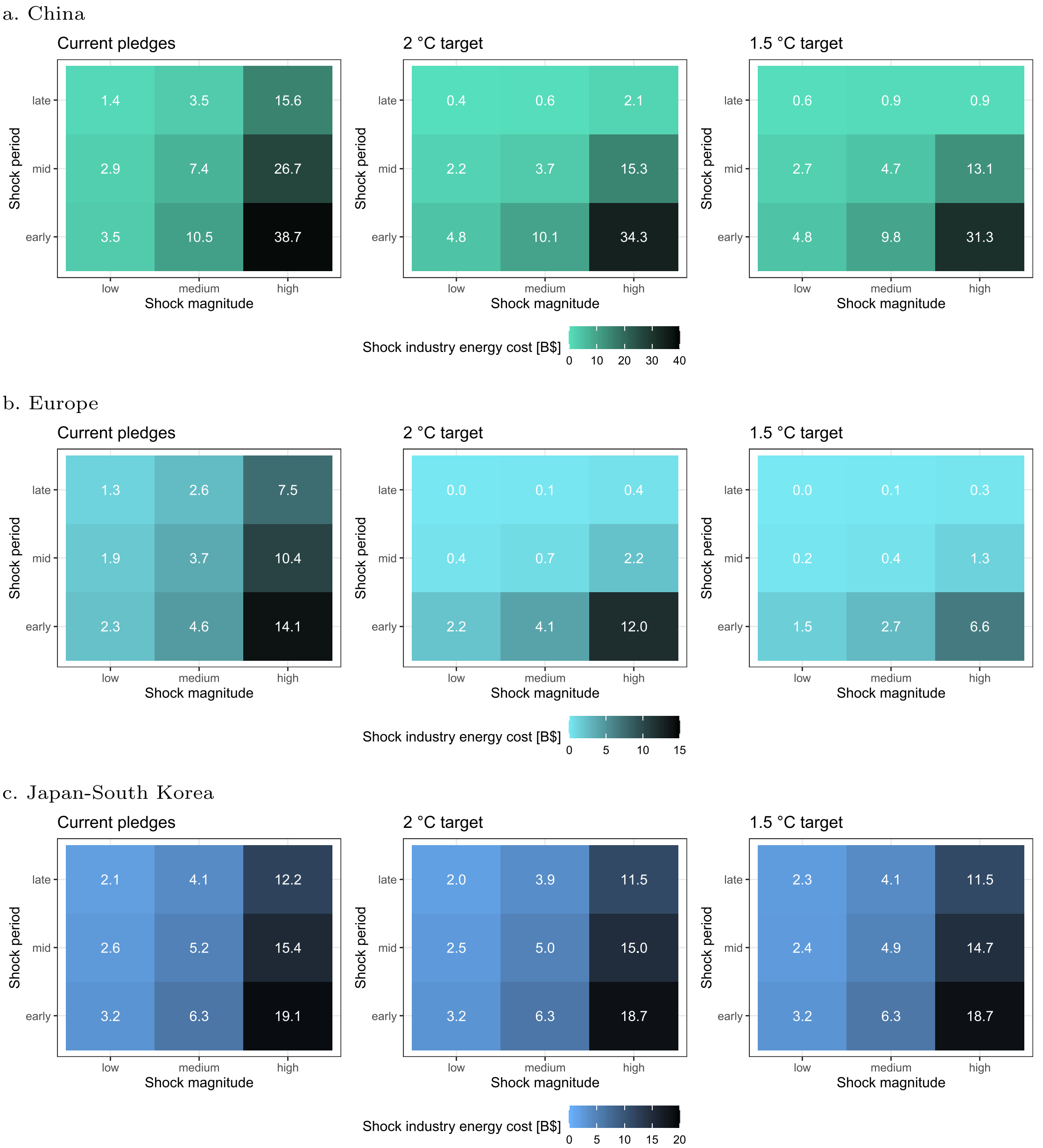


Figure 3. Economic impact of energy shocks on fuel expenditures for the steel industry. (a)–(c) The cost of inaction for steelmakers, expressed in billions USD (2005), to secure natural gas supply during an energy shock without reducing manufacturing output in China (a), Europe (b), and Japan–South Korea (c).

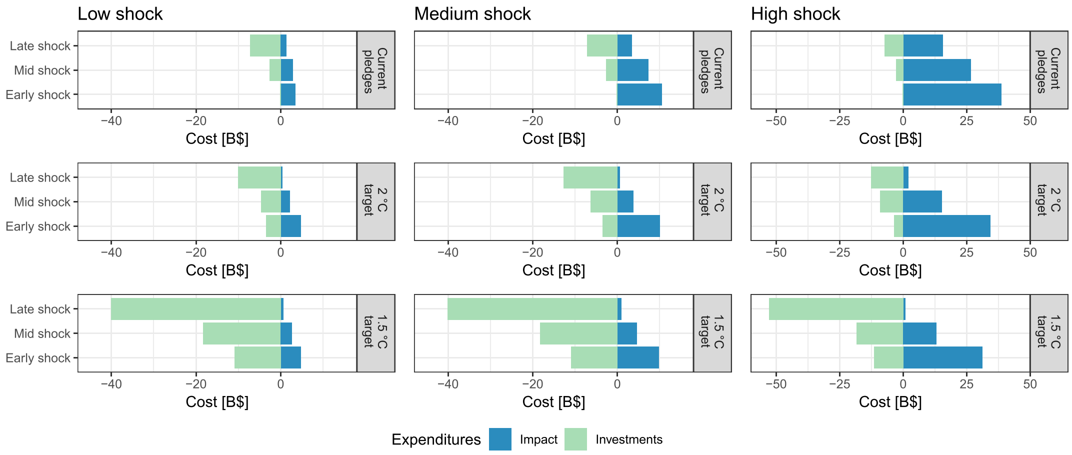
The impact of a gas price shock on countries varies depending on their energy trade balances, with surcharges proportional to the amount of imported fossil fuels in their energy mix. The steel industry is particularly susceptible to such shocks, as 70% of global crude steel production is located in regions with significant energy dependencies.

We evaluate the ‘cost of inaction’, defined as the economic setbacks steelmakers face when they delay or fail to invest in energy security strategies to mitigate the effects of energy shocks. The discrepancy in fuel expenses between the non-shocked counterfactual scenario and the shocked scenario indicates the potential financial repercussions of a sudden energy crisis. Figure 3 shows that the risk from premature or significant shocks is intensified by the lack of a timely diversification of the heat supply.

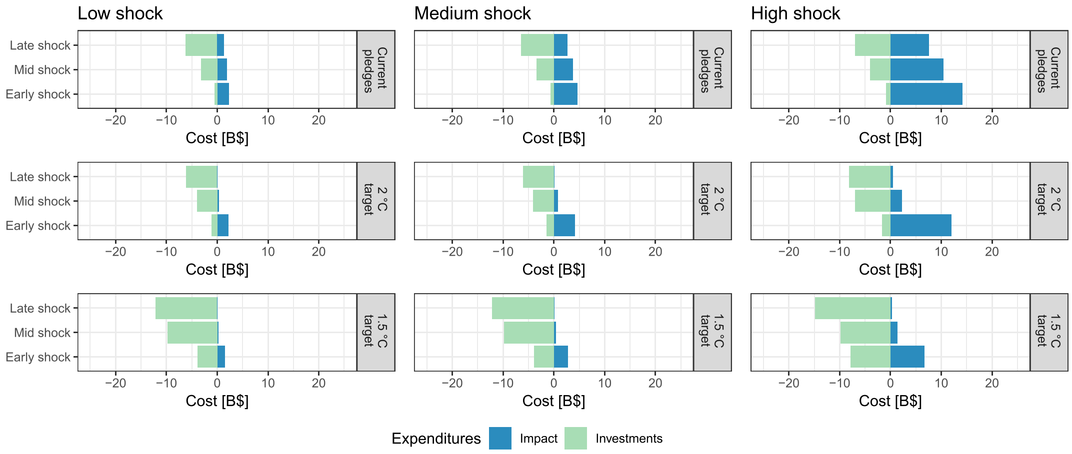
In scenarios that limit global temperature to 2 °C and 1.5 °C, the improvement in resilience to shocks through hydrogen adoption becomes apparent. This is especially noticeable once the share of alternative fuels exceeds 80%, at which point the economic impact is limited to a minimal fraction of the industry’s value.

The benefits of avoided fuel expenditures under gas price shocks come at a cost: the cumulative investments in green hydrogen technologies prior to those shocks. Figure 4 demonstrates the correlation between the benefits and costs of preventive action. Increasing the stringency of climate targets ensures higher financial commitments for hydrogen

a. China



b. Europe



c. Japan-South Korea

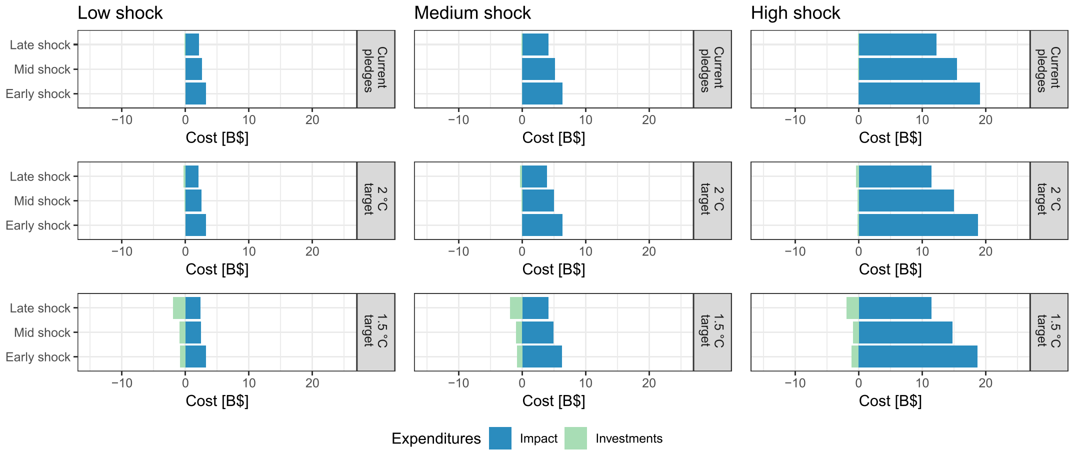


Figure 4. Interplay between financial impacts of energy crises and preemptive investments in hydrogen technologies. (a)–(c), An inverse relationship is observed between the capital allocated for developing hydrogen supply and the additional fuel costs incurred by steelmakers during an energy market shock in China (a), Europe (b), and Japan–South Korea (c).

adoption and consequently for energy diversification, thereby mitigating the economic fallout of energy crises in regions dependent on natural gas imports. The distribution of investment flows over time also matters in determining the steelmaking industry's ability to withstand market disruptions: speeding up investments boosts the industry's resilience against future financial risks (supplementary figures 4–6 and supplementary table 1). Overall, figure 4 highlights the possibility of reallocating funds towards the development of reliable and clean hydrogen infrastructure for a more sustainable and resilient steelmaking sector. This cost transfer could offset potential expenditures on natural gas procurement that steelmakers would otherwise incur when exposed to shock-induced high fuel prices.

4. Discussion

Implementing hydrogen as a sustainable heat generation method could act as an interim solution for decarbonization before other low-carbon steel technologies become a viable strategy, contingent on sufficient renewable energy capacity and the implementation of effective carbon pricing policies.

Proactive policymaking can mitigate the costs associated with inaction during sudden energy shocks by investing early in the development of a secure and resilient energy infrastructure. Reducing reliance on natural gas can provide long-term economic benefits for energy-importing countries and facilitate the decarbonization of emission-intensive, hard-to-abate industries. This transition can support energy-dependent countries in achieving strategic energy autonomy, a key priority on their national agendas to address risks related to debt and inflation. As energy diversification through sustainable technologies progresses, hydrogen is likely to be increasingly recognized as a crucial measure for diminishing the impact of international geopolitical dynamics on the energy sector and critical industries.

Limitations stem from the inherent uncertainties in modelling long-term scenarios. On the one hand, a full shift towards electricity-based manufacturing in the steel industry over the next decades might be overly optimistic. In such scenarios, fossil fuel dependency from heat generation might be underestimated, and hydrogen would play an even bigger role as a bridge fuel towards green steelmaking. On the other hand, projecting global steel demand based on past correlations with GDP per capita may be blind to unexpected saturation points or price elasticity of green steel demand, potentially reducing future crude steel consumption. However, the ongoing need for maintenance and replacement of steel components in public infrastructure could maintain demand at a relatively stable level, with energy consumption changes primarily dependent on efficiency improvements and fuel substitution. Future research could expand the exploratory approach initiated with this work.

Overall, this research highlights the combined environmental and economic benefits of green hydrogen in decarbonizing the iron and steel industry, and the role of stringent climate policies in fostering its timely adoption. Prioritizing hydrogen investments over the coming decades can help industries and policymakers reduce the impact of global fuel markets on heat generation costs, mitigating some of the economic risks linked to geopolitical instability. The adoption of hydrogen in steelmaking could serve as a model also for other high-emission industries like cement and petrochemicals, which face similar environmental and economic challenges due to their dependence on fossil fuels [29, 36]. Also in these cases, this strategy could offer the societal benefit of decarbonizing hard-to-abate sectors while enhancing energy independence and resilience to geopolitical tensions.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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