Hydrogen Supply for Steelmaking's Energy Transition

An IAM-based study on economic and environmental opportunities of fuel diversification under the threat of energy shocks

Thesis Report

Nicola Leuratti

TU Delft

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Nicola Leuratti

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Thesis committee:

Chair:	Prof. Dr. Ir. Jan Kwakkel
Supervisors:	Dr. Linda Kamp
	Dr. Giacomo Marangoni
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Student number:	5471877

Faculty of Electrical Engineering, Mathematics and Computer Science

Summary

In the pursuit of low-carbon technologies and sustainable alternatives to fossil fuels essential to hand on to future generations a safe and livable planet, hydrogen has attracted engineering interest as a promising vector for storing and carrying clean energy that would help decarbonize society. Scientific research and technological trends indicate that heavy industries, especially steelmaking, might represent an excellent opportunity to consistently integrate the consumption of hydrogen into the manufacturing processes. This is likely to deliver substantial emissions savings as the steel industry, widely recognized to be a hard-to-abate sector, accounts for a large portion of the global pollution every year. Besides the heated debate on the technical and financial challenges related to deployment constraints and cost increases, the geopolitical risk of energy crises impacting the economic output of industries in energy-importing countries is neglected in the decision-making considerations, overlooking the critical implications of energy diversification on long-term planning.

The aim of this study is thus to investigate the competition between hydrogen and natural gas for high-temperature heat generation in steel manufacturing while considering the potential impact of energy shocks on fuel expenditures. Addressing these dynamics would have significant consequences for the interplay between policymaking and industrial energy transition as it uncovers the relevance of sustainable energy resiliency to energy crises induced by geopolitical disruptions.

To achieve the objectives of the project, an Integrated Assessment Model-based study has been conducted using the WITCH model, which required several improvements in the framework. The steel industry module was conceptualized and developed to describe the technology sets, the financial and technical constraints, the future projections of the steel market and the energy supply structure. Moreover, even though a prior version of the hydrogen supply was already in the model, the equations of the related module were modified to account for the consumption of hydrogen as a fuel in steel mills and to ensure compatibility with the expansion to the industrial sector. To allow for accurate integration of energy shocks in the model algorithm, the existing dynamics that describe the trajectories of fuel costs were then expanded and used to account for different shocks' intensities, time periods and the degree of energy dependency of the affected region. Finally, a scenario architecture suitable to capture the main variables of the analysis was designed to prepare a sensitivity analysis focused on the magnitude of the shock, the year of occurrence and the level of environmental commitment implemented.

The outcome of the simulations shows that most of the production of steel will be located in energy-dependent countries, where energy shocks impact fuel expenditures on a national scale. The financial damages perceived by steelmakers are exacerbated by large magnitudes of the increase in price and by early shocks, which would strike the industry before the development of alternative sourcing of fuels. The regulatory push to support sustainable technologies has the potential to effectively dampen the impact of shocks and decarbonize the energy mix in steelmaking by accelerating investment cycles and promoting the deployment of low-carbon hydrogen. Further explorations of the correlation between preventive investments in hydrogen and perceived disruptions in industrial production have proven how large-scale investments for alternative and secure supply of hydrogen yield long-lasting resiliency to energy crises, while lagging intervention exposes the industry to the risk of wide costs of inaction.

The results of the research have practical significance for both industrial and political decision-making. Risk-averse managers of steelmaking facilities might decide to allocate financial resources for early conversion from natural gas to hydrogen to guard against the possibility of energy shock backlash. Policymakers can produce long-term plans to stimulate the transition to green hydrogen with tailored carbon pricing, which would result in an expense transfer from the potential costs of the backlash of energy shock to the proactive development of secure and resilient hydrogen production. Besides the contribution to national environmental goals, this transformation would yield stabilization and permanent immunization of the industrial energy supply against the reoccurrence of shocks. This can safeguard not only the manufacturing sector but also the national economy overall, as the increased expenditures endured by steelmakers would translate into rising costs for infrastructural development in the country.

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Nomenclature

List of Abbreviations

BAT Best Available Technology

BF-BOF Blast Furnace Basic Oxygen Furnace

BoT Balance of Trade

CCS Carbon Capture and Storage

DRI-EAF Direct Reduced Iron Electric Arc Furnace

EVs Electric Vehicles

GHG Green House Gasses

HTA Hard To Abate

IAM Integrated Assessment Model

ICE Internal Combustion Engine

LCOH Levelized Cost Of Hydrogen

P2G Power To Gas

PEM Proton Exchange Membrane

RCB Remaining Carbon Budget

SGR Steam Gas Reforming

SOEC Solid Oxide Electrolysis Cell

List of Symbols

δ Capital depreciation rate

η Degree of relative risk aversion

λ Steel mills inertia parameter

ρ Discount rate

ξ Transformation efficiency

D_steel Steel demand

ei_bf Electricity intensity - blast furnace

ei_eaf Electricity intensity - electric arc furnace

hi_bf Heat intensity - blast furnace

hi_eaf Heat intensity - electric arc furnace

K_EN_j Capital stock of j technology

P_steel Steel production

Q_EN_j Energy generation of j technology

Q_FUEL_f Energy consumption of f fuel

$Q\_IN_{j,f}$ Energy consumption of f fuel in j technology

Q_OUT_f Energy production from extraction of f fuel

QEL_OUT_j Energy generation of j technology

S Steel production capacity

t Time-step

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Introduction

In this introductory chapter, the general context of the report is outlined by highlighting the necessity of a sustainable energy carrier infrastructure to support the energy transformation of the current economy and by describing the potential of hydrogen as a decarbonization driver in heavy industry, a crucial sector responsible for large amounts of emissions every year. Afterward, the importance of considering the impact of geopolitical disruptions in policymaking is introduced with regard to the specific case of hydrogen for hard-to-abate industries. Finally, the problem studied, the scope of the work and the research questions is summarized and the thesis report structure is presented.

1.1. The crucial role of sustainable energy carriers in achieving net zero

Technology and innovation have propelled our society to levels of welfare never achieved in the entire history of humanity, with remarkable improvements on life quality and expectancy but at the same time with serious consequences on the planetary equilibrium. Global warming, once debated to be merely part of recurrent Earth's climate cycles, is nowadays attributed to anthropogenic causes by the entire scientific community. The unprecedented changes in global temperature detected are proved to be the effect of postindustrial human activities, especially of the release of greenhouse gases (GHG) in the atmosphere resulting from the production and consumption of goods and services.

Today's extremely energy-intensive economy is characterized by a massive use of fossil fuels as energy carriers and the increasing concern for global warming deriving from the systematic use of coal, oil and natural gas is deeply influencing governments and regulatory institutions. Countries and coalitions all over the world have been trying to shift their energy infrastructure from the traditional fossil-based system to sustainable energy technologies. This process is crucial as the energy sector, which consists of energy production and consumption in the industry, residential, commercial and transport, accounts for more than 80% of the total greenhouse gas emissions generated in the European Union (EEA, 2021) and almost 75% of the global greenhouse gas emissions (Ritchie et al., 2020).

Tackling the main challenges of developing a sustainable energy infrastructure would contribute considerably to meeting some of the most important climate change targets set by international coalitions, especially limiting the temperature increase to 1.5 C° by globally reaching net-zero around 2050 (IPCC, 2022). However, the current infrastructure needs to adapt and evolve in several directions to be able to sustain this transition. A significant discussion revolves around the theme of energy carriers and their strategic position in the energy supply chain as the connection of primary sources and end-use applications.

1.2. Hydrogen: a complementary decarbonization driver for industrial sector

The replacement of fossil fuels with low-carbon electricity as energy source, also known as direct electrification, is nowadays an affirmed solution for supporting the decarbonization efforts of our society, especially for transportation and buildings. This option will represent the backbone of the future green infrastructure even if substantial investments and deployment of commercially available technologies will be necessary in the near future (Chen et al., 2022).

At the same time, the momentum gained by the progressive shift to cleaner systems also exposed some of the barriers that technological innovation will face and new ideas have been explored: the implementation of an infrastructure to produce, store, distribute and transform hydrogen generated from electrolysis is now recognized to have decarbonization potential for hard-to-abate and hard-to-electrify sectors as a clean synthetic fuel and as a complementary energy vector (Hosseini and Wahid, 2016). Forerunning initiatives for hydrogen adoption have been proposed and upheld in countries like Europe, with the RePower EU Plan, and China, with the Hydrogen Industry Development Plan 2021-2035, to promote financial and political support for technological development and integration. The introduction of similar programs in national development plans is considered a strategic choice for carbon neutrality goals and energy systems transformation.

Steel, cement and chemicals are the heavy industries with the largest contribution to GHG emissions, around 70% of the entire industrial sector, and therefore with the highest potential of delivering fossil fuels savings and emissions reduction. These applications are expected to experience increasing demand for hydrogen but the current prospects are not sufficient to successfully meet most of the national and global climate pledges, as emerging sustainable technologies are usually characterized by higher risks related to technological immaturity and financial returns uncertainty (Alkemade and Suurs, 2012).
Moreover, the lack of policies to stimulate demand and to support an international hydrogen market are identified to be the main barriers to the attraction of investments (IEA, 2022) and several governments across the world are lagging in addressing these challenges with sufficient attention.

1.3. The impact of unforeseen geopolitical events on the long-run resiliency

The debate surrounding future energy vectors has gained significant traction in recent years. Yet, the political milieu necessary to support technological advancement is often overlooked, underestimating the importance of global politics and energy sources international trade in the decision-making processes of the current era's complex and intricate geopolitical arena. Unforeseen disruptions in energy-exporting regions are a variable that cannot be ignored because of their impact on the delicate equilibrium between nations and therefore potentially affecting energy markets, with significant repercussions on national economies across the world. Commodity price shocks, induced scarcity of natural resources, geopolitical instabilities and military conflicts are examples of events that frequently disturb the socioeconomic environment where technology innovation takes place, with consequences on deployment costs and international trade (Ciola et al., 2023).

In particular, many examples from the near past indicate that energy price shocks are often caused by turmoil in the supply industry of the most dominant energy source and that international trade development contributes to dampening the shocks' effect on the global economy (van de Ven and Fouquet, 2017). These dynamics merit wider investigation as global energy crises have been producing consequences on the energy transition and raising awareness about energy security and diversification, issues that concern sustainable development goals and pledges of countries and coalitions.

1.4. Project overview and outline

This thesis aims to study the decarbonization potential of hydrogen in the steel industry and to analyze the competition for financial and technological resources of energy vectors under the threat of energy shocks. The results will be used to assess the role played by hydrogen technologies deployment and by policy and regulatory activities in enhancing energy resiliency and security of steel manufacturing. Therefore, the following research question is intended to be answered:

"How can the adoption of hydrogen in steelmaking support the industry decarbonization and the resiliency to energy shocks as an alternative heat carrier in energy-dependent countries?"

To do so, an Integrated Assessment Model (IAM)-based study will be conducted. The WITCH model will be used to integrate comprehensive modeling of hydrogen in the steel industry and to produce long-term development scenarios. A combined analysis of geopolitical impact and vulnerability to energy shocks will be included in the research to derive relevant insights on the resiliency of the future energy carriers' infrastructure in heavy industry.
This project will be supported by RFF-CMCC European Institute on Economics and the Environment (EIEE), the research institute that developed the WITCH model. The team has provided the opportunity to collaborate with the researchers and scientists who created and evolved the model to expand the hydrogen section and develop an industry module by spending a visiting period at the Milan office of Via Bergognone 34, Italy.

The present document is structured as follows.
Chapter 2 presents an overview of the scientific publications and the most relevant research on decarbonization strategies for heavy industry, the technological advancements of hydrogen technologies, its potential as a sustainable energy carrier and the role of energy dependency on the markets during energy crises. In Chapter 3, the model is introduced and the development methodology to achieve the research objectives is described, covering the modeling of hydrogen supply for steelmaking and the integration of energy shocks proportional to the degree of national energy dependency. Chapter 4 contains the processing of the model outcome and the analytics investigated for the steel industry projections as well as the identified patterns in the correlations between investments in hydrogen and the impact of energy crises. In Chapter 5, the discussion of the findings and the implication of considering energy resiliency in the decision-making debates concerning investments to develop a secure supply of energy is presented. To provide a comprehensive picture of the study, the key limitations encountered and acknowledged are then detailed. Finally, Chapter 6 addresses the research questions and the practical implications represented by the analysis of hydrogen potential for policymaking. It then concludes the report by addressing the potential of future work to delve into the analysis with a broader understanding of technological and geopolitical dynamics.

2

Literature Review

This chapter presents the literature review conducted to collect information from the most relevant studies produced on the topic of this thesis. This is a prerequisite to provide the background context, summarize the state-of-the-art research, and justify the academic position of the work. The reviewed literature is detailed starting with the characteristics and challenges of the heavy industrial sector, followed by an overview of the current role of hydrogen among energy carriers mix. Finally, the geopolitical perspective of the project is introduced by explaining the role of energy shocks in the transition of energy-dependent countries.

2.1. Transitioning hard-to-abate industries

The existing body of literature on future energy carrier systems consists of a wide range of research both for scope and approach, demonstrating the relevance of the topic with regard to decarbonization projects across sectors and countries.

Several studies regarding the deep electrification of transportation and buildings seem to agree on its pivotal role in greenhouse gas mitigation both in the short and long-term scenarios. Electric vehicles (EVs) are nowadays recognized to be cost-effective competitors of internal combustion engines (ICEs) and the market growth experienced seems to confirm their potential to limit the generation of GHG in road transport. The fleet electrification in EU, for instance, could decarbonize between 70% and 80% of sector emissions based on the percentage of electrified cars in the total fleet (Krause et al., 2020). Similarly, due to the technological maturity, 90% of personal transport needs in the United States can be met by current electric vehicles' performance, with a potential reduction of 60% in gasoline consumption, especially in the cities (Needell et al., 2016).
Many of these results are inducing the promotion of a phase-out of ICEs by governments, accelerating the adoption of EVs by attracting more investments and subsidies. The increasing share of renewables in the power sector and the consequential decrease of the carbon footprint of grid electricity will also produce a cumulative effect, abating life cycle emissions and costs (R. Zhang and Fujimori, 2020).

Even more promising is the direct electrification of residential and commercial buildings. Almost 100% of the energy consumption of a building can be covered with electric technologies that are in use today and the main challenges seem to be related to costs rather than technical constraints. Nonetheless, full electrification is already a cost-effective solution in particular for milder climates and new residential buildings (Deason and Borgeson, 2019).

The main contribution to environmental mitigation for the sector is the electrification of energy end-uses of the building, which is demonstrated to be an economically feasible and solid strategy for energy efficiency improvements by optimization models; results show that electrifying end-uses is also a preferred choice for long-term policy and regulatory activity, with cities and urban areas becoming increasingly important in environmental targets (Leibowicz et al., 2018).

On the other hand, direct electrification of industrial operations is currently a crucial aspect of the growing concern for the global carbon budget. Research and development efforts have been producing new solutions to electrify also several manufacturing processes, even where thermal sources used to be irreplaceable: advanced technologies, such as arc furnaces, plasma technologies and infrared/microwave heating are becoming profitable options for large-scale production of many industrial goods across different industries (Lechtenböhmer et al., 2016).

However, the production of steel, cement and petrochemicals has been at the heart of the debate around the transition of the industrial sector to cleaner technologies. In fact, these industries are the largest sources of industrial emissions but the levels of high-temperature heat required for the transformation of raw materials into refined products are impractical to achieve even with modern industrial electric technologies. Moreover, some of the most important processes of this sector rely heavily on fossil fuels not only for high-temperature energy but also as chemical feedstock.
The iron and steel industry, accounting for almost 8% of the global GHG emissions alone, requires clean alternatives to fossil fuels for the chemical reduction of iron ore and for the high-heat operation of blast furnaces since both of these processes are almost entirely fueled by coal or natural gas (Fan and Friedmann, 2021).
Cement production requires the powering of industrial kilns while petrochemical industries need oil and natural gas as input for chemical production, with a cumulative share of GHG emissions of 11% in 2020 (IEA, 2020a).
Different options have been studied for each of these crucial manufacturers, trying to identify every possible strategy to reduce the emissions generated during the operation of production plants.

Among hard-to-abate (HTA) industries, steelmaking has been recognized for its favorable position in the transition to low-carbon technologies. The environmental impact of treating iron ore to manufacture steel is drawing the attention of researchers and engineers working to develop efficient solutions to tackle process emissions while containing costs and keeping the final product competitive on a global market characterized by tight profit margins. Innovation and technical learning appear to indicate that the steel industry is also a promising sector for improvements in energy efficiency and alternative fuels. For the production of iron and steel, widely acknowledged studies (Rissman et al., 2020; Napp et al., 2014; Ren et al., 2021) presented technical pathways to decarbonize the industry and highlighted the necessity of energy savings by phasing out inefficient furnaces for best available technologies (BAT) and by recovering waste gas as thermal source. On top of energy efficiency, ultra-low carbon technologies such as hydrogen-based steelmaking and carbon capture and storage (CCS) integration seem to be the only viable technological options for a deep emissions abatement.

In the modern steel and iron industry, two technologies account for almost the entire global production of steel: blast furnaces (BF), with nearly 70% of the industrial production, and electric arc furnaces (EAF), covering almost 30% of the remaining steelmaking output. Moreover, three production routes are based on these technologies with important differences in terms of processes, material and energy intensities, namely the blast furnace basic oxygen furnace (BF-BOF), the direct reduced iron electric arc furnace (DRI-EAF) and the steel scarp electric arc furnace (scrap-EAF). Steel recycling, also known as secondary

steel production, is almost entirely based on scrap-EAF, which is the most energy-efficient process but at the same time severely limited by the availability of steel scrap (Fan and Friedmann, 2021). Primary steel production is the most polluting and technically complex route in the sector. Nonetheless, projections show that it will experience a stable demand increase in the future as steel continues to represent a fundamental element for urban and infrastructural growth, especially in developing countries (IEA, 2020b).
The BF-BOF route consists of the reduction of iron ore in a BF fuelled by coal, followed by the transformation into steel in the BOF. DRI-EAF is based on the reduction of iron by means of a reducing gas, usually syngas, to feed the EAF with charged material for the production of steel (Fan and Friedmann, 2021).
The steelmaking processes that will compete in the market are distinguished by different factors on a technical and economic level. As previously mentioned, BF-BOF is largely the most diffused option in the industry while DRI-EAF is relatively a less mature and more expensive technology. However, the difference in energy intensity makes DRI-EAF a more fuel-efficient technology, with relevant implications on the future potential of this production route.

These challenges represent a tremendous opportunity for emissions savings and hydrogen is progressively gaining a leading position as the future decarbonization driver of the steel manufacturing industry.

2.2. Hydrogen technological outlook

Despite the current research on the potential of hydrogen as an innovative solution for the decarbonization of the energy sector, this element has been studied and applied several times for the past 200 years. The first electrolysis and the following development of liquid hydrogen and fuel cells date back to the 19th century (Dawood et al., 2020). Large-scale applications of hydrogen propulsion characterized the following century, with fuel cell road vehicles developed at General Motors, but also airships with hydrogen as lifting gas for long-distance transports and jet engines with liquid hydrogen fuel for NASA's space exploration (Smolinka et al., 2022).

The engineering interest in hydrogen is justified by some of its properties. Not only it is the simplest and most abundant element in the universe, hydrogen is also an effective energy carrier with 120 MJ/kg, almost three times the energy content of gasoline. Moreover, it is widely recognized as a promising sustainable fuel as it does not produce CO_2 when burned and as it is suitable for storage in compressed tanks and distribution in pipelines. However, when considering the volumetric value, the energy density of hydrogen is substantially lower: carrying only 8MJ of energy per liter poses some relevant limitations to high-density storage.

From a technical perspective, hydrogen does not exist naturally thus it requires the extraction from other compounds. It can be produced by both renewable and non-renewable sources: the first route consists of separating hydrogen and oxygen in water via electrolysis, the second is the separation from hydrocarbons by heating with the reforming process.
The production route is nowadays used to classify different types of hydrogen based on their environmental impact. In particular, it is defined as green hydrogen when produced with electrolysis powered by renewable energies, blue hydrogen when produced by reforming fossil fuels with CCS (85-95 % of sequestration efficiency) and grey hydrogen when produced from fossil fuels without CCS (Dermühl and Riedel, 2023).

Two key electrolysis technologies are Proton Exchange Membrane (PEM) cell and Solid Oxide Electrolysis Cell (SOEC), which have been recognized by experts as the most promising systems for the production of clean hydrogen in the future, attracting investments and R&D efforts. PEM cells are a commercially mature technology that relies on a polymer electrolyte for the conduction of protons, with high efficiency and power density. SOECs are based on ion-conducting ceramic as electrolyte, an immature system characterized by high costs. However, the strongest cost reduction is expected from this technology and the potential efficiencies achievable make SOEC one of the most interesting solutions for low-carbon hydrogen production (Schmidt et al., 2017).

The infrastructure required to sustain the development of a hydrogen economy would require a transportation network to connect supply and demand. The competition with traditional systems based on fossil fuels can be heavily influenced by the costs needed to upscale a cleaner but less affirmed technology.
It is noteworthy, however, that hydrogen presents properties that can limit the amount of time and resources necessary for the implementation of the infrastructure. Several studies and the following technical tests have demonstrated the viability of retrofitting the current natural gas network to hydrogen delivery. The main challenges appear to be related to pipelines' material integrity, which is subject to material degradation induced by the interaction of hydrogen molecules with pipe steel when pure or natural gas-blended hydrogen is injected into the existing infrastructure (Pluvinage, 2021). However, hydrogen embrittlement has different mitigation options to allow pipeline reassignment to cut infrastructure costs when shifting from natural gas to hydrogen, such as pipeline coating, gaseous inhibitors mixing, increased maintenance and outer safety pipeline addition. Similar solutions, despite representing additional expenditures, would decrease transmission costs and enhance the investment attractiveness of hydrogen technologies (Cerniauskas et al., 2020).

Another route for efficient infrastructure deployment consists of creating localized networks of producers and consumers that can benefit from hydrogen development. The idea of power-to-gas (P2G) energy hubs is already considered a valid strategy to offset emissions of the industrial sector and stimulate a cost-effective use of surplus energy with integrated demand-side response (H. Zhang et al., 2022,Mukherjee et al., 2019). Substantial funding has been allocated by governments in the EU and US to promote hydrogen hubs in strategic locations with a high density of industrial activity and large availability of renewable sources, especially onshore and offshore wind.
For instance, Rotterdam is currently positioning its port and the surrounding industrial area as Europe's hydrogen hub, with ambitious projects to expand pipelines toward the chemical industrial complex of Chemelot and therefore toward heavy industries in Belgium and Germany (BCI, 2021).

Among the potential uses of hydrogen as a decarbonization vector in transport, buildings and industry, a relevant application is the combustion of this element to produce high-temperature heat, qualifying hydrogen as a sustainable fuel for the future of steelmaking. With a working temperature of 1200 °C, the existing steel mills rely for 95% on fossil fuel-based burners, generating substantial consequences on the environment due to GHG emissions as presented previously. This poses a barrier to energy source switching, as the heat quality required in steel furnaces must meet the process temperature constraints.

Green and blue hydrogen are documented to be some of the most versatile and lowest costly alternatives to natural gas and coal because they involve only limited redesigns of the infrastructure (IRENA, 2022) while achieving up to 2100 °C of temperature. At the same time, the expected technological progress is likely to drive down the levelized cost of hydrogen (LCOH) in the future, as an increasing number of projects will be deployed.
In particular, blue hydrogen is reported to be one of the most cost-effective solutions to reduce emissions from steel manufacturing also compared to high-heating electrification, which is proven to require more invasive infrastructural modification with higher costs and lower return on investments (Freidmann et al., 2019).

Despite the increasing awareness of hydrogen compatibility with industrial heat generation, some major implications must be considered to give a comprehensive analysis of the sector's potential for transitioning. The switch to a low-carbon fuel would have significant consequences on the steel market: first, as mentioned above, it would inevitably cause higher steel prices due to increased technical costs, which would have substantial effects on the penetration of low-carbon steel in a market characterized by tight profit margins and high international competition.
Additionally, negative feedback on investment attraction might be experienced on the financial level, especially without the implementation of specific policies to keep green steel competitive. In fact, lack of demand for the more expensive and less polluting solution can delay the investment cycles necessary to trigger the scale expansion (IRENA, 2022) that helped, for example, wind and solar technologies to become commercially competitive.

Despite the challenges outlined so far, hydrogen may still represent a breakthrough for the energy transition when the concept of energy dependency is introduced in the analysis. Green hydrogen, as opposed to fossil fuels, does not rely on the extraction from underground deposits spread unevenly around the world but can be produced independently based on the national availability of renewable energy. Thus, with energy security being an increasingly relevant topic on the political agenda, hydrogen should be considered under more criteria that are not limited to a mere cost analysis.

2.3. Energy crises vulnerability

As the economic output of most developed and developing nations has been heavily dependent on the continuous supply of energy that is crucial to propelling production, the concept of energy security is more relevant than ever during the transition to a sustainable society.
Energy security is commonly described by the interplay of four main indicators, known as the four As (Kruyt et al., 2009): Availability (resource existence perspective), Accessibility (geopolitical perspective), Affordability (economical perspective) and Acceptability (environmental and social perspective).

The substantial reliance of our economy on fossil fuels, accounting for 80% of global energy production, induces a strong dependence on international trade of coal, oil and natural gas in countries where these resources are scarce (Asif and Muneer, 2007). By looking at the national energy balance of trade (BoT) data, it becomes evident how the security of supply is a fundamental necessity for several developing and developed economies in Europe and Asia, major fossil fuels importing regions. At the same time, some of the most relevant exporting countries are in geographical areas marked by political instability, such as MENA (Middle East and North Africa) and CACR (Central Asia and Caspian Region).

This fragile equilibrium threatened by geopolitical disruptions is likely to be strengthened by the transition to sustainable, abundant and decentralized renewable energies (Scholten, 2018). However, during the transformation of the energy infrastructure, the risk of disruptive events affecting the price of fossil resources lingers in several countries, as demonstrated by distant and recent historical examples: the invasion of Ukraine launched by Russia in 2022 is sadly one of them, but the same actors were responsible for the European gas crisis in 2009 (Bilgin, 2009).
The consequences of conflicts and international tension on oil and natural gas prices volatility have evidence with an even longer history, especially in the MENA region: relevant examples are the Suez crisis in 1956 or the OPEC embargo in 1973, both cases of regional wars with global resonance on energy prices (Hamilton, 2011). The European Central Bank recorded and tracked price dynamics of supply shocks, reporting relative changes in fuel prices ranging from 50% up to 300% and the related decline in net imports of fossil fuel products affecting the economic output, the financial sector and the labor market (ECB, 2022). The body of literature surrounding energy shocks indicates how energy insecurity represents a threat to the economic well-being of importing countries: the security of supply can easily affect the production costs of goods and generate widespread financial damage.

A complementary perspective on the topic is the environmental consequences of such disruptive events. Researchers have investigated the interaction between fossil fuel prices and renewable energy development and the analyses suggest that the financial performance of renewable energy firms can benefit from the increasing prices of fossil fuels, gaining market advantage and higher returns (Dutta, 2017, Song et al., 2019).

However, the price volatility of fossil resources seems to draw the attention of governments and policymakers only to the short-term planning concurrent with energy crises, demonstrating the lack of consistency necessary to radically address the challenges of the energy sector.

2.4. Literature gap and research questions

Among the literature presented to outline the existing research on the technical, economic and geopolitical dynamics affecting the development of hydrogen as a sustainable fuel, a lack of detailed studies exploring the implications of energy shocks for industrial management and policymaking was identified. There is untapped potential to apply climate modeling, IAMs in particular, for a comprehensive analysis of the impact of energy crises on the steel industry and the role that hydrogen might play in enhancing energy diversification and resiliency. A similar study can highlight unexplored correlations between energy dependency and economic risk, with potential significance for long-term planning of energy supply and consequently for economic growth and environmental performance.

To address the presented knowledge gap and therefore contribute to the advancement of research by integrating an innovative perspective in model-based decarbonization studies, the following research question was formulated.

Research Question

How can the adoption of hydrogen in steelmaking support the industry decarbonization and the resiliency to energy shocks as an alternative heat carrier in energy-dependent countries?

The analysis is thus structured through the subquestions that define the conceptual approach used to answer the main research question.

Research Sub-questions

- What is the decarbonization potential of hydrogen in the future of the steel industry as an alternative heat carrier competing with natural gas?
- What impact would energy shocks have on the fuel supply of national steel industries?
- What role can investments in hydrogen play in enhancing energy resiliency and security under the threat of energy crises?

3 Methods

In this chapter, the research approach and methodology are defined after a brief description of the WITCH model, focused on the existing features related to hydrogen technologies. The framework applied and the development implemented to include the industrial use of hydrogen in the model is then presented. Similarly, the following sections describe the integration of energy shocks in the simulation and the scenario analysis performed on the resulting version of the model. Finally, a description of the model formalization, including assumptions and parametrization, concludes the chapter.

3.1. The WITCH model

WITCH (World Induced Technical Change Hybrid) is a state-of-the-art optimal growth model developed at the European Institute on Economics and the Environment (EIEE), a research institute founded by Resources for the Future (RFF) and the Euro Mediterranean Center on Climate Change (CMCC). The model performs long-term optimizations through a unified framework accounting for crucial elements of climate change and scientists and researchers from all over the EU have been using this tool to study climate change mitigation and adaptation policies, producing several scenarios reviewed by the International Panel on Climate Change (IPCC).

The WITCH framework is based on a mixed approach: the top-down modeling of the economy by means of a Cobb-Douglas function of energy, labour and capital is linked with the energy supply, which is in turn modeled as a nested CEST production function where different technologies compete for investments regulated by elasticities of substitution. On the other hand, the bottom-up structure is used to model single technologies with a granular definition of costs, efficiencies and deployment constraints.
Moreover, WITCH has a specific focus on R&D development and technical learning, with endogenous representation of learn-by-researching, learn-by-doing, technological spillovers and impact of innovation on investment costs. Additional features are included in the IAM framework by the soft-linking of complementary models: the Global Biosphere Management Model (GLOBIOM) and Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) are respectively a land use and a climate change model that provides WITCH with inputs for estimates of GHG emissions and concentration in the atmosphere.

The general equilibrium optimization accounts for up to 17 native regions with cooperative and non-cooperative set up of coalitions, each one with its own non-linear optimization of intertemporal utility of consumption per capita. In order to achieve a perfect foresight global solution, an iterative algorithm for

the open loop Nash equilibrium is implemented for each region n and time period t, with 2005 as a base year and a time horizon of 150 years modeled in 30 periods of 5 years each.
The agents' utility (Equation 3.1) is based on macroeconomic quantities where C is total consumption, l is population, η is the degree of relative risk aversion and β is the result of the standard geometric discounting rule described in Equation 3.2, where Δ_t is the 5-years time step and ρ is the discount rate.
Total consumption, defined in Equation 3.3, accounts for the budget constraint and is therefore built by removing from Y, which is the economic output of the Cobb-Douglas production function, every investment and O&M cost related to technology developments, fuel extraction and the expenditures for adaptation and electricity grid infrastructure.

$$W(n) = \sum_t l(t,n) \frac{\left(\frac{C(t,n)}{l(t,n)}\right)^{1-\eta} - 1}{1-\eta} \beta^t \tag{3.1}$$

$$\beta = (1+\rho)^{-\Delta_t} \tag{3.2}$$

$$\begin{aligned} C(t,n) = {} & Y(t,n) - \\ & - \sum_j \left(I_{RD,j}(t,n) + I_j(t,n) + (oem_j(t,n) \times K_j(t,n))\right) - \\ & - \sum_j \left(I_{OUT,f}(t,n) + (oem\_ex_f(t,n) \times Q_{OUT,f}(t,n))\right) - \\ & - I_{FG}(t,n) - I_{GRID}(t,n) - I_{adap}(t,n) \end{aligned} \tag{3.3}$$

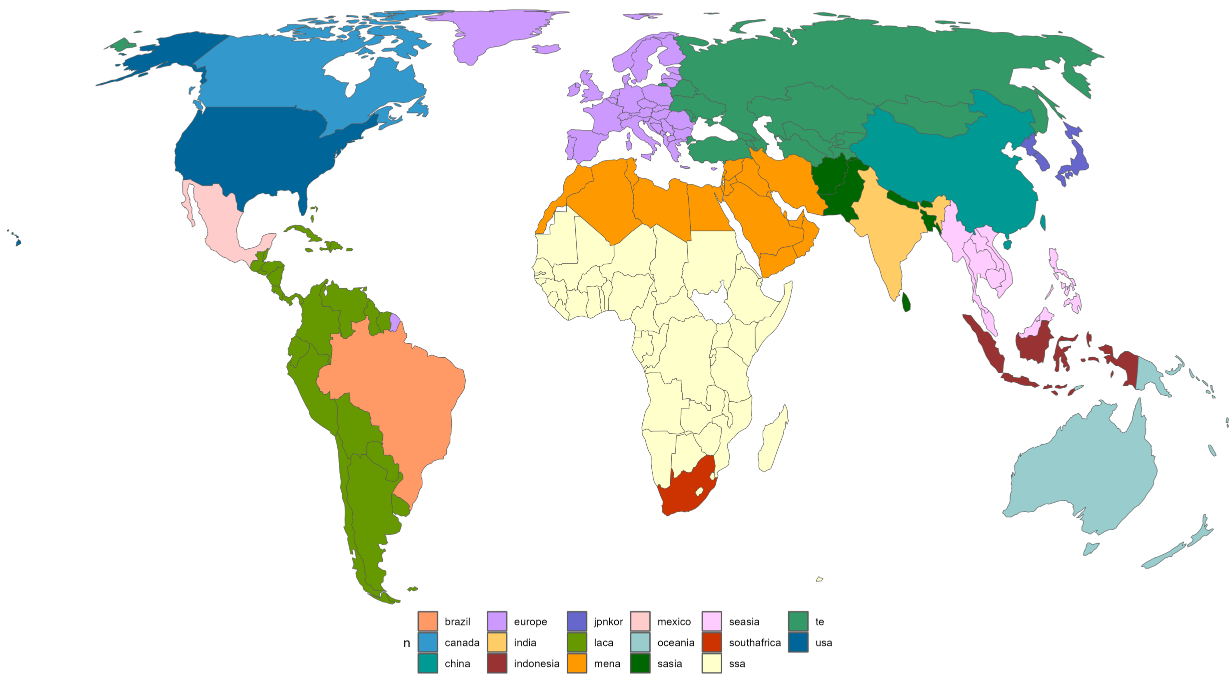

Figure 3.1: WITCH 17 regions

A crucial aspect of the project has been the collaboration with EIEE and with the scientists and researchers of the institute, which was granted during the visiting period in Milan. Furthermore, the CMCC allowed the use of the ZEUS supercomputer for the entire project: with 12528 processor cores and a peak performance of 1.202 TFlop/s, ZEUS was a decisive tool to handle the computational burden of a complex model such as WITCH. The aim of the collaboration was to share the knowledge and resources of the research center to facilitate the development of the hydrogen module and the implementation of a tailored industrial module.

The existing supply model of hydrogen existing in WITCH is based on previous work done for the transportation sectors, where the mitigation potential of fuel cell vehicles was studied. The hydrogen module defined two different production methods, namely electrolysis and steam gas reforming, with further technological diversification: electrolysis is represented by SOEC and PEM electrolyzers while steam gas reforming is either with CCS or without it. Techno-economic parameters are summarized in Table 3.1 and in Table 3.2. Additionally, the infrastructure is modeled with pipelines and refueling stations based on regional data.

A set of equations is used to define the capacity and production constraints of hydrogen technologies. For each production technology $jh2$, equation 3.4 describes the energy capital [TW] that accumulates over time depending on the ratio between investments I_{jh2} and costs $CAPEX_{jh2}$. The dynamics related to the yearly depreciation of capital are described by δ_{jh2}. Equation 3.5 defines the production efficiency by accounting for the transformation efficiency ξ_{jh2} of each hydrogen technology. The sum of the input energy coming from technologies that feed energy to hydrogen technologies ($Q\_IN_{jices}(t,n)$) and from storage ($Q\_IN_{storage}(t,n)$) is therefore adjusted as shown. The operational constraints related to the capacity factor $\mu_{jh2}(t,n)$ are outlined with equation 3.6.

$$K\_EN_{jh2}(t+1,n) = K_{jh2}(t,n)(1-\delta_{jh2}(t+1,n))^{\Delta t} + \Delta t \frac{I_{jh2}(t,n)}{CAPEX_{jh2}(t,n)} \quad (3.4)$$

$$Q\_EN_{jh2}(t,n) = \left(\sum (Q\_IN_{jices}(t,n) + Q\_IN_{storage}(t,n))\right) * \xi_{jh2} \quad (3.5)$$

$$Q\_EN_{jh2}(t,n) < K\_EN_{jh2}(t,n) * \mu_{jh2}(t,n) \quad (3.6)$$

To simulate the dynamics of positive feedback on investment costs generated by the cumulative installation of hydrogen technologies and the learn-by-doing process, the module contains a looped equation that uses investments, knowledge stock and cumulative installation as proxies for R&D and experience learning. For every iteration, the equation computes the stock of electrolyzers dividing the aggregate investments in hydrogen supply sectors, accounting for hydrogen and renewable hydrocarbon fuels production, by the investment cost of the previous time period. The cumulative stock of SOEC and PEM is then compared with the base-year stock to derive the learning factor, which is in turn used to set the investment cost for the following iteration.
With this process, an endogenous learning curve is defined to describe the projections of future costs.

	SOEC		PEM	
Parameters	Value	Source	Value	Source
Lifetime [y]	25	Previous modeling	25	Previous modeling
Operating hours [h/y]	5000	Previous modeling	5000	Previous modeling
O&M [% of investment]	4%	Previous modeling	4%	Previous modeling
Efficiency before 2025	77%	Previous modeling	60%	Previous modeling
Efficiency between 2025 and 2050	80%	Previous modeling	65%	Previous modeling
Efficiency after 2050	85%	Previous modeling	70%	Previous modeling

Table 3.1: SOEC and PEM parameters

	SGR_CCS		SGR	
Parameters	Value	Source	Value	Source
Lifetime [y]	25	Previous modeling	25	Previous modeling
Operating hours [h/y]	5000	Previous modeling	5000	Previous modeling
O&M [% of investment]	4%	Previous modeling	4%	Previous modeling
Efficiency before 2025	70%	Previous modeling	75%	Previous modeling
Efficiency after 2025	75%	Previous modeling	80%	Previous modeling

Table 3.2: SGR_CCS and SGR parameters

3.2. Steel industry and hydrogen module development

For the purpose of this study, significant changes and expansions of the model were required as the master version of WITCH included hydrogen consumption only for the transportation sector. Thus, to develop an accurate analysis on hard-to-abate industries, two different approaches have been evaluated.

The first approach consists of a top-down implementation of hydrogen supply and demand within the CES production function of the model. Expanding the production function to account for the industrial use of hydrogen entails splitting the non-electric energy node of the CES tree, creating a substitution option between using fossil fuels or hydrogen as energy input. This strategy has the advantage of using the inbuilt dynamics of an optimization model, being able to capture technical and economic feedback produced during the iterations and granting higher flexibility on variables. Moreover, from a coding perspective, it requires less invasive interventions on the model, resulting in a faster implementation route. However, the drawbacks of the procedure mentioned above have substantial consequences on the granularity of the results: the CES approach does not allow a sectoral disentanglement of the output, which would result in aggregated data of all non-electric consumption of hydrogen from different sectors. Additionally, it limits the possibility of characterizing accurately the parameters specific to industrial production. To avoid such limitations, the output of the model should be processed based on assumptions and estimates.

Therefore, the second approach was deemed the most insightful and appropriate for the project as it consists of a bottom-up framework where the industrial sector is separated from the CES structure. Although this implementation requires more development of the code, the definition of an industrial module with exogenous demand and technologies offers the opportunity for a deeper analysis of the techno-economic dynamics peculiar to steelmaking.

Based on the selected strategy, the industry module is built starting from the technologies involved in the supply chain. Steel furnaces are the key systems introduced in the model with technical and operational features derived from the IEA's levelized costs of steel production and sector analysis (IEA, 2020b). The dominant technologies presented in Chapter 2 are the blast furnace and the electric arc furnace, currently accounting for almost the entire technology mix.

Each element of the set is parametrized with technical and economic indicators. Capital expenditures (CAPEX) values account for engineering, procurement and construction annualized costs per ton of steel produced. Operational expenditures (OPEX) include maintenance, replacement parts and associated engineering while excluding fuel costs that are computed separately in the model. The lifetime has been introduced in the technology modeling to compute the depreciation rate of the assets, according to Equation 3.7. The standard exponential depreciation rate is re-calibrated to account for the finite lifetime of a 1% per annum linear depreciation rate, which yields the equivalent parameter shown in Equation 3.8. The depreciation affects the capital stock of steel technologies over time (Equation 3.9), describing the capital growth model used by the algorithm.

$$\int_0^{\infty} e^{-\delta_j(t,n)t} dt = \left(1 - \frac{1}{2} \cdot 0.01 \cdot lifetime(j)\right) lifetime(j) \tag{3.7}$$

$$\delta_j(t,n) = \frac{1}{lifetime(j) - \frac{0.01}{2} \cdot lifetime(j)^2} \tag{3.8}$$

$$K\_EN_{jsteel}(t+1,n) = K_{jsteel}(t,n)(1 - \delta_{jsteel}(t+1,n))^{\Delta t} + \Delta t \frac{I_{jsteel}(t,n)}{CAPEX_{jsteel}(t,n)} \tag{3.9}$$

Additionally, other relevant technologies linked to the module are the electric and non-electric sources of energy that are in competition to provide electricity and heat to steel mills. The energy supply structure modeled for the steel production is explained in Figure 3.2 and in the legends (Table 3.3 and 3.4): the two main steel production routes have a variable output of trillion tonnes of steel per year (K_EN) that adds up to the total steel production in each country, defining the upstream consumption of energy carriers.

The energy supply is modeled through the heat intensity coefficients (hi) and the electricity intensity coefficients (ei), which are used to represent the asymmetric energy demand of each technology per million tonnes of steel produced. Material metabolism studies report current values of energy consumption per tonne of steel produced and break down the total energy demand into heat and electricity consumed in each stage of the steelmaking process (Li et al., 2018). The energy supply is divided between heat sources and electricity sources, where the heat sources are natural gas for industrial use and green, blue and grey hydrogen, while the electricity sources are a representation of the national grid mix.

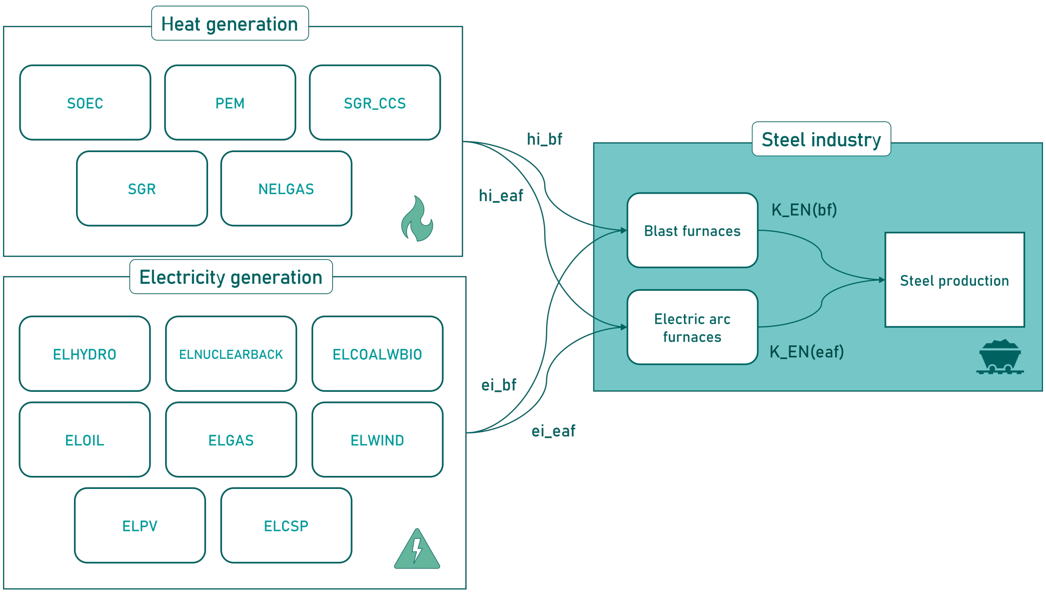

Figure 3.2: Steel energy supply structure

Heat generation technologies		
Production	Technology	Label
Green hydrogen	Solid Oxide Electrolyzer Cell	SOEC
Green hydrogen	Proton Exchange Membrane	PEM
Blue hydrogen	Steam Gas Rreforming with CCS	SGR_CCS
Grey hydrogen	Steam Gas Reforming	SGR
Natural gas	Gas for non-electric use	NELGAS

Table 3.3: Steel heat supply legend

Electricity generation technologies		
Production	Technology	Label
Electricity from hydropower	Hydropower plants	CES_ELHYDRO
Electricity from nuclear fission	Nuclear plants	CES_ELNUCLEARBACK
Electricity from coal and biomass	Solid electricity plants	CES_ELCOALWBIO
Electricity from oil	Oil electricity plants	CES_OIL
Electricity form gas	Gas electricity plants	CES_ELGAS
Electricity from wind	Wind park	CES_ELWIND
Electricity from photovoltaic	Solar park	CES_ELPV
Electricity from CSP	Concentrated Solar Power plants	CES_ELCSP

Table 3.4: Steel electricity supply legend

To accurately depict the industry development on a regional level, an exogenous demand curve was derived from the literature. Several studies have highlighted the dependence of steel demand in a given country on the national GDP per capita, according to the steel intensity of use hypothesis (Warell and Olsson, 2009, Dohrn and Krätschell, 2014, and Crompton, 2015). The research documented that regression models show an inverted U-shaped relationship, with a strong correlation between the economic development of a country and the national consumption of steel. The demand function captures the transition from agricultural economies to manufacturing systems to service-based societies, exhibiting first an increase in steel consumption during the mechanization period followed by a decrease when shifting to a predominant tertiary sector. Based on the research mentioned, the steel intensity of use has been formulated as a function of national GDP per capita over time, shown in equation 3.10.

$$IU(t,n) = \alpha_0 + \alpha_1 \left(\frac{GDP(t,n)}{Capita(t,n)}\right) + \alpha_2 \left(\frac{GDP(t,n)}{Capita(t,n)}\right)^2 + \alpha_3\, t + \sum_{C=1}^{n-1} \alpha_c\, D_c \tag{3.10}$$

Where IU is the intensity of use in Gtons per billion dollars of GDP and α_i are the regression coefficients. The regression is based on steel consumption data from the International Iron and Steel Institutes and annual GDP and population data from United Nations. For the selected model, the regression produced the following results:

Constant	α_0	0.044
GDP per capita	α_1	0.155e-5
(GDP per capita)^2	α_2	-0.285e-5
Time trend	α_3	-0.001

The steel demand is derived as follows:

$$D_{steel}(t,n) = IU(t,n) \times GDP(t,n) \times 10^3 \tag{3.11}$$

Where D_{steel} is the demand of steel in Ttons of steel consumed per country. The competition in a global market characterized by high capital intensity and low-profit margin influences the development of steelmaking industries, where low raw material, labor and energy prices are crucial for profitability and influence the geographical distribution of steel industry clusters. The national steel manufacturing industry size is defined based on global production shares. The steel production shares are derived from a linear regression performed on national data from the Global Steel Plant Tracker database of the Global Energy Monitor of total, announced and under-construction capacity of steel production between 2070 and 2020, explained in Equations 3.12, 3.13 and 3.14. Finally, the global demand is divided across countries based on the resulting steel production shares (Equation 3.15).

$$S_{2070}(n) = S_{current}(n) + S_{construction}(n) + S_{announced}(n) \tag{3.12}$$

$$S(t,n) = \left(\frac{S_{2070}(n) - S_{2020}(n)}{t_{2070} - t_{2020}} \right) (t - t_{2070}) + S_{2070}(n) \tag{3.13}$$

$$production\_share(t,n) = \frac{S(t,n)}{\sum_n S(t,n)} \tag{3.14}$$

$$P_{steel}(t,n) = \left(\sum_n D_{steel}(t,n) \right) \times production\_share(t,n) \tag{3.15}$$

The sectoral constraints and dynamics are implemented in the model through the set of equations described below. The available infrastructural capacity for steel production must be, in all regions and at all times, larger than or equal to the amount of steel produced, as specified in Equation 3.16. The capacity constraint represents a crucial link between the parametrization of the steel industry and the macroeconomic variables of the model that are inherited. Equally important are Equations 3.17, 3.18, 3.19 and 3.20, which impose the energy supply structure shown in Figure 3.2 and introduce the competition between energy technologies and fuels in the algorithm. The equations mentioned above are used to bind the technology-specific energy vectors to the related furnaces, forcing the model to choose between a limited set of heat and electricity technologies to meet the energy demand of the steelworks.

$$\sum_{jsteel} K\_EN(t,n) \geq P_{steel}(t,n) \tag{3.16}$$

$$K\_EN_{bf}(t,n) \times hi\_bf = \sum_{fsteel} Q\_IN_{bf}(t,n) \tag{3.17}$$

$$K\_EN_{eaf}(t,n) \times hi\_eaf = \sum_{fsteel} Q\_IN_{eaf}(t,n) \tag{3.18}$$

$$K\_EN_{bf}(t,n) \times ei\_bf = \sum_{ices\_steel} QEL\_OUT_{bf}(t,n) \tag{3.19}$$

$$K\_EN_{eaf}(t,n) \times ei\_eaf = \sum_{ices\_steel} QEL\_OUT_{eaf}(t,n) \tag{3.20}$$

The master version of WITCH, which is the most up-to-date and consolidated version shared by the entire developers' team, required some changes to ensure compatibility with the newly developed steel industry sector. To enable the competition of hydrogen with fossil fuels, the supply module was modified to account for the production of grey, blue and green hydrogen as a fuel instead of being an energy measure. Moreover, a new class of technologies was defined to track every technology in the model that can be fed by hydrogen, $jh2\_dmnd$, which in the framework of the project consists of fuel cell vehicles, fuel cell trucks, blast furnaces and electric arc furnaces. This set was then used to convert some of the existing equations to a new formulation while maintaining the output unchanged: these equations are necessary to link the energy produced by hydrogen technologies to the fuel supply capacity (Equation 3.21) and to divide that energy across the demand-side technologies (Equation 3.22). With this alternative structure of the code, the supply side is disentangled more sharply from the demand side, where the conversion coefficients can be introduced to model the losses specific for each sector and technology.

$$\sum_{jh2} Q\_EN(t,n) = Q\_FUEL_{h2}(t,n) \tag{3.21}$$

$$Q\_FUEL_{h2}(t,n) = \sum_{jh2\_dmnd} Q\_IN_{h2}(t,n) \tag{3.22}$$

The introduction of this modification was also necessary to expand the static calibration module to account for the industrial use of nonelectric gas outside the CES at the beginning of the simulation. The reference consumption of gas outside the power sector was hence corrected by removing the steel mills' consumption of gas in 2005 from the related node of the production function.
Moreover, the hydrogen module development has additional functionality for the accounting of hydrogen supply: as already shown in Figure 3.2, hydrogen can be produced as "green" by electrolyzers, namely PEM and SOEC technology, as "blue" by steam gas reforming paired with CCS, and as "grey" by traditional steam gas reforming. The following set of equations was introduced to compute the internal competition between hydrogen supply technologies, where green (Equation 3.23), blue (Equation 3.24) and grey (Equation 3.25) hydrogen production is tracked with energy supply shares.

$$Steel\_industry\_h2_{green} = \frac{Q\_EN_{pem}(t,n) + Q\_EN_{soec}(t,n)}{Q\_FUEL_{h2}(t,n)} \times \sum_{jsteel} Q\_IN_{h2}(t,n) \tag{3.23}$$

$$Steel\_industry\_h2_{blue} = \frac{Q\_EN_{sgr\_ccs}(t,n)}{Q\_FUEL_{h2}(t,n)} \times \sum_{jsteel} Q\_IN_{h2}(t,n) \tag{3.24}$$

$$Steel\_industry\_h2_{grey} = \frac{Q\_EN_{sgr}(t,n)}{Q\_FUEL_{h2}(t,n)} \times \sum_{jsteel} Q\_IN_{h2}(t,n) \tag{3.25}$$

3.3. Energy shocks integration

To bring the analysis from the sectoral technology perspective to the socioeconomic viewpoint sought by the project, external factors had to be added to the optimization problem.
As previously outlined in Chapter 2, widespread interest from the scientific community revolves around the introduction of hydrogen into the gas networks as a sustainable alternative for heating generation, especially in heavy industry. Hydrogen can be used mixed in different percentages with natural gas to partially or totally tackle the emissions from methane combustion and the procedure to retrofit the infrastructure, despite having costs and technical constraints, is negligible compared to fuel expenditures, which is also an assumption of the model development.

Simulating an energy shock in the model that accurately captures the dynamics of an abrupt soar in fossil fuel prices requires a broader understanding of the global trade mechanism. In the natural gas module, the extraction of this resource is introduced in the algorithm through the fossil fuel availability curves. The availability functions describe the relationship between the cumulative extraction of the resource and its production cost, assuming marginal costs equal to fuel prices under the hypothesis of perfect competition in the market. The calibration of these curves is based on forecasts provided by the World Energy Outlook and the ROSE project, coordinated by the Potsdam Institute for Climate Impact Research. Before each iteration of the main solver, the global fuel demand is used to derive the international price, which in turn is used to extract the regional cumulative production from the availability curves. The extraction for each timestep is then computed as the difference between the cumulative production of two consecutive periods. Equations 3.26, 3.27 and 3.28 show the underlying formulation of the gas extraction algorithm, where fun is the interpolation of the global supply curves and fun_n of regional supply curves. The trade emerges as a consequence of the imbalance between regional demand and production levels. Lastly, the average fuel price is affected by another component, the price markup, which describes the regional differences related mainly to infrastructure and transportation additional costs.

$$FUEL\_PRICE_{gas}(t) = fun\left(\sum_n Q\_FUEL_{gas}(t,n)\right) \tag{3.26}$$

$$cum\_prodpp_{gas}(t,n) = fun\_n^{-1}(FUEL\_PRICE_{gas}(t)) \tag{3.27}$$

$$Q\_OUT_{gas}(t,n) = prodpp_{gas}(t,n) = \frac{cum\_prodpp_{gas}(t+1,n) - cum\_prodpp_{gas}(t+1,n)}{\Delta t} \tag{3.28}$$

The national energy dependency is considered for the implementation of energy shocks in order to differentiate the impact of a supply-side shock on natural gas prices. In fact, the consequences of a sudden rise in fuel costs induced by geopolitical disruptions of exporting countries would be proportional to the share of imported resources in the national energy mix of importing countries: the BoT of every region is therefore combined with the price shock to compute the stronger backlash perceived in the national energy sectors of countries that depend largely on imported fuels. To capture the trading dynamics, the fuel cost equation of the core energy module (Equation 3.30) was modified by developing the average cost of fuel term: first, the two factors affecting $MCOST\_FUEL$ are made explicit and rearranged to isolate the difference between resource consumption and extraction. Then, the natural gas price shock term is introduced as shown in Equation 3.31.

$$MCOST\_FUEL_f(t) = FUEL\_PRICE_f(t,n) + p\_markup_f(t,n) \tag{3.29}$$

$$\begin{aligned} COST\_FUEL_f(t) = {} & MCOST\_FUEL_f \times Q\_FUEL_f(t,n) - \\ & -FUEL\_PRICE_f(t,n) \times Q\_OUT_f(t,n) \end{aligned} \tag{3.30}$$

$$\begin{aligned} COST\_FUEL_{gas}(t,n) = {} & FUEL\_PRICEgas(t,n) \times (1 + pshock_{gas}(t,n)) \times \\ & \times (Q\_FUEL_{gas}(t,n) - Q\_OUT_{gas}(t,n)) + \\ & + p\_markup_{gas}(t,n) \times Q\_FUEL_{gas}(t,n) \end{aligned} \tag{3.31}$$

Using this formulation for energy shocks forces the model to consider the impact of the price peak only on the fraction of resources imported by every nation, represented by the difference between Q_FUEL and Q_OUT. At the same time, for countries with large amounts of exported natural gas, the difference between the two terms is negative and the $COST\_FUEL$, therefore, represents a revenue. The increased revenues of exporting countries are assumed to replicate the advantage of the availability of scarce resources in the global market.
The logic explained above is visualized in Figure 3.3

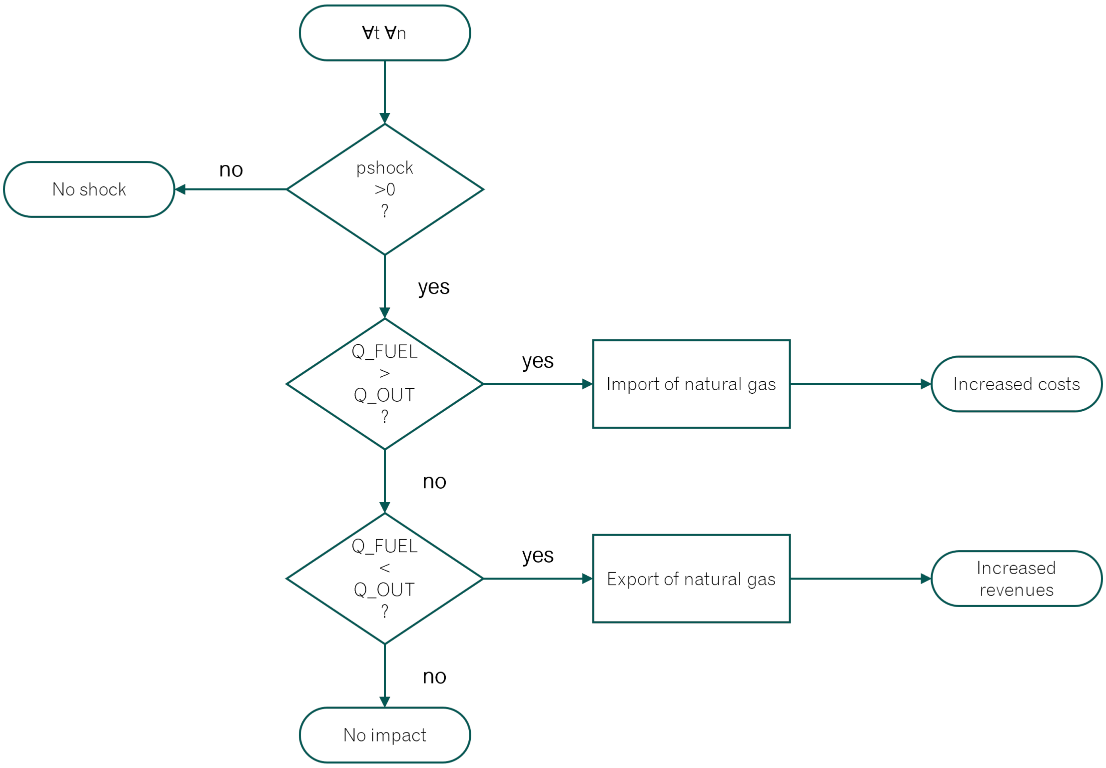

Figure 3.3: Energy shocks flowchart

3.4. Scenario architecture

To investigate the impact of energy shocks and to delve into the role played by climate policies and sustainable energy investments, a scenario framework was developed by combining three different dimensions in the architecture.
The first dimension is the time of occurrence of the energy shock, which is the timestep in the simulation when the model experiences the price shock. The year of occurrence plays a crucial role in the analysis as it represents the time available for society before disruptive events and therefore the potential time window for the industrial transition to alternative fuels.
The second dimension is the magnitude of the shock, modeled as a percentage increase in the market price of natural gas. Again, the intensity of the price peak has relevant consequences on the study because it expands the set of scenarios to account for the severity of geopolitical disruptions and the related impacts on fossil fuel supply.
The third dimension is the policy framework implemented in the model, working as a measure for the future environmental ambitions of countries and coalitions. More demanding and stringent measures pursued by governments can influence the energy mix and the development of alternative solutions to traditional fossil systems, which in turn affect energy dependency and the national vulnerability to shocks.

For each policy narrative, a benchmark scenario without any disruptive events is generated to work as a reference for the analyses of energy shocks' effects. This is also a crucial step to guarantee the desired behavior of the simulation because in WITCH, which is a perfect foresight model, agents can predict future events and anticipate the shocks. To avoid the contamination of the results, the reference scenario is used in every simulation to extract all relevant variables and fix the values until the timestep preceding the energy crisis year.

The current policy scenario implemented is based on the extrapolation of current pledges and commitments from 2020, with environmental and technological targets to limit global emissions and increase the share of renewables in the energy mix. This definition is used to represent the minimum effort with limited ambitions of future climate policies, resulting in a mild decrease in emissions.

The environmental target narratives are developed on the remaining carbon budget (RCB) concept, defined as the cumulative emissions of CO_2e from the start of 2018 to the end of the century to limit global warming beneath a target temperature increase. The scientific community and regulatory bodies agreed on common targets since the Paris Agreement, with the ambition of limiting global temperature to no more than 1.5 C° above pre-industrial levels. In the climate policy debate, also a 2 C° value is frequently reported as the upper limit for global warming, which would entail more serious consequences on human life on Earth. The RCB is introduced in the simulation with a bisection algorithm that compares the effect of different carbon taxes on global cumulative emissions until converging to the required carbon budget.

The resulting architecture is summarized in Table 3.5. Developing a three-dimension sensitivity analysis will be used to identify the most relevant scenarios and to delve into policy-relevant insights based on a comprehensive assessment.

	Early shock	Mid shock	Late Shock
Current policies	Current pledges **Low**-early shock	Current pledges **Low**-mid shock	Current pledges **Low**-late shock
	Current pledges **Medium**-early shock	Current pledges **Medium**-mid shock	Current pledges **Medium**-late shock
	Current pledges **High**-early shock	Current pledges **High**-mid shock	Current pledges **High**-late shock
2 C° scenario	2 C° target **Low**-early shock	2 C° target **Low**-mid shock	2 C° target **Low**-late shock
	2 C° target **Medium**-early shock	2 C° target **Medium**-mid shock	2 C° target **Medium**-late shock
	2 C° target **High**-early shock	2 C° target **High**-mid shock	2 C° target **High**-late shock
1.5 C° scenario	1.5 C° target **Low**-early shock	1.5 C° target **Low**-mid shock	1.5 C° target **Low**-late shock
	1.5 C° target **Medium**-early shock	1.5 C° target **Medium**-mid shock	1.5 C° target **Medium**-late shock
	1.5 C° target **High**-early shock	1.5 C° target **High**-mid shock	1.5 C° target **High**-late shock

Table 3.5: Scenario architecture

3.5. Model formalization

The integration of the bottom-up structure of the steel industry module into a predominantly top-down model like WITCH is shown in Figure 3.4: steelmaking, similarly to the transport sector, is disentangled from the CES production function of Energy, Capital and Labour while being connected to the technology pool to account for the energy consumption associated to the production of fuels. The aggregate economic value, with the rest of consumption accounting for residential and services energy demand, is ultimately combined in the Output $Y(t,n)$. To implement the simulation described in the previous sections, several assumptions were used to characterize the technology sets, the steel demand, the competition between fuels in the heat supply and the scenario analysis.

The furnaces modeled in the simulation to transform the energy input in the equivalent crude steel output were introduced with the parameters summarized in Table 3.6. Blast furnaces are a mature technology with lower costs compared to electric arc furnaces. However, electric arc furnaces are almost three times more efficient in converting the energy input into the material output.

	Blast furnaces		**Electric arc furnaces**	
Parameters	Value	Source	Value	Source
Lifetime [y]	40	IEA, 2022	40	IEA, 2022
Capex [$/ton]	94	IEA, 2020	136	IEA, 2020
Opex [$/ton]	87	IEA, 2020	125	IEA, 2020
Heat intensity [TWh/Mton]	5.5741	Li et al., 2018	0.5064	Li et al., 2018
Electric intensity [TWh/Mton]	0.3122	Li et al., 2018	1.2768	Li et al., 2018

Table 3.6: Steel furnaces characteristics

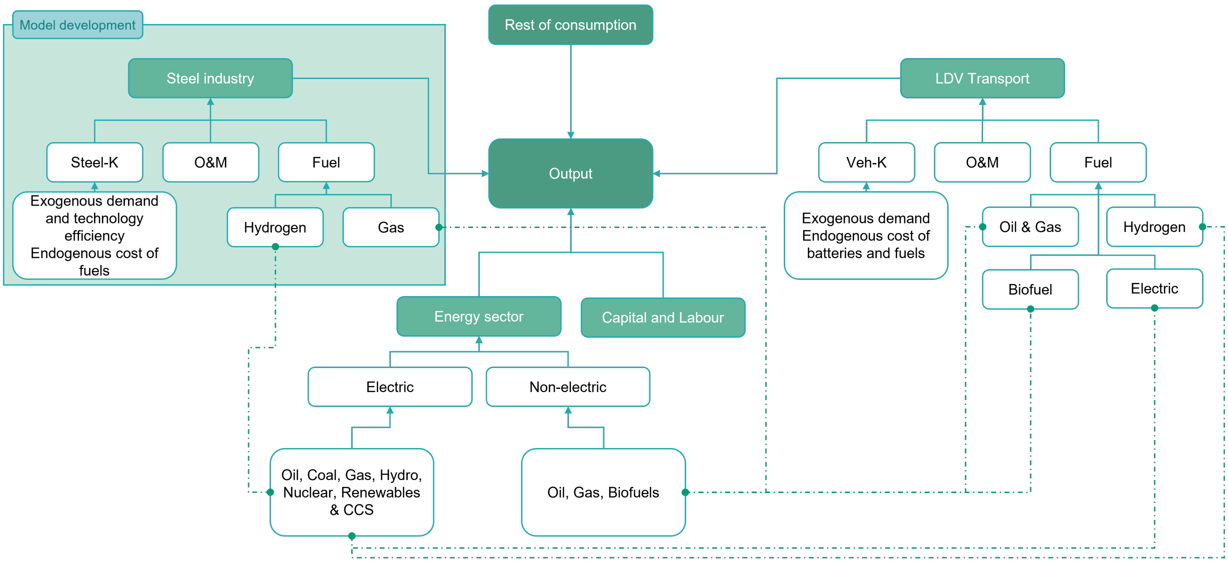

Figure 3.4: Representation of the WITCH master structure and module development and integration

Steel demand definition is a crucial element of the optimization problem. As previously mentioned, the demand is exogenously defined based on the steel intensity of use hypothesis and therefore driven by the GDP per capita of consumers. This results in a global pool demand that is rigid and therefore unmoved by external factors like fuel prices.

A cardinal dynamic of the simulation is the competition between natural gas and hydrogen for heat generation, which is predominantly regulated by relative prices per unit of heat produced. From an investment perspective, it was assumed that retrofitting and development expenditures are negligible compared to fuel costs when considering strategic industrial hubs with pipeline reassignments to support both gas and hydrogen supply as previously indicated in Chapter 2. This decision is realistic for pioneering applications of hydrogen such as the integration in industrial processes, where large consumers are connected with customized production of low-carbon hydrogen. The increased investment costs for infrastructural adaptation are therefore excluded in the optimization algorithm that regulates the market share, as fuel costs can range up to thousands of billions of dollars yearly on a global scale.

Another relevant aspect that was assumed to regulate the competition between natural gas and hydrogen is the possibility of fuel blending. Hydrogen can penetrate the fuel mix for heat generation in increasing percentages without the inertia that would characterize the deployment of an alternative technology for the production of high-temperature heat. Common applications of hydrogen as combustion agents already present the use of hydrogen blending in natural gas, usually ranging from 5% to 30%. For larger shares of hydrogen in the fuel mix, despite the necessity of infrastructural adaptation, the substitution inertia is virtually negligible.

Moreover, the integration of energy shocks, which is a pivotal dynamic for the study as it impacts the fuel expenditures in steelmaking and therefore affects the economic optimum, is modeled on the assumptions of a global fuel price from a perfectly competitive natural gas market. For this reason, regional differentiation of the consequences on energy markets is defined using the percentage of imported natural gas over the total consumption as the only fraction affected by the price shock.

The scenario architecture introduced in Table 3.5 is formulated to cover the three main variables of sensitivity to energy shocks.

When defining the time variable, the selected timeframe of 50 years from 2020 to 2070 has been divided into three sections to model an early shock in 2030, a mid shock in 2040 and a late shock in 2050.
To account for the intensity variable, low shocks of 50% price increase, medium shocks of 100% and high shocks of 300% are identified among several historical examples and used as reference magnitudes in the model. In particular, a joint analysis from Bloomberg and the European Central Bank, whose values are used as benchmarks, tracked the relative annual change in oil prices after the OPEC embargo in 1973, the Iranian revolution in 1978 and the 2003 energy crisis ECB, 2022.

Climate policies, and carbon pricing as a consequence, are assumed to be represented by environmental targets implemented in the model. RCBs are the subject of studies and debates on a global scale, given their scientific importance, and the most recent values used for this project have been extracted from a renowned study of Earth System Science Data (Forster et al., 2023) based on an annual review of the IPCC approach: in the bisection algorithm of carbon pricing, 1150 GTons and 650 GTons of CO_2e are applied to yield a related temperature increase of 2 C° and 1.5 C° respectively.

The parametrized scenario analysis is summarized in Table 3.7.

	Early shock	**Mid shock**	**Late Shock**
Current policies	Current pledges Shock year: 2030 Shock magnitude: 50%	Current pledges Shock year: 2040 Shock magnitude: 50%	Current pledges Shock year: 2050 Shock magnitude: 50%
	Current pledges Shock year: 2030 Shock magnitude: 100%	Current pledges Shock year: 2040 Shock magnitude: 100%	Current pledges Shock year: 2050 Shock magnitude: 100%
	Current pledges Shock year: 2030 Shock magnitude: 300%	Current pledges Shock year: 2040 Shock magnitude: 300%	Current pledges Shock year: 2050 Shock magnitude: 300%
2 C° scenario	Carbon budget: 1150 GTons Shock year: 2030 Shock magnitude: 50%	Carbon budget: 1150 GTons Shock year: 2040 Shock magnitude: 50%	Carbon budget: 1150 GTons Shock year: 2050 Shock magnitude: 50%
	Carbon budget: 1150 GTons Shock year: 2030 Shock magnitude: 100%	Carbon budget: 1150 GTons Shock year: 2040 Shock magnitude: 100%	Carbon budget: 1150 GTons Shock year: 2050 Shock magnitude: 100%
	Carbon budget: 1150 GTons Shock year: 2030 Shock magnitude: 300%	Carbon budget: 1150 GTons Shock year: 2040 Shock magnitude: 300%	Carbon budget: 1150 GTons Shock year: 2050 Shock magnitude: 300%
1.5 C° scenario	Carbon budget: 650 GTons Shock year: 2030 Shock magnitude: 50%	Carbon budget: 650 GTons Shock year: 2040 Shock magnitude: 50%	Carbon budget: 650 GTons Shock year: 2050 Shock magnitude: 50%
	Carbon budget: 650 GTons Shock year: 2030 Shock magnitude: 100%	Carbon budget: 650 GTons Shock year: 2040 Shock magnitude: 100%	Carbon budget: 650 GTons Shock year: 2050 Shock magnitude: 100%
	Carbon budget: 650 GTons Shock year: 2030 Shock magnitude: 300%	Carbon budget: 650 GTons Shock year: 2040 Shock magnitude: 300%	Carbon budget: 650 GTons Shock year: 2050 Shock magnitude: 300%

Table 3.7: Scenario architecture with parameters implemented

Finally, the optimization algorithm required a specific intervention to modify the agents' foresight in the open-loop Nash equilibrium. Correcting the intertemporal optimal growth horizon of the model is crucial to guarantee an unbiased output of the optimization, as the perfect foresight growth algorithm can predict the

occurrence of fuel shocks and thus agents can prepare for the crisis.
A myopic run is therefore forced into the simulation by limiting the foresight horizon of agents to $tshock - 1$ by means of the reference scenarios used as a baseline for the preshock iterations of the algorithm. The time-dependent fixing of variables allows for simulating the uncertainty of large-scale and unforeseen international turmoils, which are assumed to be unpredictable both in terms of year and magnitude of occurrence.

4

Results

Within this chapter, the results obtained from the simulation are presented. The first section summarizes the outcome of the steel sector modeling by presenting the global demand for crude steel, the regional production breakdown and the evolution of technology mix in the sector. The following section presents a comprehensive analysis of the decarbonization potential for hydrogen in energy-dependent countries. Then, the financial disruption produced by shocks varying in time and magnitude is described. The fourth section explores the economic and financial consequences of the transition to a hydrogen-based energy supply on the vulnerability of the steel industry to energy crises.

4.1. Steel industry future outlook

The outcome of the exogenous characterization of the steelmaking industry demand, based on the intensity of use hypothesis, is presented in Figure 4.1. When comparing the results of the model with historical data from the International Energy Agency (IEA) and the World Steel Association (WSA), the model output presents a demand increase consistent with real-world data, maintaining a deviation lower than 10%. The industry expansion trend is driven by large emerging economies with increasing GDP per capita and population, where urban and infrastructural development requires substantial availability of steel and a peak demand of 2.5 Gtons in 2045. Similarly, the industry contraction after 2045 represents a saturation phase where most of the regions reached sufficient levels of development.

Moreover, in Figure 4.2, steel production is displayed with the regional breakdown of production shares. During the scenario forecast, the main player is undoubtedly China, which gains a progressively more dominant role as a producer, up to 55% of the global production. A group of regions, consisting of Europe, Russia, USA, Japan and South Korea, experiences the same pattern of losing the initial relevance in the market over time while emerging regions, especially India, south-east Asia countries and Indonesia, take over and gain increasing production shares. During the sectoral analysis, a deep dive into the steel industry of the largest producers has been carried out to extrapolate information regarding the most relevant actors that can influence the decarbonization trajectory of steelmaking, giving greater prominence to China, Europe, India and Japan & South Korea as they account for more than 75% of the global steel production.

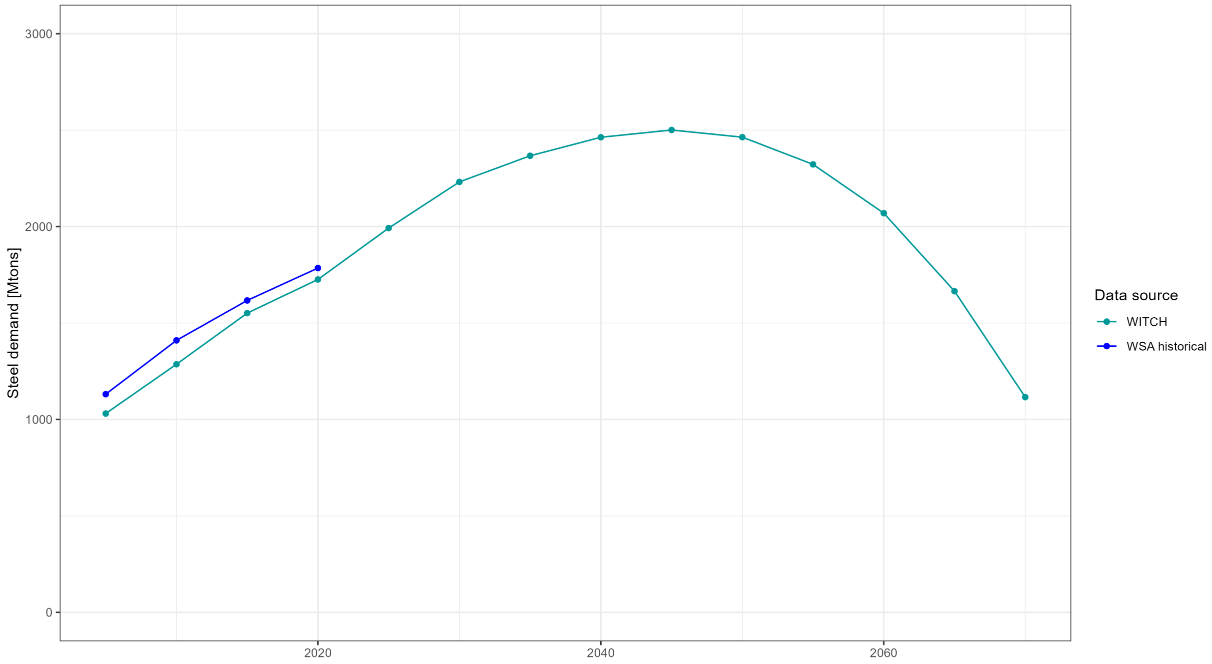

Figure 4.1: Global steel demand

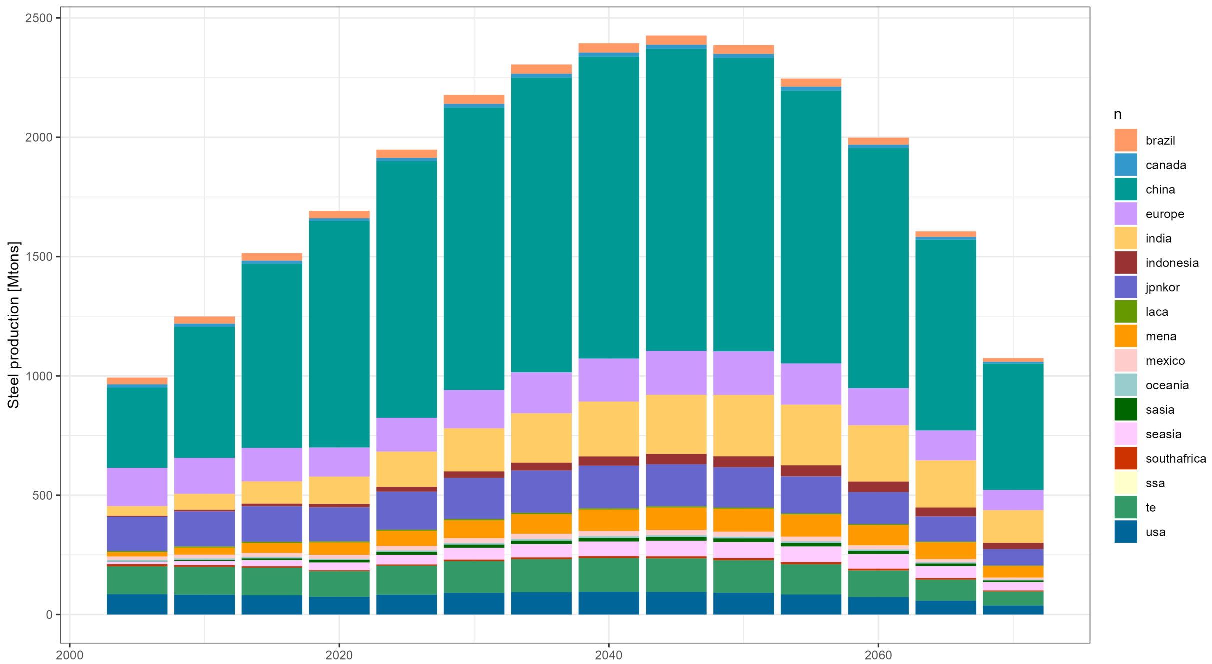

Figure 4.2: Global steel production breakdown

Besides the production and consumption of crude steel, another relevant dynamic within the industry is the technological transition that is currently happening in steel plants across the globe and that is expected to accelerate in the near future. In the left plot, Figure 4.3 illustrates the global technology mix of steel production routes over time, describing a strong transition from blast furnaces to electric arc furnaces. The trend is coherent with the Global Steel Plant Tracker, which reports mostly electric arc mills among the plants announced and currently under construction. Moreover, a similar pattern can be found in historical data when looking at the transition from open furnaces to blast furnaces that occurred in less than 40 years.

The information derived from the graph has important consequences on the energy analysis of the sector: steelmaking is shifting to a less energy-intensive production route with larger compatibility with low-carbon electrification processes, as shown in the right plot of Figure 4.3.
On the other hand, it is also noteworthy that the steel industry is projected to experience a natural contraction based on the decline of steel demand in the future and therefore the trajectories displayed benefit not only from the technological change but also from the intrinsic shrinking of the consumption of crude steel.

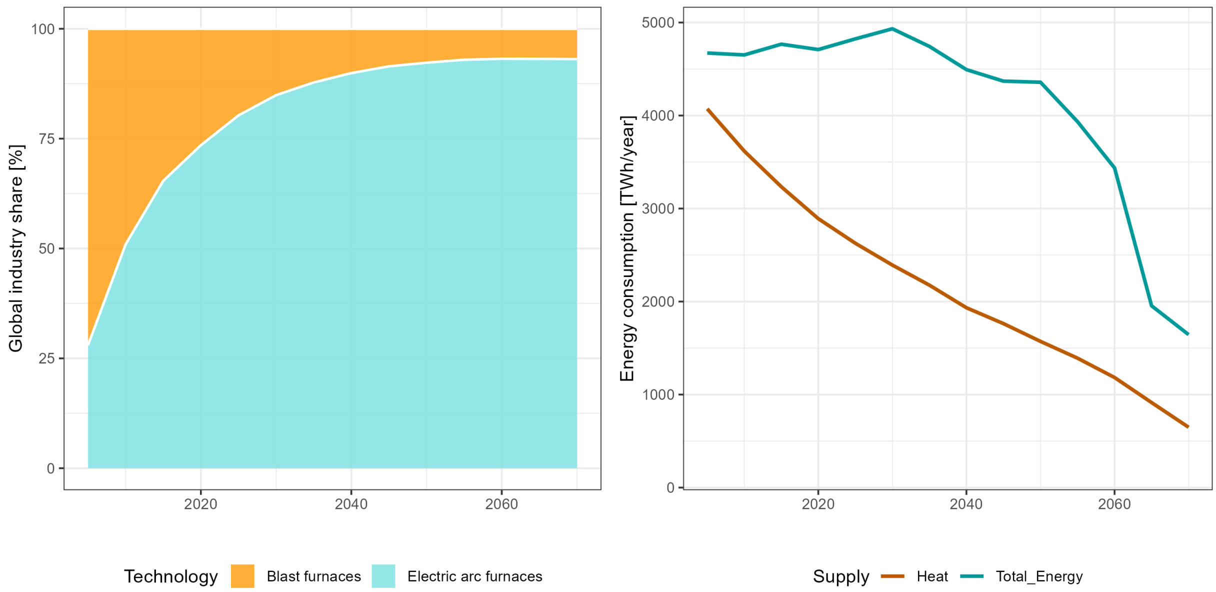

Figure 4.3: Technology and supply outlook of global steel industry

4.2. Hydrogen potential for the decarbonization of heat supply

The global scope of the analysis requires an accurate differentiation between regions when discussing the dependency on imported natural gas in national energy mixes. Figure 4.4 shows the balance of natural gas trade across the globe before any energy crises by dividing the amount of gas imported in each country by the total consumption of gas in the national energy balance.

From the model output, countries can be divided into three main categories: importing (blue gradient), exporting (green gradient) and independent (white gradient) nations. The categorization explained can be linked to Figure 3.3 to derive information about the vulnerability to energy shocks and the net effect expected not only in the steel industry but in the entirety of a national economy.
It is important to note that the balance of natural gas trade across countries varies over time, reflecting the evolution of the extraction sector of the commodity. However, the mentioned categorization is fairly maintained during the timeframe.

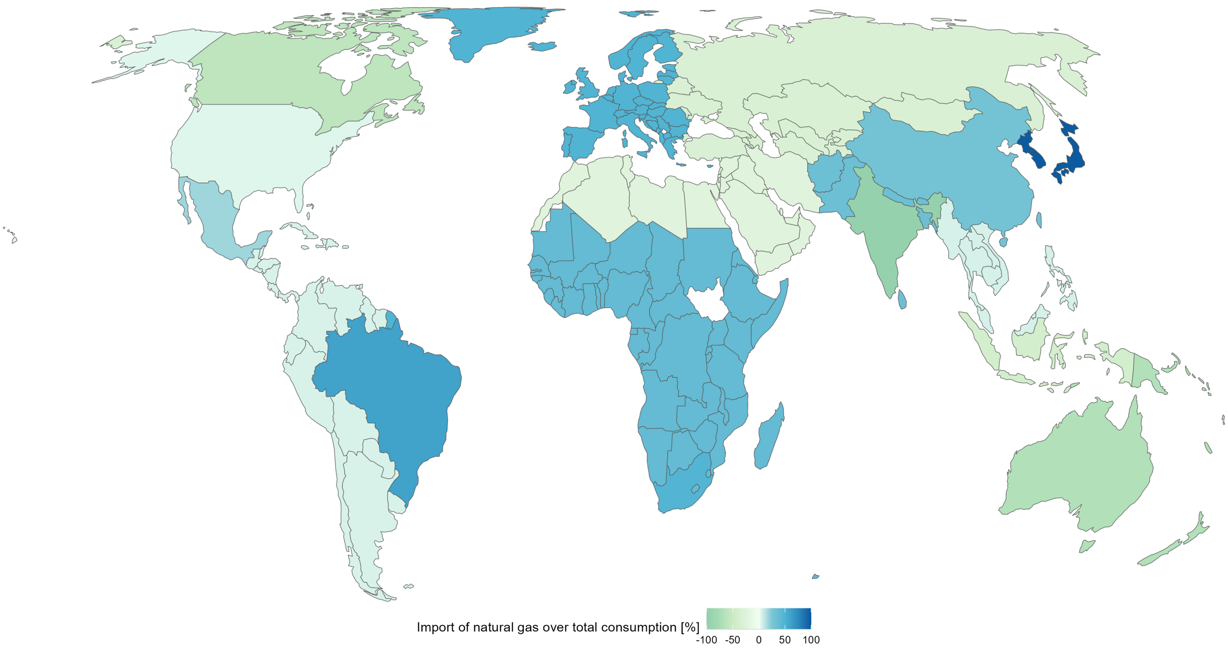

Figure 4.4: Natural gas dependency map

The BoT shows that a substantial share of steel production, ranging between 61% and 70% of global manufacturing, is located in countries with a high degree of energy dependency: China, Europe and Japan rely on imported natural gas to sustain heat generation in the national steel industries. To study the decarbonization potential of hydrogen in these countries, the three policy scenarios introduced in Table 3.7 are implemented and used to analyze the responsiveness of steelmakers to a climate policy push.

The competition between hydrogen and natural gas is linked to the exogenous inelastic demand for crude steel, thus the correspondent energy demand must be satisfied by the cumulative supply of heat carriers at any given time. Figures 4.5 and 4.6 present the outcome of the competition between heat carriers in the steel industry by displaying the absolute hydrogen consumption and the share of hydrogen in the energy mix under different regulatory scenarios.
The decarbonization potential of hydrogen as an alternative fuel becomes increasingly evident as the

energy policies push grows, demonstrating the mitigation opportunities in the steel sector.

Among the energy-dependent regions, China and Europe deserve particular attention because of the combination of some factors, namely the large size of the steel manufacturing sector, the heavy dependence on imported natural gas and the fast response to carbon pricing. Although the current pledges scenario is not sufficient to stimulate a strong switch to alternative fuels, Europe and China manifest low levels of inertia to climate policies and therefore the potential to quickly develop an effective infrastructure for the supply of hydrogen to the steel industry.
Europe, for instance, can substitute 79% of natural gas and replace it with low-carbon hydrogen under a 2 degrees scenario by 2040, demonstrating the fastest policy response, while China takes almost 10 years more to reach the same target. However, both regions can achieve almost complete decarbonization of the heat supply by 2060 if supported by consistent carbon pricing, with a 98% and 97% share of hydrogen fuel respectively for Europe and China.
A different result is obtained when analyzing the Japanese and South Korean region, which requires a much larger effort from a policy perspective to accomplish only a fraction of the equivalent decarbonization presented in the leading regions, lagging behind more reactive industries. By 2060, only a 1.5 degrees scenario yields a 78% penetration of hydrogen in the mix. The different reactions to carbon pricing are consistent with the relation between the national heat demand in steelmaking and the corresponding availability of renewable energy upholding the production of hydrogen shown in Figures A.3 and A.2.

The outcome of the competition between natural gas and hydrogen defines the emissions trajectories presented in Figure 4.7. The environmental performance shown is focused on emissions produced by heat generation in steel mills and thus consistent with the results of the fuel mix: Europe reaches the full mitigation of emissions by 2050 while China by 2060. However, given the size of the respective industries, China delivers a larger emissions abatement with a more pronounced distinction when compared to the current scenario. Over the timeframe analyzed, the heat supply switch generates a cumulative emission saving of 800 Mtons of CO_2e in China and 285 Mtons of CO_2e in Europe under a 2 degrees scenario.

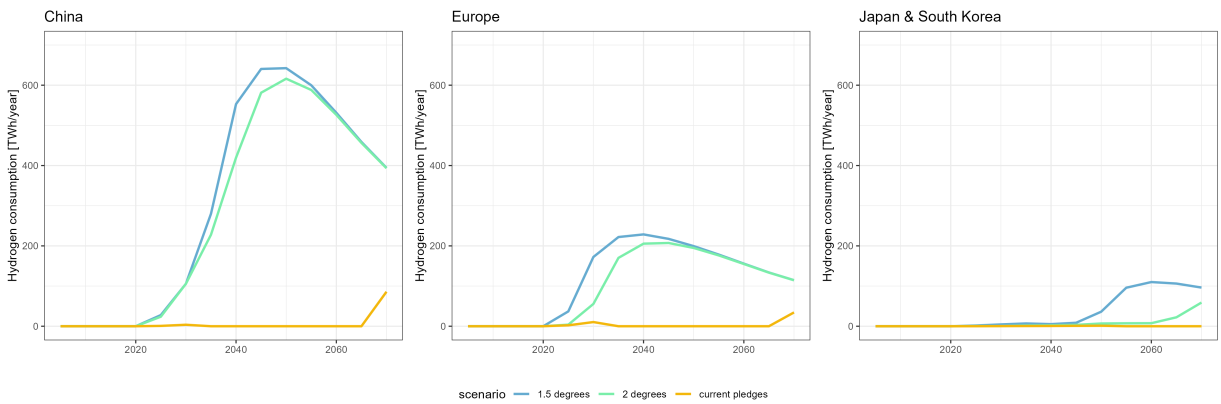

Figure 4.5: Hydrogen consumption in steel industry - baseline (no shock)

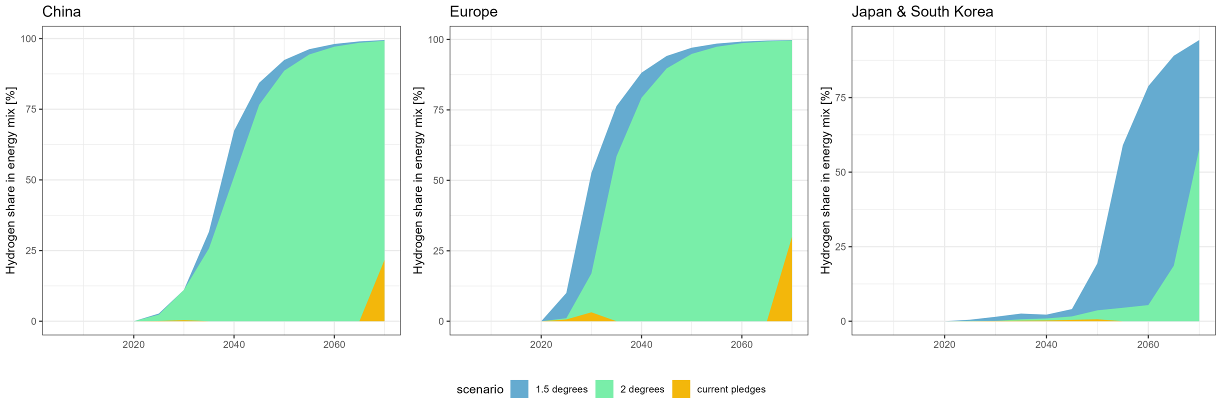

Figure 4.6: Share of hydrogen in the fuel mix of steel industry heat - baseline (no shock)

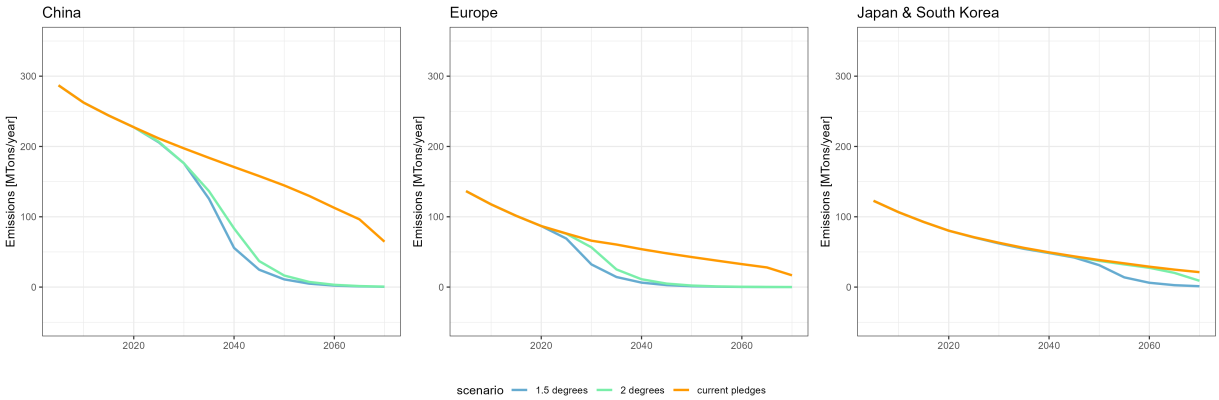

Figure 4.7: Steel industry emissions from heat generation - baseline (no shock)

4.3. Economic impact of energy shocks

The consequences on the expenditures faced by the largest producers of steel for different shock magnitudes and years of occurrence are illustrated under different policy scenarios. Figure 4.8 displays the impact of natural gas price peaks under the current pledges scenario for 50% shocks in the first row, 100% shocks in the second row and 300% shocks in the third row.
Three out of four of the leading players in the steel industry, namely China, Europe and Japan & South Korea, respond as importing countries and experience an abrupt increase in national expenditures to secure the fuel supply necessary for the respective economies, while India seems to be almost unaffected. Observing the reactions to energy crises confirms the exposure to risk of three of the main steel manufacturers, located in highly sensitive regions. The same pattern can be identified even when higher levels of environmental commitment are implemented globally, as shown in Figure 4.9 and Figure 4.10.

However, the effect of hydrogen introduction induced by carbon pricing can be identified distinctly in the second and third columns of the grid, where the expenditure spikes are progressively dampened over the years. China, Europe and Japan & South Korea manifest a behavior consistent with the energy dependency trajectories previously outlined in Figure 4.5. Policy intervention therefore enhances the energy security of agents as underlined by the evolution of costs for fuel procurement converging to zero.

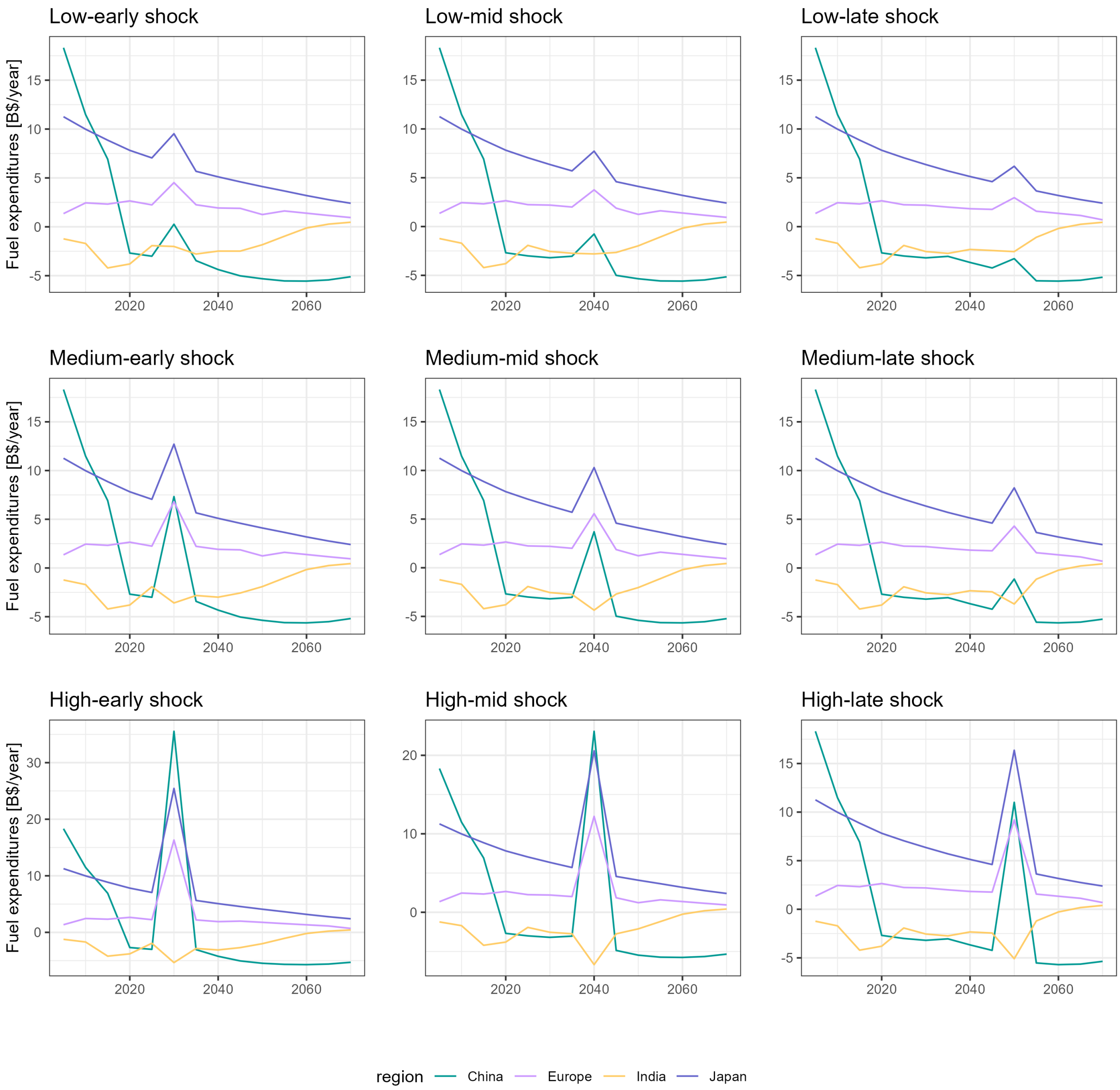

Figure 4.8: Energy shocks impact on steelmaking fuel procurement under current pledges scenario

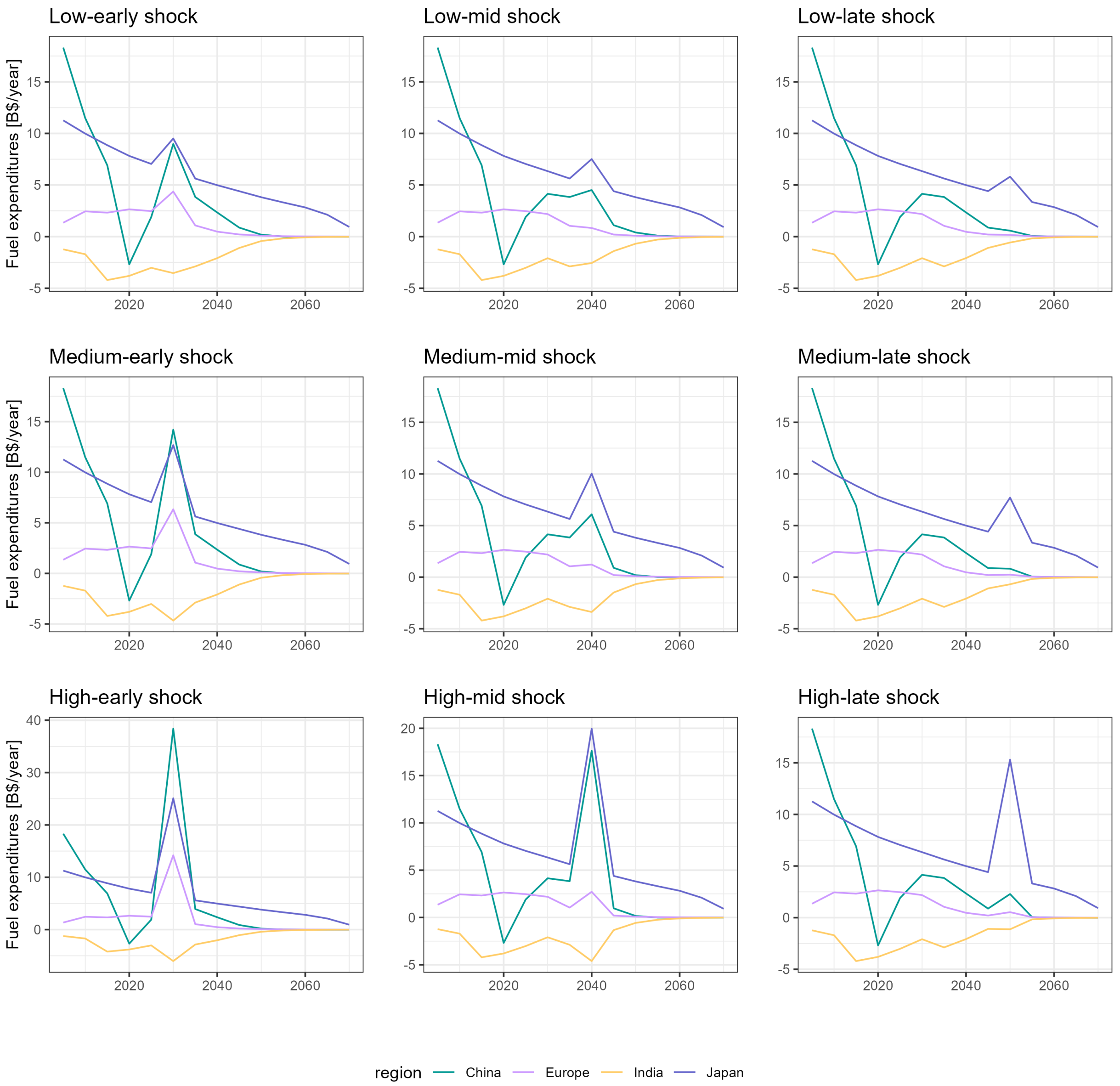

Figure 4.9: Energy shocks impact on steelmaking fuel procurement under 2 degrees scenario

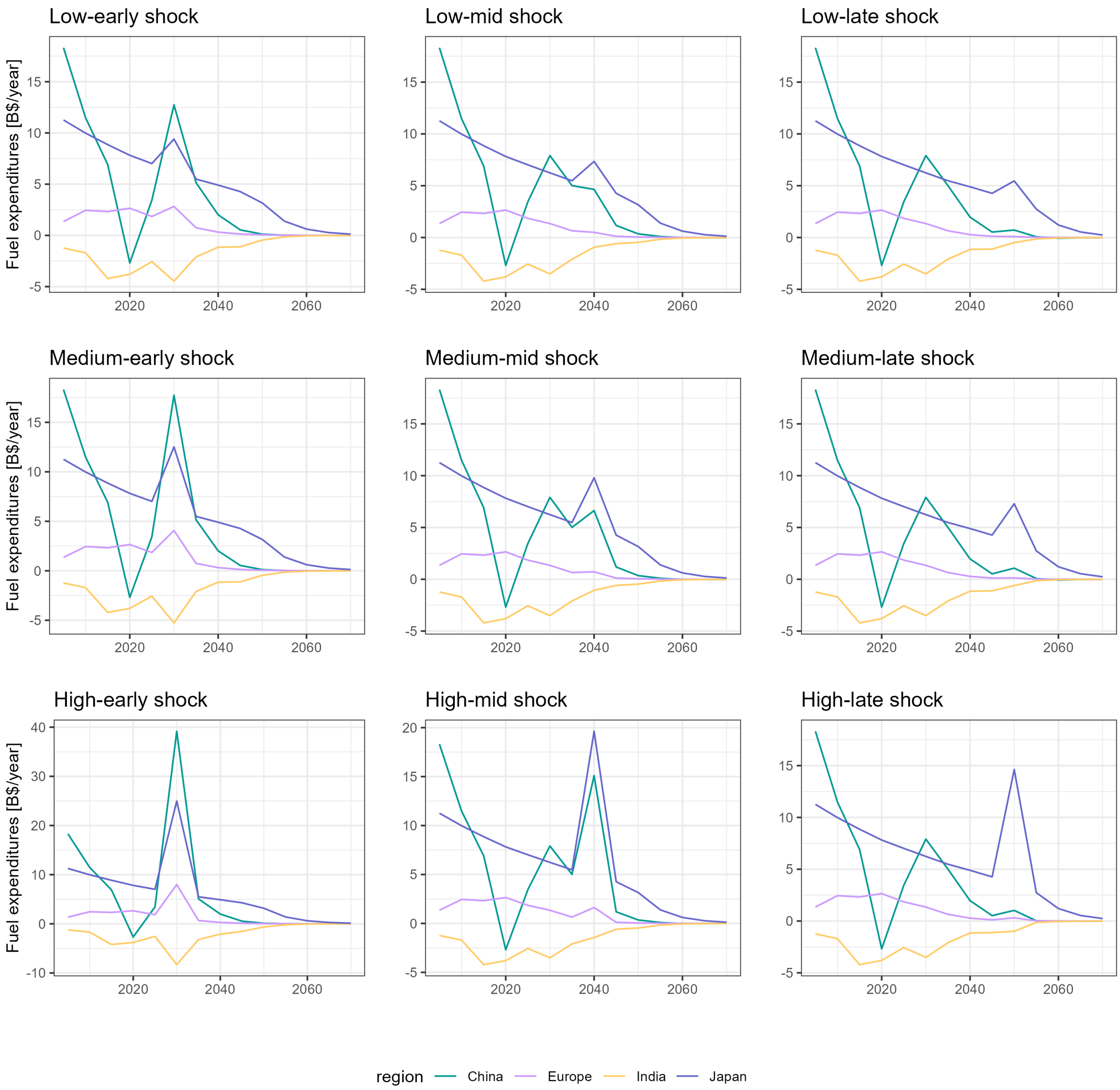

Figure 4.10: Energy shocks impact on steelmaking fuel procurement under 1.5 degrees scenario

To investigate further what has been found through the fuel expenditures analysis, an in-depth exploration of the cost of inaction, defined as the economic losses faced by steelmakers when failing to act or delaying the investments aimed at mitigating the shock's impact, was carried out by comparing the fuel costs experienced by steel industries in the year of occurrence of the shock with the corresponding value in the baseline non-shocked simulation. By fixing the model's foresight reach to the last non-disruptive year, the difference between industrial fuel expenditures in $tshock$ for the shocked and baseline simulations can be compared and used as a proxy for the economic impact perceived by the steel manufacturers across the entire scenario architecture.

The pattern identified in Figures 4.11 and 4.12 captures relevant information about the sensitivity to the three dimensions of the analysis: early shocks reverberate proportionally to the shock magnitude for every policy framework considered, inflicting the largest impact on the steelmaking costs.

However, when observing mid and late shocks, limited economic repercussions regardless of the shock magnitudes after 2035 (mid and late shocks) in Europe and after 2045 (late shock) in China are observed under 1.5 and 2 degrees scenarios. Above a diversification threshold of 87% in the supply mix, the potential impact of different amplitudes of shock on steelmakers' expenditures is limited between 1.13 and 1.71 billion dollars.

The cost of inaction can affect a considerable fraction of the economic output of the industry when the stabilization of the fuel supply is overlooked. The burden of the shock in different years in fact ranges widely when considering best- and worst-case combinations of variables: in Europe, early shocks vary from 1.5 B$ to 14.1 B$, mid shocks from 0.22 B$ to 10.4 B$ and late shocks from 0.04 B$ to 7.5 B$. In China, early shocks range from 4.8 B$ to 38.7 B$, mid shocks from 2.2 B$ to 26.7 B$ and late shocks from 0.6 B$ to 15.6 B$.

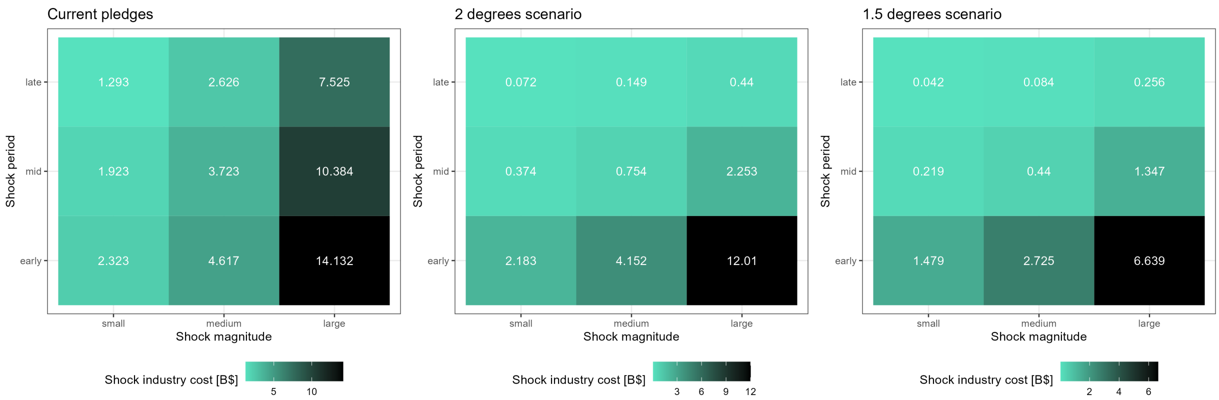

Figure 4.11: Economic impact on European heat supply of steel industry

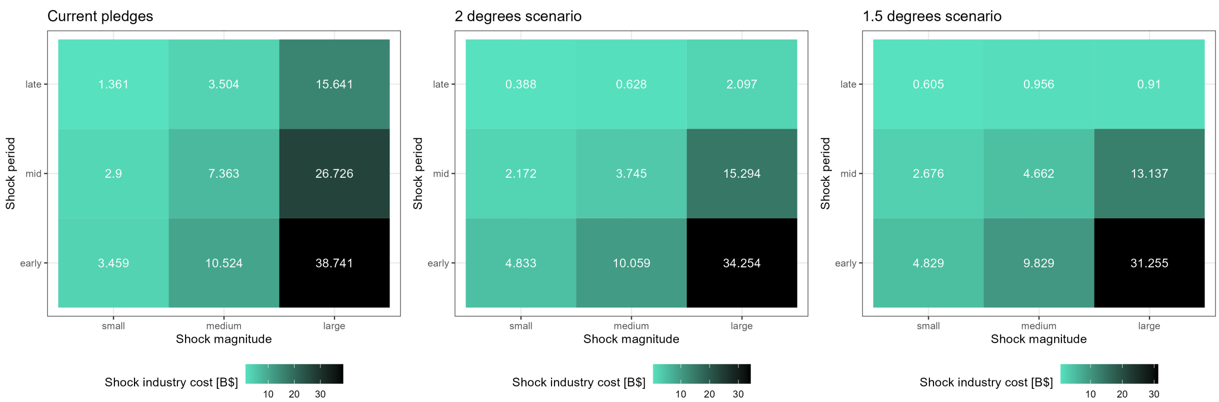

Figure 4.12: Economic impact on Chinese heat supply of steel industry

4.4. Energy security and resiliency assessment

The concept of developing energy security in the steel heat supply can also be analyzed using the national investments in hydrogen technologies made before the shock's occurrence, as the cumulative amount of financial resources allocated for hydrogen is found to represent an indicator of energy diversification and therefore of resiliency to geopolitical-induced price shocks.
In Figures 4.13 and 4.14, a sample case of a medium-size price shock of 100% is used to introduce the net present cost of hydrogen supply investments between $t0$ and $tshock - 1$ under different policy scenarios, with a discount rate assumed at ρ=3% (Emmerling et al., 2019), while comparative values for ρ=5% can be found in Figure A.9 and A.10. The level of investment shows an inverse proportionality with the economic disruption caused by an energy crisis in natural gas importing regions, meaning that the upscale of financial efforts entails dampened economic backlash. Again, the results confirm how earlier investments aimed at creating a hydrogen supply infrastructure can promote energy diversification and therefore enhance resiliency to shocks, while delaying the investment cycles exposes the industry to financial risk.

In fact, comparing the level of investments in Europe and in China gives information on the different readiness of the two nations in activating the flow of financial resources to hydrogen technologies summarized in Table 4.1. Most of the investments in Europe across scenarios are concentrated in the 2030-2040 decade while in China the largest efforts occur between 2040 and 2050.

Europe				**China**			
		Low shock				Low shock	
	2020-2030	2030-2040	2040-2050		2020-2030	2030-2040	2040-2050
Current pledges	8%	44%	**48%**	Current pledges	3%	35%	**62%**
2 degrees	18%	**48%**	34%	2 degrees	34%	12%	**54%**
1.5 degrees	32%	**49%**	19%	1.5 degrees	27%	18%	**55%**
		Medium shock				Medium shock	
	2020-2030	2030-2040	2040-2050		2020-2030	2030-2040	2040-2050
Current pledges	9%	44%	**47%**	Current pledges	3%	35%	**62%**
2 degrees	23%	**44%**	33%	2 degrees	27%	22%%	**51%**
1.5 degrees	32%	**48%**	20%	1.5 degrees	27%	18%	**55%**
		High shock				High shock	
	2020-2030	2030-2040	2040-2050		2020-2030	2030-2040	2040-2050
Current pledges	11%	**46%**	43%	Current pledges	3%	36%	**61%**
2 degrees	20%	**65%**	15%	2 degrees	28%	**43%**	29%
1.5 degrees	**52%**	14%	34%	1.5 degrees	22%	13%	**66%**

Table 4.1: Breakdown of hydrogen investment cycles - the values displayed represent the share of financial resources per decade over the total investment allocated by 2050

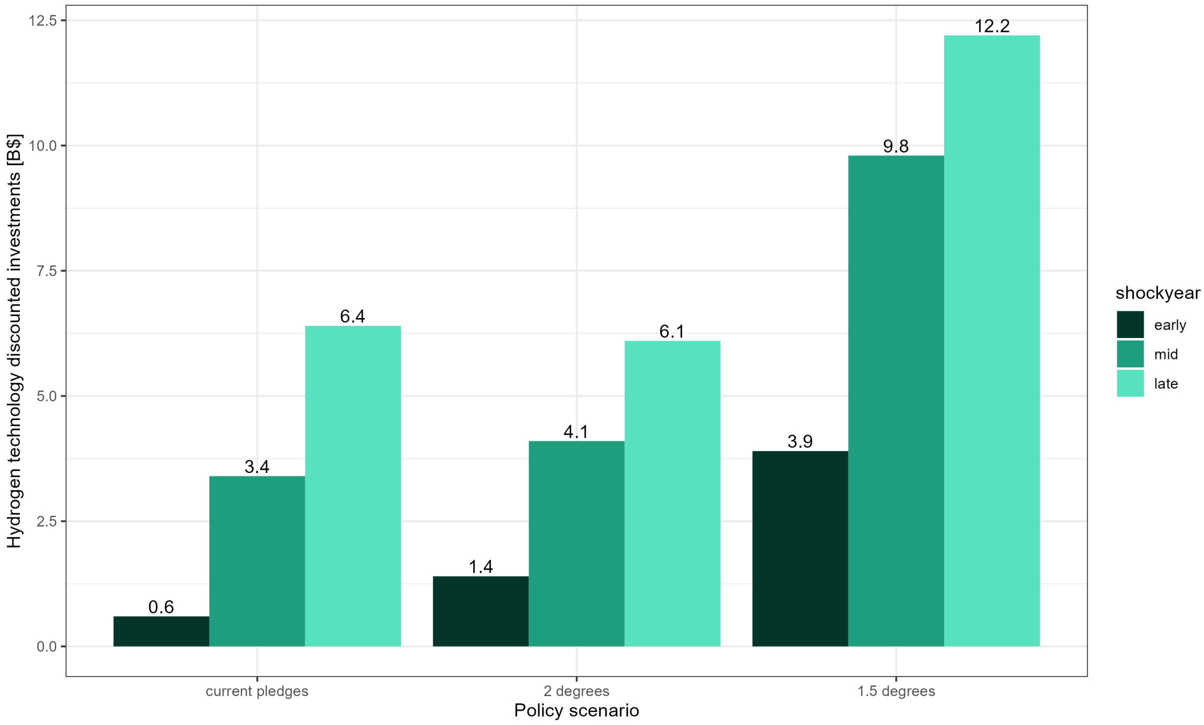

Figure 4.13: Pre-shock cumulative investments in hydrogen technologies - Europe

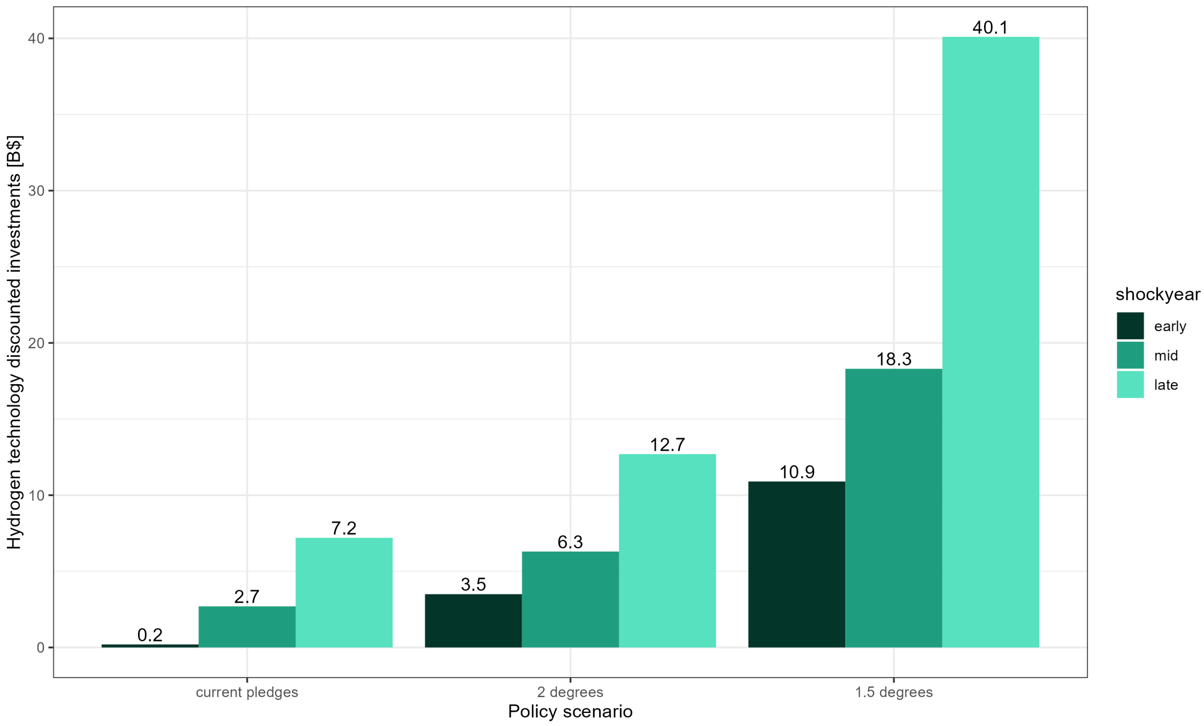

Figure 4.14: Pre-shock cumulative investments in hydrogen technologies - China

The correlation between preventive investments and the cost of inaction is investigated in Figure 4.15 and 4.16, where every combination of $tshock$, $pshosck$ and policy scenario is visualized to summarize the dominant patterns in Europe and China.

As expected, larger magnitudes of shocks are responsible for increasing economic impact across scenarios being investments equal, while delayed shock periods shift the outcome to higher levels of investments and lower financial repercussions on fuel expenditures.

Besides the two variables linked to the uncertain nature of the energy crises, which are considered external factors and therefore not influenceable by agents' actions, the pivotal dimension representing policymaking intervention is the climate policy scenario, modeled as carbon pricing tailored to a target carbon budget.
Overall, more intense carbon taxes produces higher values of cumulative investments while lowering the cost of inaction, demonstrating the influence of regulatory activity on shock mitigation. The potential impact range of different shock intensities is also shrunk, progressively immunizing the industry to all levels of disruptions. On the other hand, a similar trend entails an expense transfer from natural gas procurement costs to hydrogen capacity development as a result of pricing strategies aimed at taxing fossil fuels' consumption.

Alongside the perspective of security of supply, the increasing allocation of financial resources towards hydrogen deployment yielded by severe carbon pricing is also considered for its beneficial impact on emissions: decreasing carbon budgets implemented in the optimization are an indicator of the environmental benefit produced by the corresponding emissions abatement, as previously presented in Figure 4.7.

The correlation arising from the scatter points layout supports the most important dynamic identified in the analysis: rapid allocation of investments in hydrogen production induced by carbon taxes is an effective strategy to develop a sustainable supply of heat, granting lasting energy resiliency to price shocks in steelmaking.

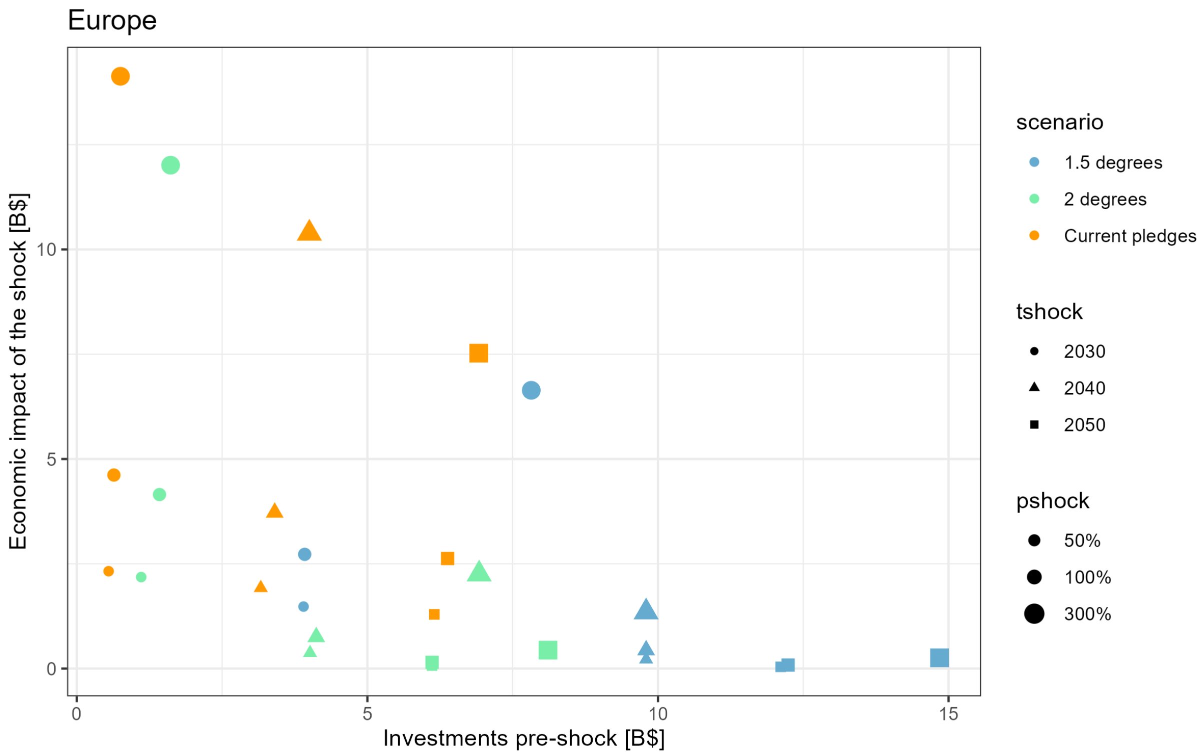

Figure 4.15: Investments-impact correlation on regional level (Europe)

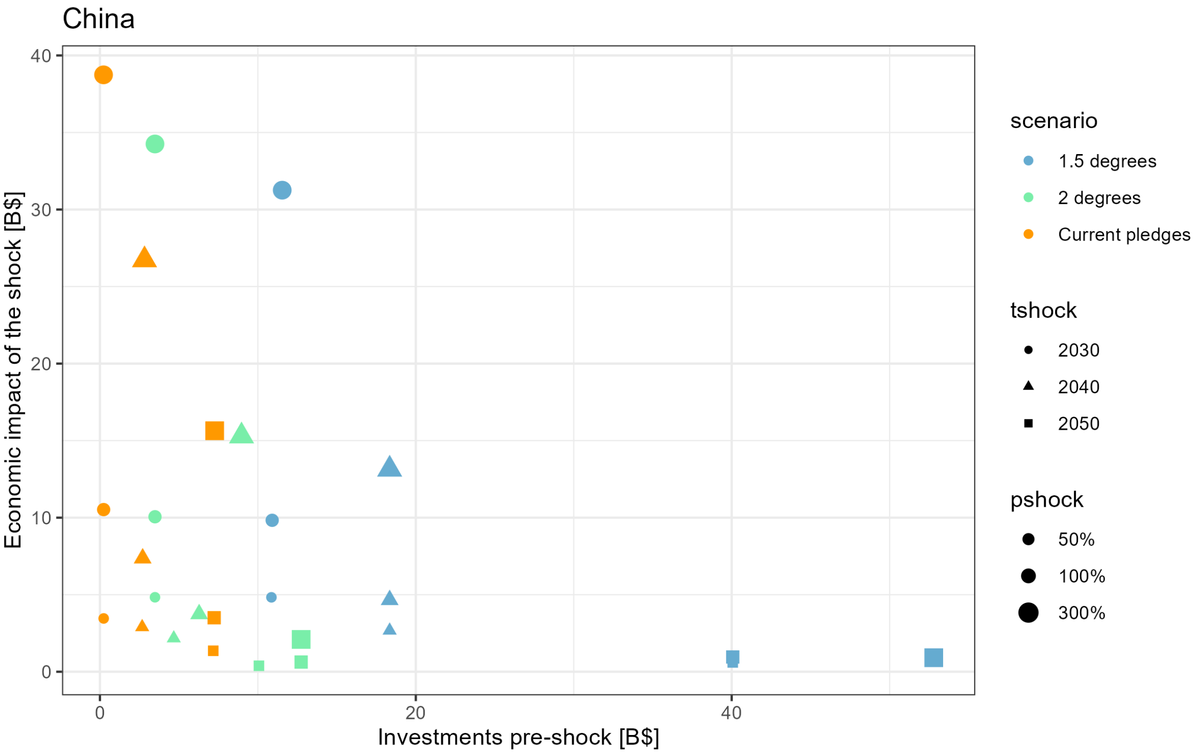

Figure 4.16: Investments-impact correlation on regional level (China)

5

Discussion

In this chapter, the results presented in Chapter 4 are interpreted and contextualized following the line of reasoning of the study: first, the relevance of the security of heat supply in the future of steelmaking is underlined and the potential for hydrogen to play a substantial role in the transition is described. Second, the impact of energy crises on the expenditures faced by steelmakers is considered and linked with the policy intervention's role in stimulating adequate investments in hydrogen. The implications of developing energy resiliency for the heat supply in steel manufacturing are then presented from a financial and geopolitical perspective. A separate section summarizing the main limitations found and acknowledged during the study concludes the chapter.

5.1. Interpretation of results

The trajectories of future developments of the steel industry show an increase in the demand for crude steel until 2050, consistent with renowned projections of the International Energy Agency (IEA, 2020b), which forecast 2.5 Gt/year of global production in 2050. As a consequence of the exogenous modeling of demand, the industry expansion trend is driven by large emerging economies with increasing GDP per capita and population, where urban and infrastructural development requires substantial availability of steel. Similarly, the industry contraction after 2045 represents a saturation phase where most of the regions reached sufficient levels of development and the consumption of crude steel for urban and infrastructural expansion ceases. Most of the demand is met by industries concentrated in China, Europe, India and Japan: an asymmetrical production distribution affects the sensitivity to energy shocks in the simulation, as the geographical differences in terms of fossil fuels and renewable energies depend on regional availability and trade.

Despite fuel efficiency improvements and the decline of raw steel demand shrinking the energy consumption over time, heat generation still plays a substantial role in the transition of steelmaking energy supply, both from an energy and environmental perspective.
The potential to effectively decarbonize the heat supply through the introduction of hydrogen in the fuel mix is dependent on the availability of hydrogen technology and infrastructure, which in turn is closely related to the climate policy push, demonstrating the mitigation opportunities in the steel sector and the importance of policymaking. The adoption of hydrogen for heat supply transformation may fail without fossil fuel taxation to create favorable conditions for competition against imported natural gas, as the current trajectories describe an evolution far from any environmental goal.

Among the energy-dependent regions, China and Europe have the potential to lead the transition in the respective steel industries, as the availability of renewable energy supporting the technological advancement of low-carbon hydrogen allows a timely penetration of hydrogen in the supply mix when active carbon pricing is implemented by governments. Given the global relevance of European and Chinese steelmaking, which also share a widespread dependence on imported fossil fuels, these players can represent an example of rapid and successful adoption of hydrogen in the upcoming decades, backing the electrification shift in the long run.
Hydrogen therefore represents a crucial element for short-term emissions abatement preceding the complete electrification of heat supply in the long run and acting as a bridging technology.

When higher penetration of hydrogen in the steelmaking fuel mix is achieved, the environmental benefits affect a relevant fraction of the industrial carbon footprint. The cumulative decarbonization potential of the European and Chinese fuel supply for heat generation equals 12% of the emissions of the sector globally, which would be in line with the Sustainable Development Scenario produced by IEA (IEA, 2020b). A similar result has major consequences for a sector that is currently not on a trajectory compatible with climate targets and it would contribute to the multilateral efforts in technological progress alongside electrification, energy efficiency, CCS and asset modernization (OECD, 2022). The resulting decarbonization evolution describes a pathway addressing several challenges outlined within the core system boundary of the Science Based Targets initiative (SBTi) for the iron and steel manufactuing decarbonization approach (Chan et al., 2023), underlying the reliable role of hydrogen in the net-zero ambitions for the steel industry.

Besides the environmental benefit, transitioning the heat supply of steel mills to alternative and sustainable solutions changes the fuel procurement structure of the industry, relieving the dependency on natural gas and decoupling the fuel expenditures from the international trade dynamics. As most of the facilities for the production of crude steel are located in highly sensitive areas, steel manufacturing is an industry extremely exposed to energy shocks' risk. However, for the same reason, it also presents substantial opportunities for avoided fuel costs and for economically justifiable decarbonization.

When considering long-term financial performance, given the unpredictable nature of energy shocks which have historically ranged in intensity and frequency, the best course of action is represented by a rapid and significant acceleration of investments in hydrogen technologies that secure adequate supply capacity. The results showed how the timing and strength of financial flows can make a difference up to several orders of magnitude in the economic consequences perceived by steelmakers. If the diversification of supply is achieved, the economic effects linger over time and regardless of the magnitude of external shocks. Therefore, steelmaking can benefit from potential avoided costs indefinitely and endure future shocks, while the cost of inaction threatens steelmakers also after the end of the energy crisis.

As expected, the level of investments in hydrogen thus represents an indicator of the degree of national energy resiliency, where growing financial efforts produce stronger protection. An inverse proportionality between the deployment of hydrogen technologies and the economic disruption perceived during a shock has significant implications for steelmaking, one of the largest manufacturing industries in the world and a long-lasting element of modern society.

Steel manufacturers might deem the support of hydrogen infrastructural development a strategically effective decision, as they would keep the potential backlash of energy shocks beneath a tolerable threshold, demonstrating a high degree of risk aversion and therefore the willingness to prompt the transition to a sustainable and secure energy supply infrastructure.
Realizing the steelmaking transition would set an example for other heavy industries with common challenges and a similar degree of risk aversion. Cement and petrochemical manufacturers, two of the largest

emitters in the industrial sector, depend heavily on fossil fuels procurement for high-temperature heat generation and industrial processes and therefore share analogous dynamics in terms of environmental undertaking and economic vulnerability to energy shocks.

Furthermore, enhancing energy diversification and security has widespread implications for the geopolitical interaction between countries and coalitions because decreasing the energy dependency of importing countries would limit the market value of fossil fuels and ease the tension in geographic areas historically disputed for the control of resources like natural gas, oil or coal. The transition to renewables-based energy systems would limit the instrumentalization of fossil fuels supply practiced by energy-exporting regions and promote symmetrical relationships in energy markets (Scholten, 2018).

5.2. Limitations

During the model development performed to provide WITCH with the functionalities needed for the study, several limitations were encountered and their consequences on the analysis were acknowledged.

The technology trend in the steel industry shows a rapid shift of manufacturing capacity from BF to EAF from the beginning of the simulation in 2005. The model, despite the undeniable momentum registered in the adoption of furnaces based on electric arc technology, anticipates the adoption of electrification, producing a technological evolution that overestimates early electrification's role compared to real data. However, it is noteworthy that electrification is responsible for the decrease in heat demand for steelmaking, which is the focus of the optimization algorithm for fuel competition. Larger values of heat consumption would increase the reliance of steelmakers on fossil fuels and exacerbate the vulnerability in importing countries, where hydrogen would represent an even more strategic decarbonization driver before electrification takes over, emphasizing the importance of the results presented.

Moreover, while the focus of the modeling has been on the competition between hydrogen and natural gas, the internal competition between grey, blue and green hydrogen is overlooked. With different production processes involved, large differences can be expected in terms of economic and environmental performance when relying on steam gas reforming rather than electrolysis. The module adaptation failed to accurately describe the deployment dynamics of the hydrogen-sourcing technologies, resulting in a less accurate projection of blue and grey hydrogen costs which in turn resulted in 100% green hydrogen consumption. In fact, the linear competition algorithm of WITCH generates a sudden switch between unconstrained technologies in a set: capital accumulation is not taken into account for SGR and SGR_CCS in the hydrogen competition, although grey hydrogen represents a major part of the current hydrogen supply and blue hydrogen is recognized to be an essential technology in future applications (Dermühl and Riedel, 2023).

Another limitation of the modeling process consists of the interplay between the exogenous characterization of the steel demand projections, which depends on GDP per capita, and the macroeconomic dynamics of the optimization. In the WITCH model, GDP baseline trends are based on the OECD projections and depend on the Shared Socioeconomic Pathway (SSP) ”Middle of the Road” implemented in the simulation, where all regions get richer over time even if at different paces. The steady increase in GDP entails a demand saturation point followed by the contraction of crude steel consumption. However, the decrease in steel application for infrastructural development could be compensated by the necessity of maintenance and replacement of steel products, which would stabilize the demand to a nearly constant level. With a stabilized demand, energy consumption would follow relying mainly on energy efficiency and fuel switching for consumption curb.

6

Conclusions

At the outset of the project, the aim of exploring the economic and environmental opportunities of developing hydrogen supply for the steel industry as an alternative and sustainable heat carrier was formulated. The study delved into the implications of considering the threat of energy crises induced by geopolitical disruptions to investigate the beneficial effect of developing energy resiliency through fuel diversification in energy-importing countries.

By developing the hydrogen supply for the steel industry in the WITCH model, a comprehensive analysis was implemented by means of a tailored scenario analysis based on the degree of climate policy in place, and the time and magnitude of the shock affecting the global fuel prices.
The study of the model outcome and the processing of the derived data allowed the research subquestions, used to effectively structure the line of reasoning, to be answered as follows:

What is the decarbonization potential of hydrogen in the future of the steel industry as an alternative heat carrier competing with natural gas?
The industry assessment underlined the relevance of heat supply necessary to support the growing demand for crude steel expected in the near future, especially before electrification takes over the mitigation effort. To sustain the heat generation in steelmaking, the competition between natural gas and hydrogen, representing a sustainable and alternative fuel, was demonstrated to be highly sensitive to climate policies' influence. With an adequate capacity of renewable energy upholding the production of low-carbon hydrogen, deep integration of hydrogen in the fuel mix is made possible by the implementation of carbon pricing strategies that would trigger investment cycles for hydrogen development. The decarbonization pathways derived showed the potential of substantial emissions savings from heat generation, up to 12% of the global steel manufacturing carbon footprint, with a predominant position of Europe and China as large producers with favorable conditions for hydrogen technologies deployment. Hydrogen exhibited the ideal dynamics to represent a bridging solution for steelmaking decarbonization especially in the short term, when the diffusion of high-temperature heat electrification is not sufficient for the mitigation.

What impact would energy shocks have on the fuel supply of national steel industries?
The national balance of trade showed that a large fraction of the total manufacturing capacity for crude steel is exposed to high risk related to natural gas global market shocks. Besides the amplitude of the increase in natural gas prices, which is a logical driver of economic damage, the repercussions on the steel sector depend largely on the time span before the shock: an early shock would have more

serious consequences than a shock far in the future because of the shortage of time to benefit from the development of adequate diversification of supply. Because of the uncertain and unpredictable nature of energy crises, the only viable solution to actively address the possibility of a shock is the level of governmental and regulatory activity enacted beforehand to promote renewable energy carriers, as this third variable, unlike the shock period and magnitude, can indeed represent a measure of the foresight of energy policies and the readiness of political action. In fact, the cost of inaction is demonstrated to be exacerbated when scarce activity from policymaking results in a slow and limited fund flow to fuel supply diversification.

What role can investments in hydrogen play in enhancing energy resiliency and security under the threat of energy crises?
Stringent environmental regulations drive investments in hydrogen production infrastructure, which were found to be linked with the degree of resiliency recorded during a shock. The development of a sustainable energy carrier like hydrogen was demonstrated to increase supply diversification and security by showing the inverse relationship between investments and impact in energy-dependent countries. The potential cost transfer from fuel expenditures to hydrogen supply deployment represents an opportunity for substantial and rapid investments to decrease the cost of inaction permanently, immunizing the energy supply against the possibility of recurrent energy shocks. It is important to stress that relocating the potential expenses necessary to deal with the backlash of energy shock to the proactive development of reliable hydrogen production is not just a step towards enhancing resilience but also a significant contribution to achieving the sector's environmental targets and the beneficial consequences entailed in a similar goal: addressing the externalities of an energy market dominated by fossil fuels would contribute to the mitigation of climate change as well as to stabilizing the industrial energy supply and securing economic growth in the long run.

The answer to the main research question addressed in the project, which is here reiterated, emerges as a combination and summary of answers of the three subquestions:
How can the adoption of hydrogen in steelmaking support the industry decarbonization and the resiliency to energy shocks as an alternative heat carrier in energy-dependent countries?
The adoption of hydrogen as a sustainable energy carrier for heat generation in the steel industry can represent a compelling bridge solution for decarbonization when efficiently supported by renewable energy capacity and tailored carbon taxes attracting investments. With the appropriate intervention of policymaking, the early allocation of financial resources would permanently decrease the cost of inaction occurring during unforeseen and underprepared shocks, transferring the expenses to the development of a secure and resilient energy supply. The resulting uncoupling of heat generation from fossil fuel prices would produce long-lasting financial advantages in energy-importing countries and contribute to the transition of a large emitter and hard-to-abate industry.

6.1. Research implications for policymaking

The insights derived from analyzing the outcome of the model have profound significance for policymakers involved in shaping the future of hydrogen adoption in the industry.

The recommended course of action consists of a firm deviation from the current trajectory of resource allocation for hydrogen supply as it is insufficient to effectively trigger substantial adoption of alternative heat carriers in the steelmaking energy mix.

Alongside a consistent and systematic development of renewable capacity necessary to support the production of clean energy and low-carbon hydrogen, which is a prerequisite for a successful scale-up of sustainable technologies, the governmental push must mobilize early investments in hydrogen facilities to promptly deploy adequate capacity of hydrogen supply. It is crucial to accelerate the flow of investments and to bring forward large part of the financial effort to the upcoming two decades in order to uncouple the cost of fuel procurement for heat generation from international market fluctuations by reaching a threshold share of hydrogen in the fuel mix. A similar endeavor is an active solution to address the unpredictability of shock intensity and occurrence, which are connected to wide-scale geopolitical interplays and therefore impossible to control.

The strategy recommended is based on the design of a carbon pricing structure aligned with the international decarbonization target to limit the global temperature to no more than 1.5 C° or 2 C° above pre-industrial levels, depending on the fraction of emissions curb advocated in the national steel industry. In particular, among different tools, a tailored carbon tax can induce the optimal profile of substitution to comply with the environmental pledges and develop a desired level of resiliency that is deemed financially and politically acceptable.

Establishing an informed dialogue between governmental and industrial decision-makers is advised to leverage the opportunities of the hydrogen transition and to find effective funding strategies: based on the degree of risk aversion in the organizations, steelmakers could be major investors in financing the upstream infrastructural development for hydrogen adoption knowing the presented benefit of diversification of supply, contributing to the political push for energy transition.

The recommendations proposed have widespread implications beyond the emission savings and the energy supply stabilization underlined throughout the study: regulatory activity for renewable energy funding and incentives, carbon pricing, environmental standards and climate laws influencing the flow of investments toward hydrogen would facilitate the development of a resilient industrial sector and consequently protect the national economic growth. Steel is in fact a fundamental element of infrastructural development and increased material costs caused by spiking fuel expenditures are likely to trigger a snowball effect affecting wide portions of the GDP.

Finally, the significance of the findings presented in this project should be also considered for its societal connotation. Besides the undeniable importance of developing and deploying low-emissions technologies like hydrogen to limit the global GHG budget, pursuing energy independence and consolidating self-sufficient security of supply decreases the strategic value of controlling the geographical areas where the extraction of fossil fuels is concentrated. Military disputes would downsize, contributing to world peace, easing national and international conflicts and generating positive feedback on energy markets, where energy crises are dampened and fuel prices are stabilized.

6.2. Future research

In this section, recommendations for further research that can build upon the foundation laid in this thesis are offered. These recommendations are informed by the gaps and limitations identified and are aimed at advancing the literature on sustainable fuels for energy resiliency.

Beyond developing a more precise analysis based on what has been presented in Chapter 5.2, a first interesting opportunity for the expansion of the study is the examination of spillover effects between sectors in which the development of hydrogen assumes a pivotal role. For instance, the transportation sector has several potential applications in road transport and aviation that have been drawing the attention of researchers. The buildup of hydrogen capacity could therefore benefit from R&D and financial efforts both in industry and transport: an increasing demand is likely to attract investments that would result in a faster cost decrease and lower risk in terms of financial return.

From the perspective of shock vulnerability, further research could also be conducted on suboptimal profiles of hydrogen deployment as alternative scenarios in order to broaden the optimization space. A similar intervention on the scenario architecture could investigate how forcing different development pathways for hydrogen affects the immunization to shocks and how the financial repercussions vary accordingly. This would lead to alternative solutions accounting for plausible targets of hydrogen capacity and the corresponding quantification of shock-induced disruption on steelmaking.

Lastly, although falling beyond the study’s scope, investigating the interplay of importing and exporting countries during geopolitical upheavals could point out relevant mechanisms occurring during energy crises that the current version of the model is unable to include. Taking as an instance one of the most recent pieces of evidence, which is also relevant for this project as it concerns the largest producer of steel in the world, it can be seen how China has benefited from the Russian invasion of Ukraine in 2022 despite being an importing country and therefore theoretically affected by price shocks. The Chinese government signed several deals to buy large amounts of discounted fossil resources from Russia after the cutbacks of countries that took the side of Ukraine in the conflict. Integrating the option of economic coalitions between countries during a shock could uncover significant dynamics in the energy market when the BoT is not fixed but affected by international deals during crises.

The matter described above has the potential to be the object of future research to improve the current study and explore the implications of a broader geopolitical analysis which, if combined with an exhaustive technical and economic characterization of hydrogen in the steel industry, could represent a promising opportunity to advance the literature on the field as well as to contribute to the political debate.

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Appendix: additional figures

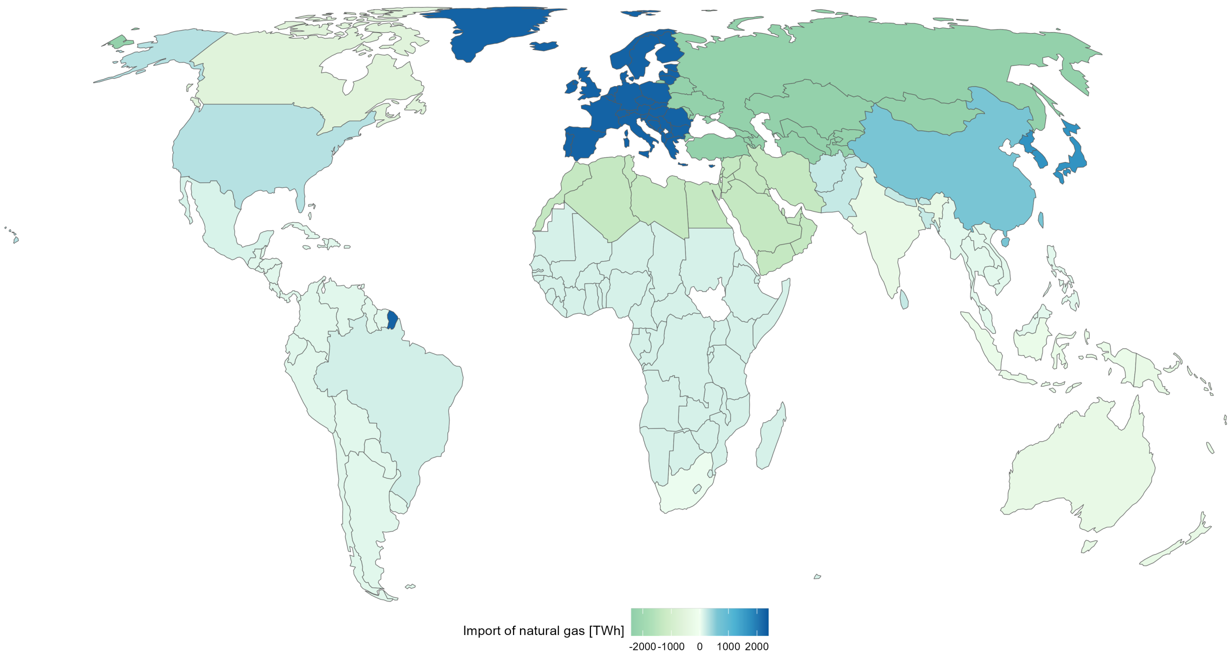

Figure A.1: Natural gas import map - absolute values

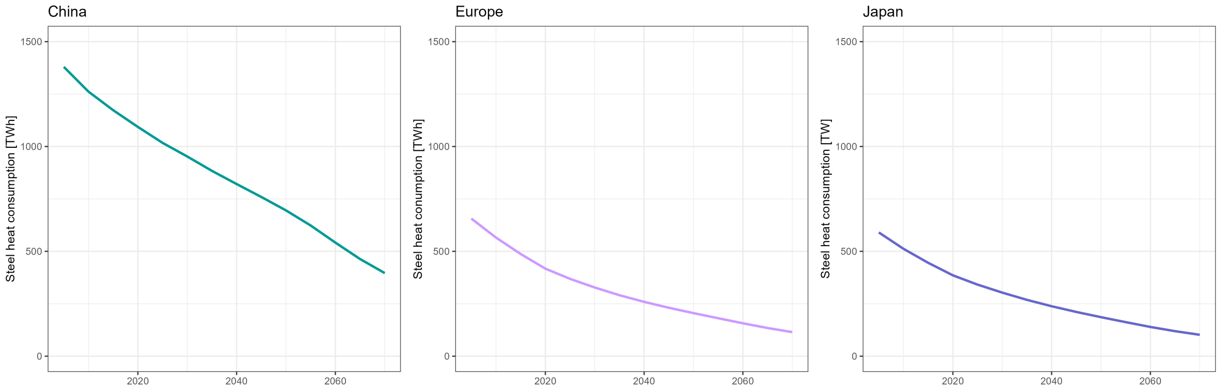

Figure A.2: Heat consumption trajectory in steel industry

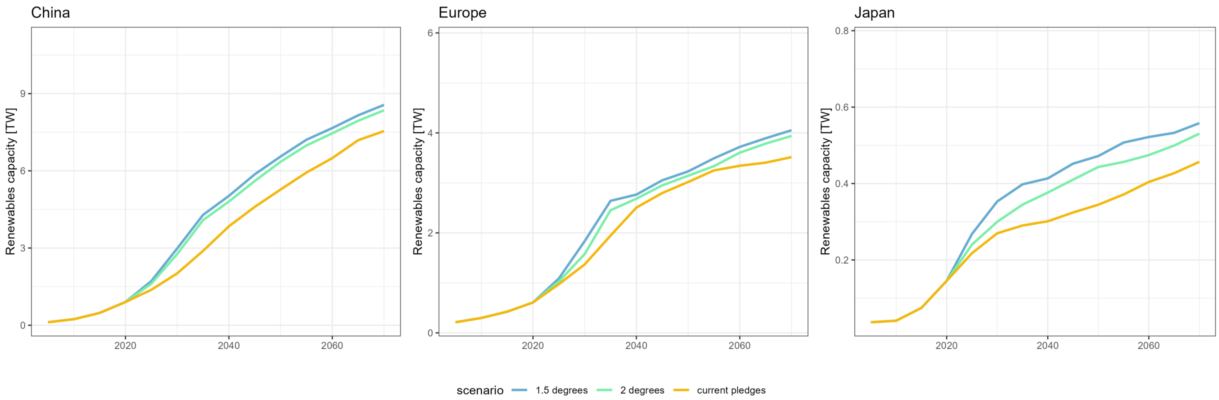

Figure A.3: Installed capacity of renewables

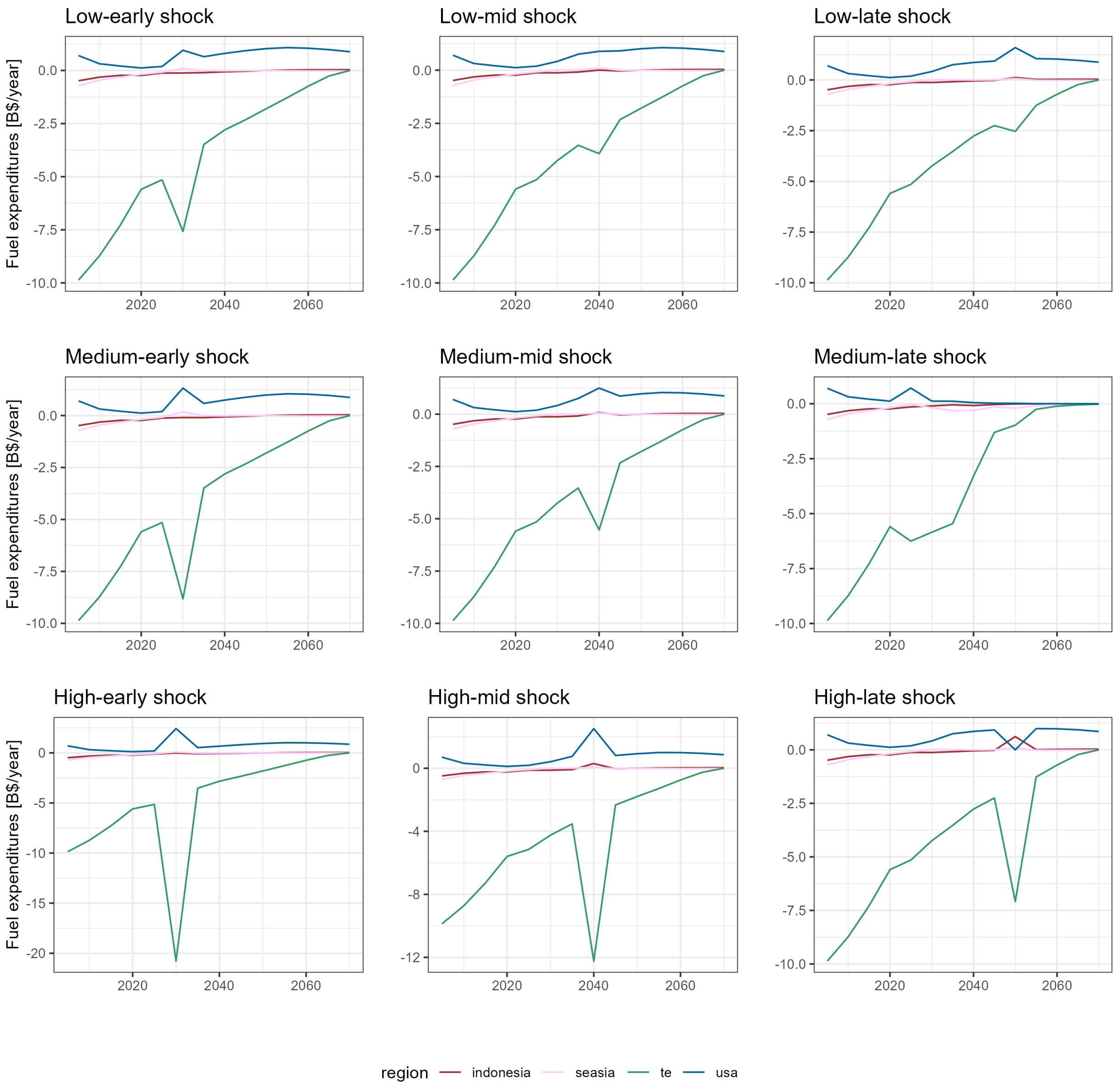

Figure A.4: Energy shocks impact on fuel costs under current pledges scenario - secondary players

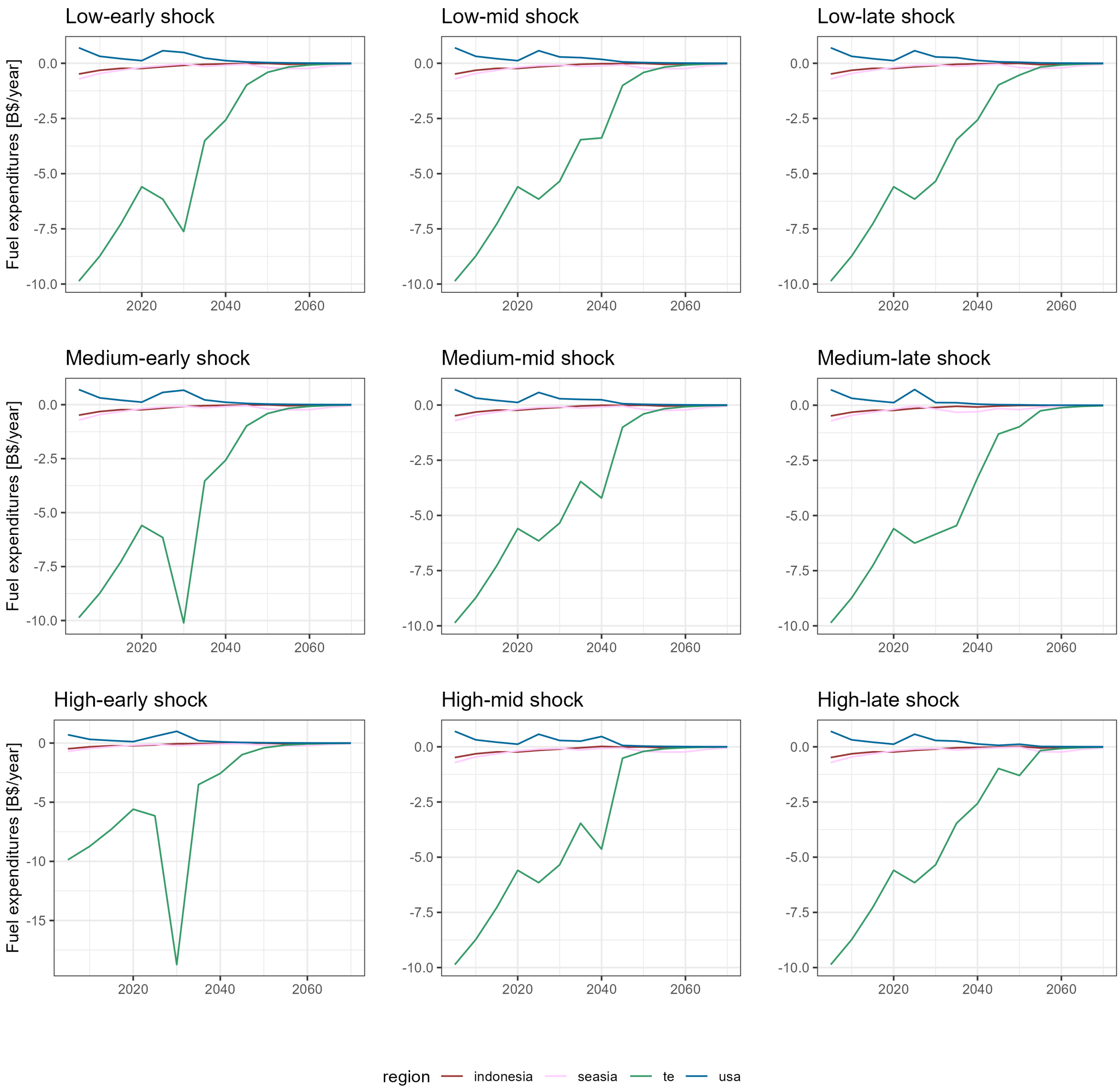

Figure A.5: Energy shocks impact on fuel costs under 2 degrees scenario - secondary players

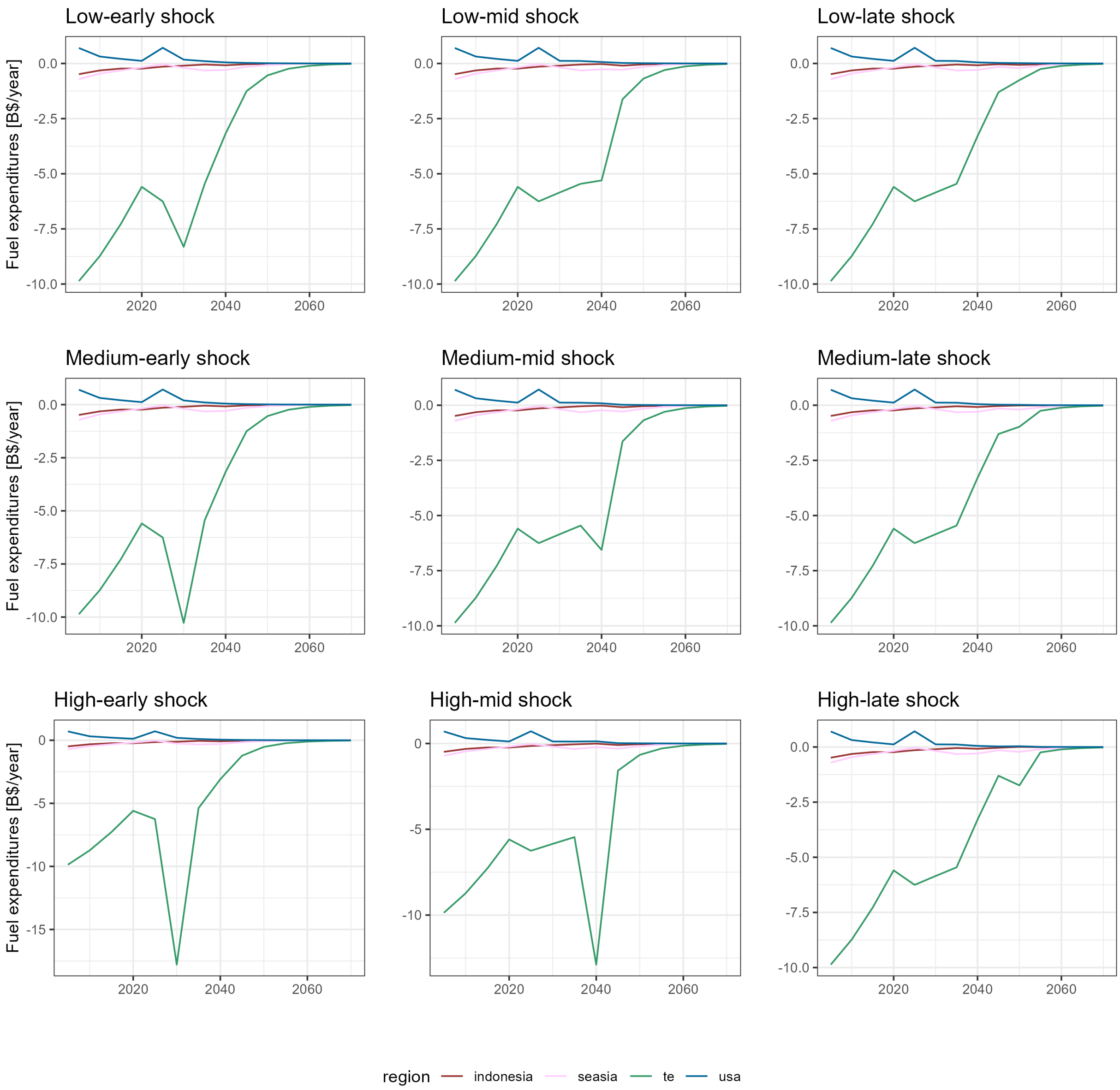

Figure A.6: Energy shocks impact on fuel costs under 1.5 degrees scenario - secondary players

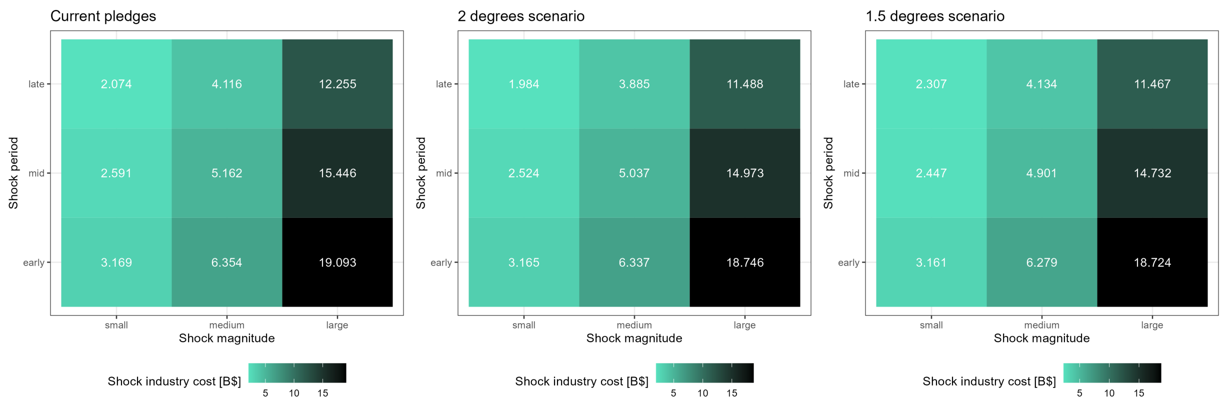

Figure A.7: Economic impact on Japanese and South Korean steel industry

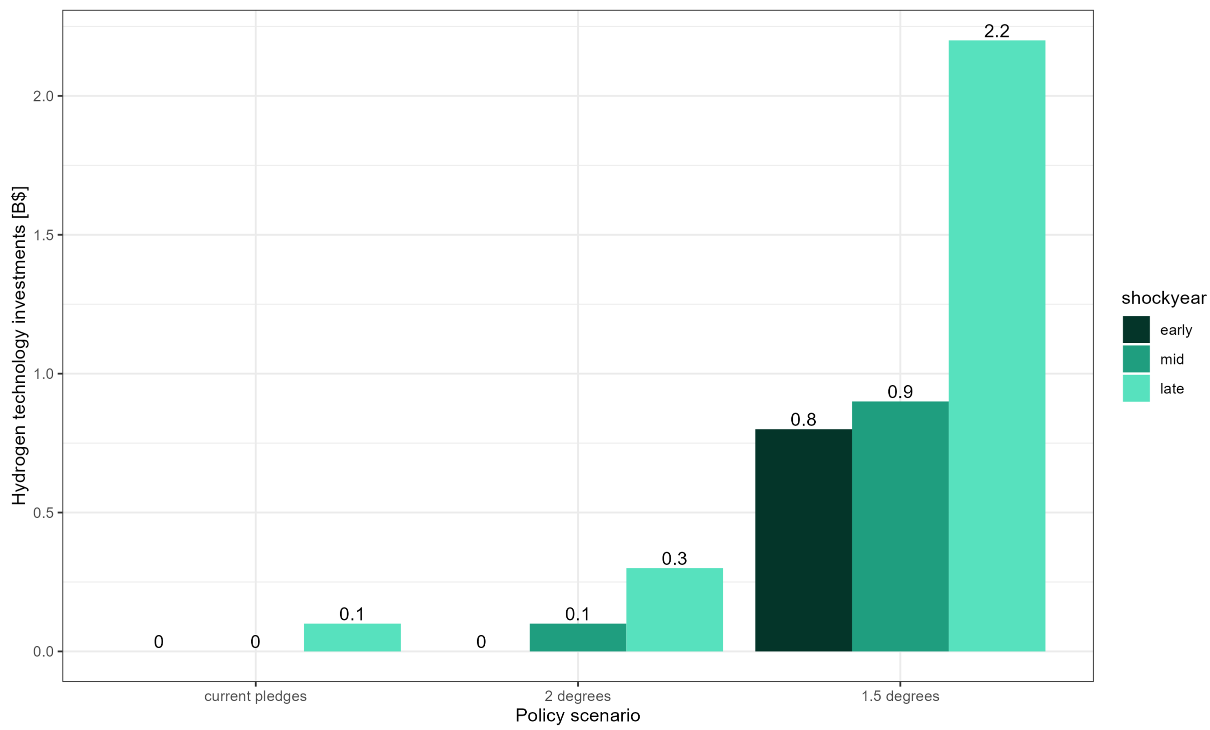

Figure A.8: Pre-shock cumulative investments in hydrogen technologies - Japan & South Korea

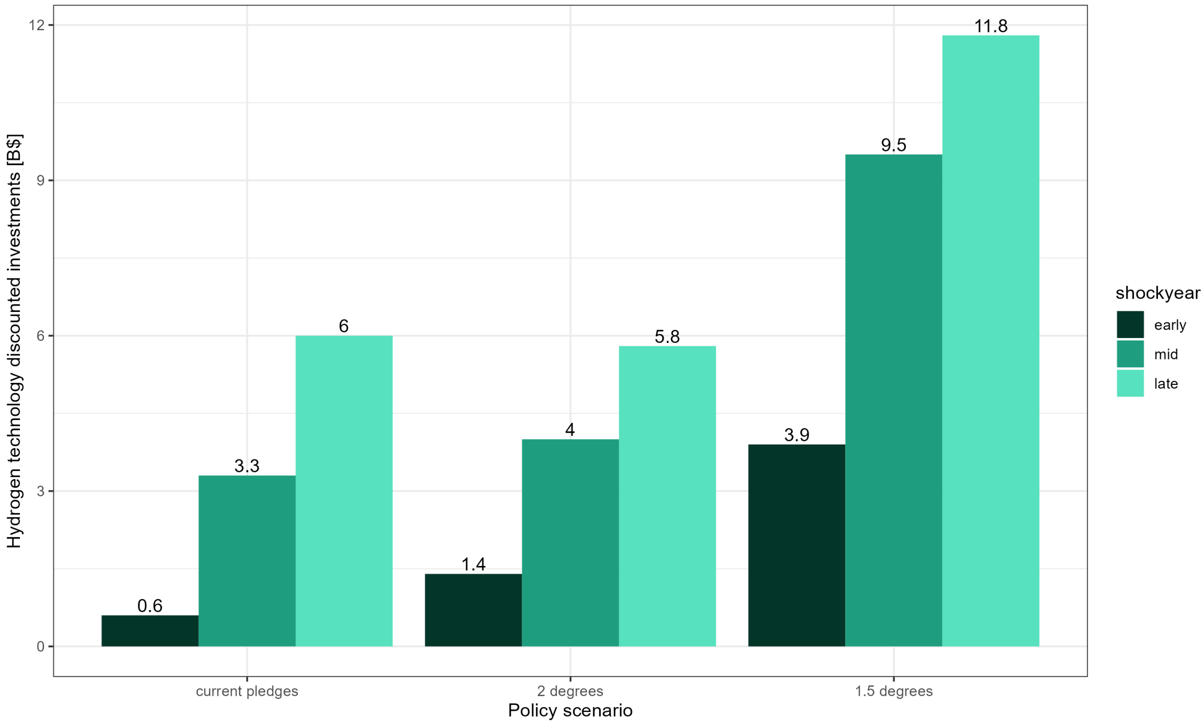

Figure A.9: Pre-shock cumulative investments in hydrogen technologies, discounted at ρ=5% - Europe

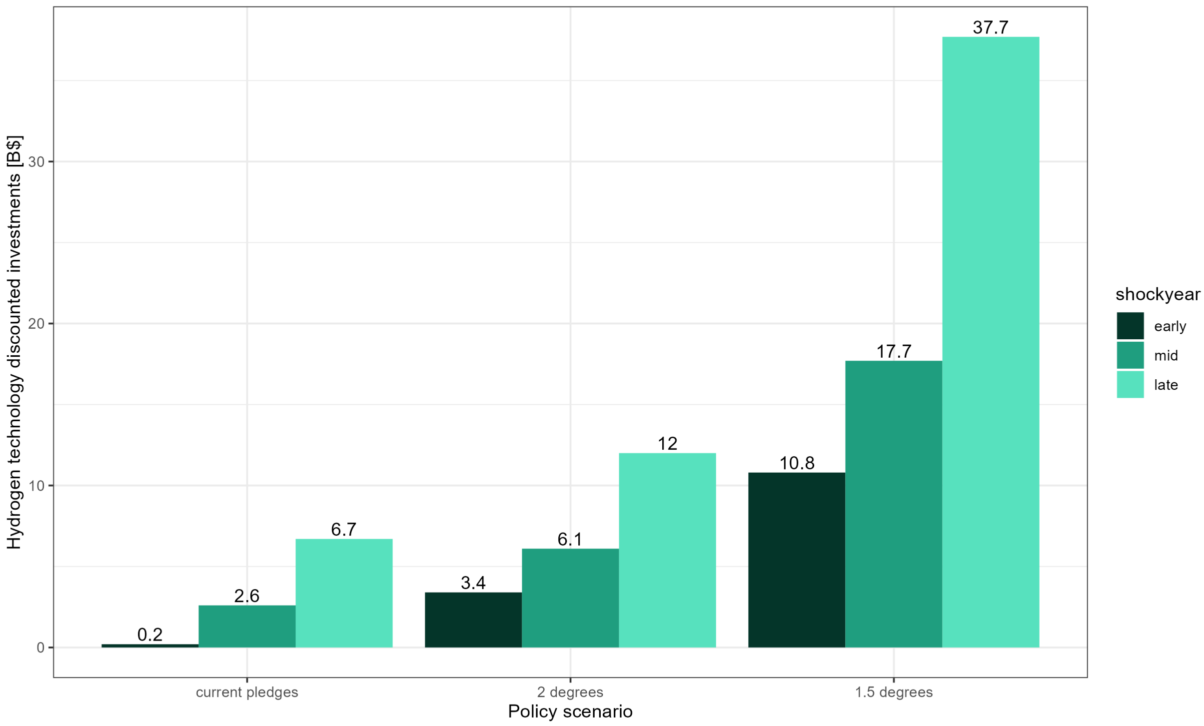

Figure A.10: Pre-shock cumulative investments in hydrogen technologies, discounted at ρ=5% - China

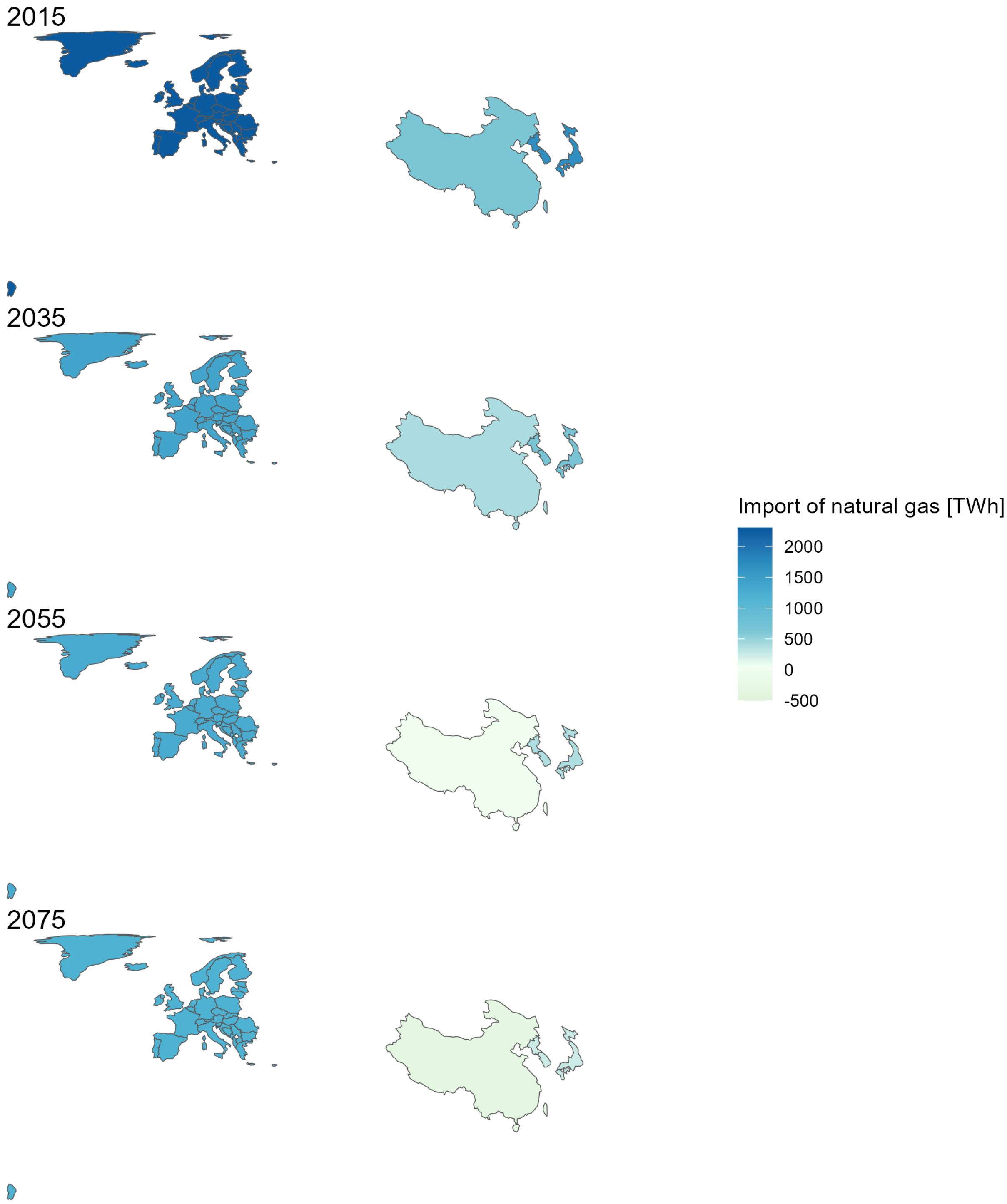

Figure A.11: Import of natural gas over time in the main steelmaking regions (2 degrees scenario)