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ISSUES BROUGHT BY ENERGY TRANSITION ON LEVELS OF FIRMS, INDUSTRIES, AND GLOBAL TRADE

SOFIA BERDYSHEVA

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Vorsitz: Prof. Dr. Tim Büthe
Prüfer*innen der Dissertation: 1) Prof. Dr. Svetlana Ikonnikova
2) Prof. Dr. Sebastian Schwenen

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Abstract

This Ph.D. thesis contains three essays focusing on energy transition and decarbonization. Energy transition aims to reduce the use of fossil fuels to combat global warming by reducing greenhouse gas emissions. Currently, energy transition is widely discussed on societal, governmental, and academic levels from the perspectives of firms, industries, and countries. Thus, this thesis addresses energy transition and associated challenges at the firm, industry, and country levels.

The first essay examines how firms' technologies (assets) portfolio evolves in response to emission-constraining regulations. The study analyzes the effect of emission "pooling" allowances on firms' strategies and investigates the characteristics that could induce firms to transform their portfolios faster. The essay contributes significantly to the literature by enhancing the existing framework and expanding the set of study questions on asset portfolio formation, where the question of the influence of the emissions constraints stays overlooked.

The second essay combines elements of complex networks and international trade theories to examine the effect of short-term shocks associated with the energy transition. The study uses international interindustry input-output (IO) and trade data from 2002 to 2018 to analyze the relationships within the network and test its vulnerability to shocks of different origins. The proposed shock propagation algorithm mimics how shock may spread further to the first-, second-, and higher-order trade partners. Thus, the study fills in the gap between the classical international trade literature, neglecting or minimizing the interindustry relationships complexity, and the IO works lacking the analysis of trade relationships. The study also provides new arguments regarding the most effective sanctions on Russia.

The third essay examines the evolution of international energy trade and highlights energy security issues. The study uses data on the physical and monetary flows of fossil fuels trade

from 2000 to 2018 to examine the dynamics of energy flow networks. We analyze the changes in individual economy positions and trade-network connectivity and test the small-world property. To address the limitations of the classical Herfindahl–Hirschman Index, a concept often used to measure the security of supply, we propose a modified energy-security index, which highlights the interplay between fuel mix and trade partner diversification while taking into account domestic supply and consumption balance.

In sum, the essays presented in this thesis cover various aspects of the transition, informing each other of the complexities and variabilities involved. The works reveal possible pitfalls of decarbonization and highlight the difference in the individual firm-, industry-, and country-reactions to the tightening emission constraints and shifts in resource usage. I believe that the insights brought by the works are of great interest to academia, industry, policy-makers, and the public alike and will help in the ongoing transition to a sustainable future.

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1 | Introduction

1.1 Motivation and Background

Climate change, characterized by shifts in temperature regimes and increased frequency and severity of extreme weather events around the globe, has been recognized as an imminent threat to our planet Berg and Boland (2014). As a result of global warming, people around the world experience and are exposed to such devastating effects as coastal flooding due to hurricane intensification and sea level rise Mousavi et al. (2010), Pall et al. (2011); an increase of probability and severity of hottest temperatures Diffenbaugh et al. (2017); severity of extreme wet conditions Min et al. (2011), and more. The affected communities face enormous economic and, more importantly, human losses Michel-Kerjan and Morlaye (2007). Therefore, the increasing number of countries considers climate change their top priority, searching for solutions to hold or mitigate it United Nations Climate Change (2015).

The well-recognized main reason for global warming is the growing level of greenhouse gas (GHG) emissions Crowley (2000). Among the most notorious components are carbon dioxide (CO2), methane, and nitrous oxide, immense volumes of which are the products of human activity Blasing (2016). The large share of GHG comes from burning fossil fuels in power and heat production, and transportation. Thus, coal power plants are the largest single source of GHG emissions. But with more than one-third of the world's total electricity produced by coal-based generation, finding and developing a scalable alternative takes time and effort. Adopting new technologies and transitioning to clean resources would require time and tremendous capital investments. Transitioning to a sustainable low GHG future is underpinned by the energy transition or replacing fossil fuels with clean alternatives. The transition process requires a comprehensive understanding of economic processes and relationships at micro, meso, and macro levels to navigate firms, industries, and governments in their actions International Energy Agency (2021a).

At the core of the transition is a shift in the portfolio of technologies Chadwick et al. (2022) and resources that we use towards cleaner and more sustainable alternatives Gaspari et al. (2021). Hence, the implementation requires technological, financial, and public support as well as coordination. For that, one shall develop a clear understanding of the firm strategies and vision of the transition paths, how and why they may vary within and across industries, geographical locations, and regulatory environments, and the future market changes (Alova (2020), Shell, ExxonMobil, and BP). Within that context, it is critical to model and project how firm goals and expectations may affect the course of the transition in order to support the design of a robust system of incentives to accelerate the transition without endangering the energy system stability.

As adopting new technologies to improve energy efficiency and reduce GHG emissions production spreads across industries and countries, the established business models call for reconsideration, and reevaluation Markard (2018). For instance, the rapid growth of renewable energy capacities in the electricity industry and the expansion of the electric vehicle fleet in the transportation industry have led to cooperation and new relationships between the power industry and automobile industry members Murdock et al. (2021). And this is just one example of how the changes on a firm level induce industry and industrial relationship transformations.

Finally, regulations of GHG emissions and the changes in emission allowances, together with policies focused on clean technologies imposed by the increasing number of governments, force further adjustments on all economic levels. Thus, the European Union-introduced Emissions Trade System is shown to bring dramatic disturbance, affecting the costs, planning horizons, and modifying firms' behavior and industry dynamics (European Parliament, Council of the European Union (2003), Fekete et al. (2021)). Firm decisions, along with the industry evolution, shape global trade, current and future supply chains, and consumption patterns.

In this context, the bottom-up understanding is crucial for global top-down modeling. It helps avoid ad-hoc assumptions on what may happen, how, and at what pace. This Ph.D. thesis, focused on the transition to the low GHG emissions future and decarbonization, starts with the analysis of the firms' transition strategy, followed by the modeling of the transition (and non-transition) related shocks and their effects on the international interindustry flow dynamics, and concludes with the analysis of the global energy trade transformation. The study of the firm transition investigates how a firm decides to adopt still expensive but long-term sustainable clean technologies transitioning away from the established "dirty" assets associated with high GHG emissions. Special consideration is given to how emission constraints and their setup may affect a firm's decisions. In view of the changes in firms' capacities, the industry-focused work investigates the effect an input or output shock may have in a specific country and on the interconnected industries around the world. Analyzing the shock consequences led us to study the global energy trade dynamics and energy security issues.

Next, we review and provide details on each essay contribution and methodology and the overview of the dissertation structure.

1.2 Contribution and methodology

1.2.1 Firm's perspective

To keep global warming within 1.5°C range, firms across various industries, including but not limited to oil and gas, transportation, and power and heat generation, have to comply with regulations and cut their emissions. The U.S. and EU Methane Emissions Reduction plans and programs translate into continuously updated and revised emission regulations, such as the U.S. Clean Air Act EPA (2021) or the EU CO_2 emission performance standards European Parliament, Council of the European Union (2019). While some regulations are local, others are developed in cooperation with other nations, for instance, the U.S.and EU initiated the Global Methane Pledge European Commission , United States of America (2021). Hence, despite their differences and location, firms face a similar challenge – how to survive and prosper in the transition, that can be dissected into two major questions: (1) under what conditions and how much to invest in clean technologies and (2) how the investment strategy should be adjusted to the changing emission restrictions and cost conditions?

In this context, the goal of the first study is to offer a model for the optimal technology portfolio selection useful for the understanding of how the future price, costs, productivity changes, and associated uncertainty may affect the transition. The model is designed to examine the effect of the firm's view and attitude to technology-related uncertainty on the technology mix. We differentiate the firms by their objectives ranging from the total value to profit and study how the imposed emission constraint (and rules on its allocation) alter the optimal outcome, thereby speeding up or slowing down the transition. Some regulations allow for emission "pooling", whereas others assign technology-linked constraints. We investigate the profit and investment effect of the emissions pooling. With this, our research provides valuable intuition on why the firm's strategies vary and how emission constraint allocations may influence the pace of the transition. The theoretical model of the firm's technology portfolio choice is complemented by the numerical simulations demonstrating and explaining the results.

Focusing on the investment decisions while differentiating the firms with respect to their objective function, the study relates to the producer theory and the firm theory. Considering shortsighted profit-maximizers, along with far-sighted total firm value-optimizers, our research leans on the asset portfolio literature, technology choice, and industry dynamics research, and an extensive list of works covers various aspects of uncertainty and investment irreversibility Miao (2005), Brown et al. (2009). However, the existing studies addressing the transition and decarbonization-related questions in the context are sparse. What requires a modified approach to the portfolio and technology choice problem and inspires this work is the necessity to account for (i) emission constraints and (ii) uncertainty on the ability to use some assets in the future. Hence, we contribute by bringing the focus to the transition effect and developing a model that allows for analyzing strategies of firms heterogeneous in terms of their beliefs with regard to the future asset value, associated uncertainties, and emission-based production constraints. The other contribution of this paper is the analysis of 1) the firm's reaction to changes in emission constraint allocation across the technologies. Incorporating multiple aspects in which firms may differ let us achieve another important goal: explain the observed differences in the firm's behavior, i.e. adoption of "clean" technologies, under the same regulatory environment. Thus, the conducted research helps inform the ongoing policy debates on emission restrictions Johansson (2009), and future targets Selçuklu et al. (2023).

To be specific, we investigate how a firm decides to alter its portfolio by transitioning from the prevalence of established to the increasing share of transitional or hybrid ones to the dominance of alternative technologies. We refer to various examples, including electricity-generating companies or utilities. One may think of a capacity mix as a portfolio with e.g., coal, natural gas, and other power production plants. With the goal of achieving 100% renewable electricity generation, the firm has to balance its financial costs and environmental benefits while modifying its generation portfolio. Intuitively, for instance, it may decide to grow the share of cleaner natural gas-fired plants first rather than investing in renewables only considering the costs. We solve for the optimal mix analytically and then, use numerical examples to illustrate how the portfolio of profit- and value-maximizing firms might differ, given their future expectations on the ability to use a particular fuel and production (and emission) efficiency changes. The studies on the optimal production and portfolio mix look into the roles of the regulatory environment uncertainty, resource depletion, the availability of new technologies, financing, and costs Pindyck (1986), Dixit and Pindyck (1998). Some works add the focus on the optimal time and staging of investments and the transition from one technology to an alternative one Shevchenko et al. (2016). Others expand into the analysis of the resource exhaustibility, considering that there could be another technology making use of alternative resources Dasgupta and Stiglitz (1981). However, in this stream of literature influence of emissions constraints on the optimal mix of assets is limited and if included then without exhaustibility considerations. We aim at addressing that limitation. The fast-growing energy transition research has primarily focused on the industry-level shifts and supply chain transformations or taken country-level perspectives Vaninsky (2021),Solomon and Krishna (2011), Naegler et al. (2021). Though relevant, works on the industry transition assume a particular firm type or asset with the rare exception of ignoring the heterogeneity in objectives, expectations, and technologies to which we pay special attention. Investigations on whether and what levels of GHG emissions are feasible with a certain set of technologies, on the other hand, make ad hoc assumptions on the mix, often avoiding the discussion of the pathway to achieving it Lund and Mathiesen (2009), Davis et al. (2018), Child et al. (2019). Alternative, agent-based approaches allow for agents' heterogeneity but lack the analysis of uncertainties Yang et al. (2021). Finally, literature on the transition from "dirty" to "clean" technologies that account for uncertainties and, in many regards, overlaps with our approach is limited in its perspective on project differentiation with respect to emission intensities, emission allocations, future efficiency changes, and so on. Yet, it was shown that differentiation in taxation of "dirty" or subsidization of "clean" technologies could foster energy transition when one discusses the supply chain components, but not the firm's portfolio of technologies Acemoglu et al. (2012a, 2016)

To sum up, the first essay analysis adds to the sparse literature on firm-level decarbonization and asset management and investing by showing how and why firms' strategies for emission reduction differ and which factors could lead to more aggressive investments in clean(er) technologies.

1.2.2 Industry perspective

Bridging from the analysis of the energy transition on the firm level, we examine how energy transition may affect industries. Initiatives, such as National Ambient Air Quality Standards in the US EPA (2014), the Law on Air Pollution Prevention and Control in China (2000), and the Directive on the limitation of emissions of certain pollutants into the air from medium combustion plants in the EU European Parliament, Council of the European Union (2015), aim to limit GHG emissions. Furthermore, various industries, especially heavy-emitting, fall under these initiatives. As a result, firms constituting those industries adjust their portfolios of technologies (assets) to meet the regulatory requirements, affecting industries. Even though not all industries use fossil fuels, they all need electricity, of which more than 60% in 2018 is produced from fossil fuels International Energy Agency (2022c), to operate, and the availability and reliability of electricity are crucial for all industries. And that is why we want to understand how energy transition, resulting in the expected decline of the share of fossil fuels usage, and as a consequence, on the demand and trade of fossil fuels may influence industries worldwide.

We consider the influence of the energy transition on the industries from the perspectives of the limitation or termination of trading relationships between fossil-related and the rest industries. We define this process of change in trading relationships as a shock and assume that the shock has several orders. The shock's first order (or the direct) effect describes the initial change in trading relationships. However, if there are no substitutes or available technologies to compensate for the lost inputs, the outputs of the affected industries will shrink due to the shortage of the inputs, causing a higher order (or indirect) shock effects since industries using the outputs from the affected industry will face the decrease of the inputs from the affected industry. We assume the shock may be due to trade barriers or natural hazards. The imposed trade barriers may have a form of sanctions or be emissions policies limiting fossil fuels trade. To analyze the effect of the shock, we utilize the data on global interindustry trade. With that, we broaden the geographical coverage of the research to the international level. This way, we extend the research question beyond monitoring direct and indirect shocks arising within global interindustry trade.

There are several frameworks for analyzing the shock that may arise in interindustry trade. The first one utilizes gravity models. Those models present bilateral trade flows as a function of bilateral trade costs Costinot and Rodríguez-Clare (2014). Specifically, this framework may be applied to reveal the welfare effects of imposing trade barriers Melitz and Ottaviano (2008), Dhingra et al. (2017). However, to our knowledge, those models look only into the effects of the first order and do not allow tracking the impact of trade barriers on the third countries.

In contrast to the gravity models, network analysis allows abstracting from the underlying economic assumptions of the gravity models and reveals how the international trade network evolved over time. This analysis estimates the heterogeneity among trading countries regarding trade volume and amount of trading partners. This heterogeneity is explained by the network structure, which is essential when speaking about shock propagation Acemoglu et al. (2012b). The underlying network may be based on monetary or physical flows of a good Chen et al. (2018), Gao et al. (2015) or several aggregated goods between countries Lee et al. (2011). In addition, in the literature on trade networks, there is ongoing research on the network's resiliency to shocks occurring when trading relationships are broken between countries or when a given country is taken out of the trading network altogether Gephart and Pace (2015), Fair et al. (2017). In this case, resiliency is measured as the portion of countries staying connected after disrupting trading relationships. However, the propagation of the shocks through the global interindustry trade network still needs to be considered.

Asunder from the discussed streams of literature that allow analyzing consequences of a change in bilateral trade either from the standpoints of the gravity models or from the perspective of the network analysis stands the analysis that utilizes the data on Input-Output (I/O) tables that provide information on the intermediate trade between industries. Usually, those tables are used for the I/O analysis to consider how shock arising on either the demand or supply side in a given industry influence on the production level per industry Vogstad (2009), Galbusera and Giannopoulos (2018). Moreover, there are models for the optimal resource allocation to minimize the negative impact of a potential shock that may be measured as the volume of the gross domestic product Garcia-Hernandez and Brouwer (2020). Furthermore, the I/O tables can be extended to include data emissions or fossil fuels used in each industry. In this case, I/O tables allow for addressing the carbon leakage problem and tracking the industry's direct and embodied emissions. Similarly, if there is available data on the fossil fuels used in each industry, in that case, one may estimate indirect energy consumption, which includes energy consumed when the inputs for the industry were produced, by industry in the country, Mongelli et al. (2006). Finally, one may distinguish between a change of technologies in the industry and the change of the plants' location to third countries. However, in most papers on this topic, the question of how a change in trading relationships between two industries may spread further stays overlooked.

The main contributions of this paper are the following. Firstly, we analyze the dynamic of interindustry global trade. This will give us an understanding of how it evolved over time. Secondly, we develop a model that would allow us to track how a shock may propagate in the interindustry trade network further than the first-order neighbors. Lastly, we apply the developed model to the data on the global interindustry trade, and estimate propagation of shocks from energy-related industries.

1.2.3 Global perspective

Fossil fuels still play an essential role in electricity generation worldwide, and they account for 64 % of world electricity generation in 2018 International Energy Agency (2022c). However, from 2002 to 2018, the share of coal decreased by 1.3% worldwide, while the share of natural gas grew by 1.7 %. This change is driven by policies aimed at reducing GHG emissions worldwide, which are aimed at reducing the role of coal power plants in the electricity generation mix. As a bridging technology, a number of researchers, including International Energy Agency (2018), Bessi et al. (2021), suggest replacing coal with a combination of natural gas and renewable energy sources. However, the distribution of the proven reserves of natural gas is uneven, and 39 countries hold approximately 90% of global natural gas reserves. At the same time, renewable energy sources are more evenly distributed among countries Overland et al. (2022), meaning that some countries depend on importing fossil fuels to meet their energy demand. For those countries, the question of energy security is crucial. That is why, after analyzing the interindustry trade networks, we turn over attention to the network of the fossil fuels trade with a similar question of countries' energy security. Furthermore, we explore: (1) the evolution of the fossil fuels trade and (2) how adding renewable energy sources has affected countries' energy security.

The evolution of the fossil fuels trade was already considered based on physical Chen et al. (2018) or monetary Gao et al. (2015) volumes, and it was examined for each fossil fuel separately and for a combination of them as well. The available results indicate that countries are highly heterogeneous in trade volumes and the number of trading partners. Furthermore, this stream looks at how the fossil fuels trade network changed over time and how the network's structure has changed, including the analysis of the communities that form the fossil fuel networks Gao et al.

(2015), Chen et al. (2016). Trade intensity between countries in comparison to trade volumes with other countries define the communities within those networks. And it was revealed, that the communities are affected by the external events, such as Iraq war in 2004 Gao et al. (2015).

Not all of those papers consider the energy security issues, but those which do, consider energy security from the perspective of market concentration and define energy security based on The Hirshman-Hirfindall index (HHI). However, the question of energy security is more complex than market concentration. There are four aspects of energy security measures named availability, affordability, acceptability, and accessibility. Availability focuses on the security of supply and shows how diverse a country's energy supply portfolio is in fuel type and the energy needed to meet its energy demand. The price aspect of energy security for both households and the interindustry is included in affordability. The environmental and social consequences are considered in the acceptability of the energy is included in the acceptability. Finally, geographical proximity to the energy sources is reflected in the accessibility Sovacool (2014).

And there are various metrics to address various aspects of energy security or a combination of them. In the third essay, we suggest an index addressing the availability dimension of energy security and that enables monitoring of the risks associated not only with market concentration for a specific fuel but also accounts for the diversification in the resources. Specifically, the essay contains our data analysis using International Energy Agency (2019) and United Nations Commodity Trade data. In addition, we use network analysis combined with market analysis tools such as concentration analysis and build an index that considers the pitfalls that the transition to energy can cause. Also, we included in this analysis the perspective of net energy importers and net energy exporters. The main contribution of this research is an energy security index that takes into account the diversity of energy sources that are available to a country on the global market but pays attention to the overall ability to meet its energy demand with its energy supply.

1.3 Structure of the dissertation

We deliver three independent research projects with varying objectives and methods. Three essays constituting this dissertation are meant to be published in academic journals and are independent of one another. That is why there will be repeated explanations of used concepts and definitions, and one may read the essays independently.

Chapter 2 consists of Essay I, where I analyze strategies that firms may have under energy transition process. Chapter 3 contains Essay II, which focuses on global interindustry trading relationships and how their resiliency to shocks from energy interindustries has changed over time. Chapter 4 (published in Energies Vol. 14, no. 17, August 2021 https://www.mdpi.com/1996-1073/14/17/5396) shows how energy transition affected global fossil fuels trade and how it impacted countries' energy security (published in Energies, please, see for the printed version).

2 | Firm's Portfolio Transition to Carbon Neutrality: Financial and Environmental Trade-offs

Berdysheva, S.; Ikonnikova, S.

Stake-holders 'preferences and regulations on carbon put pressure on firms across all the industries, bringing them to commitments on decarbonisation. Developing a strategy on how to implement that, however, is non-trivial and requires careful considerations of financial implications. In this paper, we take firm's perspective addressing the question of how to transition away from the current portfolio of assets to the one with the low carbon footprint. In doing so, we examine different emission allocation schemes and their effect on the decarbonisation path. That allows us to provide new insights on policy carbon reduction and financial efficiencies.

Analyzing firm's portfolio transformation issues, we contribute to the sparse literature on decarbonisation management and investing. With the goal is to assist in and navigate decision-making of various firms shifting away from its (high-carbon) assets and established technologies, we distinguish value- and profit-driven firms. We examine what defines the transition strategies, providing critical insights on why firms differ in their reactions to carbon allowances and technology adoption rates. Inspired by the decarbonisation challenges in energy and automotive sectors, we complete our analysis with simulations providing insights valuable for policy-makers and stake-holders. Our findings highlight the role of emission allowances allocations and expectations on future costs and on the ability to use current technology, suggesting how policies and regulations may help accelerating the decarbonisation.

2.1 Introduction

Paris Agreement, signed by 193 states and the European Union (EU) as of 2022, signifies the consensus around the world on the necessity to reduce greenhouse gas (GHG) emissions to mitigate the climate change United Nations Climate Change (2015). The discussions on how to achieve the GHG emissions reduction targets, set by the Intergovernmental Panel on Climate Change, however, have revealed multiple challenges and sparkled fierce debates on global, national, and industry levels. While all agree that transition requires the adoption of low-carbon technologies and retirement of dominating high-carbon technologies, how to induce costly investments needed to meet the emission reduction commitments remains an open question.[1]

International Energy Agency, World Energy Forum, International Renewable Energy Association and other national and international organizations, analyzing economic development have offered numerous projections and scenarios suggesting the pathways to the carbon neutrality paved by the low-carbon technologies (e.g., see International Energy Agency (2021b), European Commission, Directorate-General for Climate Action (2018), (NREL)). But research on how realistic those plans are and what is needed to incentivize the transition on an individual firm level has been lagging, focusing on policy effects on the industry-wide investments. Studies on the firm-level challenges and capabilities is sparse (e.g. see Chung and Kim (2018), Kittner et al. (2017), Vaninsky (2021)). Works on the firm transition are mainly focused on a particular asset neglecting the challenges of the entire portfolio transformation van Zuijlen et al. (2019), Babatunde et al. (2019), Skoczkowski et al. (2020).

In this study, we aim to fill in the existing gaps and understand the decarbonisation trade-offs faced by firms. We develop the firm production and investment model, solved under various emission constraints, that allows to capture firms' heterogeneity. Namely, within our framework, firms are differentiated based on their (1) time preferences, distinguishing firms by the value assigned to their assets and the uncertainty associated with the possibility to use those assets in the future; (2) cost structure, capturing the disappearing over time financial advantage of the established (high-emission) technologies, and (3) price expectations. Hence, our approach helps investigate how a profit-oriented, namely myopic and impatient, firm would transform its

[1] The growing number of initiatives and regulatory changes focusing on energy efficiency, green technologies, and limiting emissions from heavy-emitting industries is listed here `https://climatepolicydatabase.org/policies`

portfolio to comply with the emission targets, in comparison to a value-driven firm that accounts for its (growth and/or salvage) asset value when making its production and investment decisions.

In attempt to identify the factors critical for the firm's transition strategy and explain the observed differences in firms' behavior, we model the firm with a portfolio of diverse assets or technologies: (1) established (or "dirty") with high-emission footprint, (2) transitional (or "hybrid") with the reduced emission profile, and (3) alternative (or "clean") characterized by the minimum emission level. Then, introducing emission constraints, we examine how the firm would transition, reducing the share of its "dirty" assets. Following the policy debates and referring to their differences across the countries, we investigate how the possibility to "pool" the allowances[2] might affect the portfolio composition and firm's performance, in financial and emission terms.

Finally, to demonstrate the model usefulness and help the intuition, we combine theoretical analysis with numerical simulations. We run simulations that highlight the role of expectations on the ability to use non-clean technologies in the future and the interplay of those expectations with the future cost reductions for "clean" technologies. We show how the presented toolkit for the firm's portfolio transformation analysis may provide important policy relevant insights on the efficiency of the emission allowances and their possible economic and environmental implications. Hence, the results of the study are useful for navigating firm investments, cross-firm or industry transition dynamics analysis, and policy analysis, informing on the global transition trajectory and pace.

Based on its framework, our analysis relates to the works on optimal production and portfolio choice that emphasize the role of uncertainty and financing for firms and industry dynamics Dasgupta and Stiglitz (1981), Pindyck (1986), Dixit and Pindyck (1998), Miao (2005). Yet, to our best knowledge that line of research has not been combined with the analysis of decarbonisation, missing the understanding on how emission policies, cost uncertainty, and firm's time preferences may shape portfolio choice and investment strategy.

Examining the portfolio-alignment with the emission goals, we address the issues raised by regulators as well as stakeholders and hence, our analysis relates to the expanding research on Environmental, Social, and Governance (ESG) and Corporate Social Responsibility (CSR) (Matos (2020), Widyawati (2019), Gillan et al. (2021)). Earlier works the topic have been focused on

[2]For example, EU zero emissions shipping and transportation regulation provides and example of a possibility to pool the emissions.

the definition and measuring metrics of "sustainable investing", trying to incorporate environmental considerations and social impact into portfolio decisions. As the impact definitions and the framework have been evolving, the analyses have shifted to the policy related investigations, reporting, and project analysis, neglecting the portfolio and firm performance evaluations. In our work we try to address that gap marked, e.g., by Gillan et al. (2021). Another aspect in which our work relates to ESG literature, besides the combination of financial and environmental firm performance analysis, is the diversity of "sustainable" project considerations.

Research on investments in "clean" technology traditionally assesses investments in research and development (R&D) and research, development, and deployment (RDD) considering extreme case of near zero emissions Acemoglu et al. (2016), Aghion et al. (2016). Yet, the evidence on global oil and gas industry investments reveals how companies prefer to invest in *transitional or hybrid* technologies first as divesting away from the commercially preferable *established* ones (International Energy Agency (2020a), Tryggestad (2020)). We find numerous examples for companies, like BP, Shell, ExxonMobil, announcing their zero-carbon goals underpinned but moderate investments in a combination of emission-reducing and "clean" technologies. The marked cost advantage of hybrid over "clean" technologies, referred to as *alternative*, especially when full unsubsidized costs are considered [3], suggests that financially-driven firms could postpone further emission reduction till the regulatory signals or measures induce them to do so. Introducing three types of technologies, for which cost relationships is inverse to the emission footprint, allows us to enrich the existing literature with the discussion of the transition pace and the counter-play between financial and environmental values faced by firms.

The transition-associated trade-offs and the necessity to modify the value assigned to the assets, along with the ability to use certain technologies and resources, have inspired the energy and environmental policy research. To find the most efficient policy instruments, studies on the transition have to develop projections on firms' and market reaction. However rich, policy literature on the asset mixture transformation had been lagging, focused primarily on either stranded assets Firdaus and Mori (2023) or investments in "clean" technologies Cherp et al. (2018), but rarely on the both at once Rozenberg et al. (2020). Regulatory instruments facilitating the transition include: subsidies for green technologies development, implementation and utilization; additional taxation of companies from heavily-emitting industries; introduction of

[3]Renewable energy costs are competitive with electricity generation from fossil fuels. However, it depends on many factors, such as the prices of fossils, and the installation of new capacities IRENA (International Renewable Energy Agency) (2022), but the developed framework allows for costs of alternative technology be lower than the established technology.

emission prices that increase production costs; limitation of total firm's emissions; and limitation or prohibition of exploitation of certain type of projects Fekete et al. (2021). Besides the impact of an individual regulation, studies have been looking into the speed of transition, namely what may help accelerate or impede it Shevchenko et al. (2016). However, the comparison of policies efficiencies is commonly detached from the analysis of reaction differences across heterogeneous market players.

Agent-based models consider homogeneous or heterogeneous players who maximize their net present value under the given future carbon prices Yang et al. (2021) in contrast to economic studies focusing on the competition and profit-driven firms (Rugman and Verbeke (1998)). Although, in transition studies discount rate is used to reflect the uncertainty or show the role of firms' expectations or beliefs regarding the course of the transition Shevchenko et al. (2016), Yang et al. (2021), but the analyses lack its further combination with the "clean" technology cost dynamics expectations when studying the variance in policy responses within and across the industries.

Since oil and gas, electricity generation, and transportation sectors together are responsible for 60% to over 75% of individual countries CO_2 emissions EDGAR/JRC (2021) and therefore, being at the focus of the energy transition research, we develop a model that is applicable to either of those industries. In the case of oil and gas industry, one may think of their electrification and increasing use of renewable energy. In the case of power sector, the transition implies the retirement of high-emitting capacities, such as coal generation, substituting them with "transitional" less polluting natural gas-fired plants until "clean" alternative technologies, such as wind, solar, and hydrogen, are ready to take over. Finally, in the transportation sector, we consider firms whose vehicle fleet changes to displace internal combustion engine-based cars (ICEs) with hybrid and "clean" vehicles such as electric and fuel cell cars.

In what follows, we first introduce the firm production and investment model, highlighting the uncertainty and cost parameters that help us characterize value- and profit-maximizing firms, or distinguish the firms by their expectations on the pace of the transition and technological advances. Then, we solve the model under various assumptions on emission regulations to investigate the impact of the emission policy setup on the firm's choice. To help the intuition, we develop a set up stylized simulations presented along with the theoretical derivations. We conclude with a series of most notable results and their implications for industrial managers and policy-makers.

2.2 Analytical framework

We consider a rational risk-neutral firm small enough to be a price-taker or have no significant effect on the market price by its actions.[4] The model is designed and could be applied to model various types of emissions. However, with multiple examples of carbon emissions in mind, we will use carbon emissions and GHG emissions interchangeably in what follows without loss of generality. The firm observes the price and given its expectations on the future price, costs, and regulation makes its production (and investment) decision, namely it chooses quantities for three categories of technologies, established (e), transitional (t), and alternative (a). Each technology is characterized by its currently observed costs and emissions and firm's expectations on the costs and emissions in the future (2.1).

Technology	**Marginal Cost**	**Emissions**
Established	High	High
Transitional	Moderate	Moderate
Alternative	Low	Low

Table 2.1 Key characteristics of the firm's primary technological choices.

To the first, established, category we assign the projects and capacities which the firm has the most experience with and input factors of production for which are readily available. As a result, at the present moment that technology is the most cost efficient and widespread. For example, one may think about ICE vehicles and coal plants as technologies associated with that category. However financially attractive, projects in this category are characterized by high emissions and hence, considered to be unsustainable.

Moving away from the business as usual, the firm has the choice to implement transitional projects, which are more expensive but advantages when it comes to the emissions. Since transitional technologies are often rely on and may utilize the existing infrastructure and input factors, its costs are increased but not dramatically. Yet, projects and capacities related to this categories are not seen as a long-term solution, owing to the still considerable emission footprint. Thus, even those natural gas power generation is strongly preferred to coal, natural gas is considered to be a "bridge fuel". The same applies to the hybrid vehicles run on gasoline, though at much better fuel use efficiency.

[4]Further, we discuss how the price-taking assumption can be modified within our framework without loss of generality and will effect only the size rather than the direction of the effects analyzed.

Finally, we distinguish "clean" or alternative technologies. Despite the variance in marginal cost, in general, those technologies are more expensive at the moment, if considered without governmental support (subsidies, production or investment credit, or special tariffs). In the future, the reduction in cost is expected thanks to the growth in scale, experience, and related infrastructure. However, how fast and steadily the costs will drop remains unclear. The key benefit of those technologies is their minimal emission footprint.

The firm makes its decision on the combination of technologies considering the immediate profit and the value of assets. For simplicity of interpretation and to help relate our study to other works, we distinguish the firms based on their expectations and objectives. The p-type of firm maximizes its profit only assigning zero value to the assets. This is an extreme case of firm assigning very high uncertainty to the possibility to use or sell its assets in the future or of firm being extremely impatient and focused on short-term wins only.

Alternatively, more patient or optimistic about the future firms, v-type, make their choice maximizing the total value, which we define below according to Modigliani and Miller (1958). The firm's objective may also depend on the firm's development stage, growth versus maturation, and other considerations Lewis and Churchill (1983). The firms of v-type can further be differentiated based on the weight they assign to the assets as we discuss further. Hence, our framework allows for any type of firms ranging from extremely profit oriented to increasing accounting for its assets value ones. Then, an assumptions or data driven observations on the firms' asset accounting would allow one to make the projection on the entire industry decisions in aggregate.

We solve each firm's decision model varying the assumptions on regulatory environments. In attempt to cover the most frequently implemented regulations related to emissions, we consider the following three cases in our study: 1) no emission constraints, i.e. pre-transition benchmark; 2) pooled on the firm level emission constraints; 3) constraints imposed on individual technology. Next, we present theoretically derived solutions and their analysis. The results of the numerical simulations and their discussion are provided in the next Section.

2.2.1 Firm'model

Profit-oriented firm We start with a profit-maximizing firm considering a set of investment options, $n \in \{e, t, a\}$, divided into three categories, established, transitional, and alternative technologies, correspondingly. Each technology is used to produce the same output. For example, considering a transportation firm, one may think about miles driven with ICE, hybrid, or EV vehicle. In the case of power generation, any plant generate indistinguishable electricity. The properties of oil or natural gas are not affected by the technologies used in the fuel production. Hence, a per unit of output price is also equal across all the categories.

We denote the production level[5] in each category as q_n and the observed price as p^0. Given the price-taker assumption, the price is set as a parameter in the current model setup.[6] Another set of parameters is associated with the costs. Each technology is characterized by a marginal cost function consisting of a constant component, v_n, and production level dependent component, c_n. We justify such a cost structure by the practical observations suggesting that an increase in the asset use intensity, e.g. driving more miles per year, would accelerate the amortization and require additional maintenance costs.

Combining all the above, we write down the firm's profit function as:

$$\pi = \sum_{n \in \{e,t,a\}} \left[p^0 q_n - v_n q_n - \frac{1}{2} c_n q_n^2 \right] = \sum_{n \in \{e,t,a\}} \left[(p^0 - v_n) q_n - \frac{1}{2} c_n q_n^2 \right] \tag{2.1}$$

To simplify the notations, we introduce an individual technology net price $p_n^0 = p^0 - v_n$, rewriting 2.1 as:

$$\pi = \sum_{n \in \{e,t,a\}} \left[p_n^0 q_n - \frac{1}{2} c_n q_n^2 \right]. \tag{2.2}$$

Hence, the profit increases with the production but the incremental increase is slowed down by the diminishing returns parameter c. The same parameter can also be related to exhaustion, suggesting that "good locations" with high profitability are limited.

Value-oriented firm Based on the classical definition given by Modigliani and Miller (1958), the firm's value consists of its profit (π) and the present value of its remaining assets (A):

$$V = \pi + A. \tag{2.3}$$

[5]Referencing Pindyck (1986), we employ the terms "production" and "investments" interchangeably because we assume that the installation of new capacities and the subsequent production of one unit of output is facilitated by each unit of investment. In line with this assumption, we have selected the cost function accordingly.

[6]However, one may modify that to $p^0 = f(\sum_{n \in e,t,a} q_n)$. That will complicate further derivations, but not affect the effects discussed. We leave such a model extension for further research.

Apart from profit, when the firm produces from a given category n, it depletes potential for further production (Q_n) by the volume of production q_n. Those remaining assets may be sold later at a liquidation value:

$$A = \sum_{n \in \{e,t,a\}} A_n = p_n^1 \alpha_n \gamma_n (Q_n - q_n), \tag{2.4}$$

where p_n^1 is expected price of the output adjusted for the cost of production. Liquidation value is adjusted for: 1) the firm's appropriation rate $\alpha_n \in [0, \infty)$ in a category n; and 2) the firm's intrinsic probability of full realization of investment potential $\gamma_n \in [0, 1]$. The firm's appropriation rate is a profitability measure showing what portion of the future price the firm may earn as its profit. The intrinsic probability of full realization of investment potential is driven by the firm's expectations of regulatory changes in future. Both α_n and γ_n reflect the firm's expectations on production using technology from category n. The firm may expect that a regulator restricts further exploitation of the technology n. In this case, the probability of full realization of investment potential would decrease (and $\gamma_n < 1$). Under expectations that the production from the category n will be prohibited completely, $\gamma_n = 0$. Finally, when the firm is certain that the regulator will not restrict production in the given category n, $\gamma_n = 1$. We illustrate dependency of the firm's value of the level of production on the figure 2.1) for the established (e), transitional (t), and alternative (a) categories.

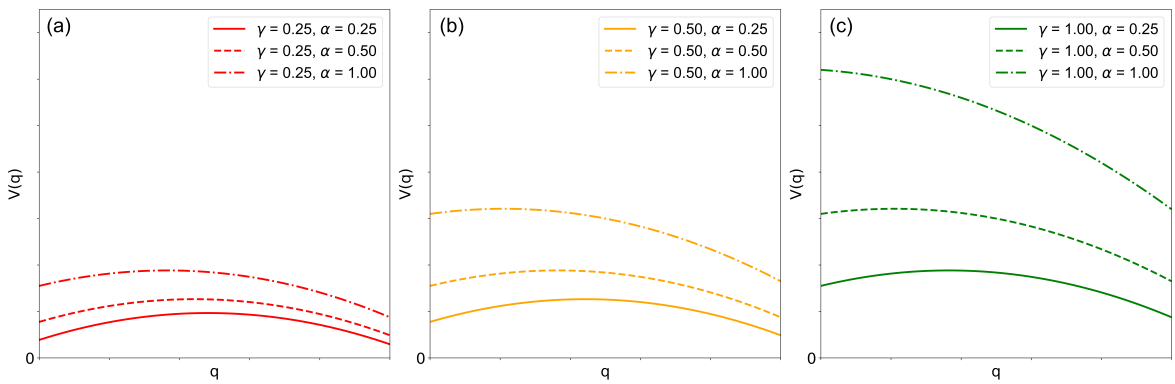


FIGURE 2.1: Firm's value under various expectations on future

The firm may be indifferent between production from established, transitional, and alternative categories if the appropriation rate compensates for the probability of full realization of investment potential. For example, the firm's value in the established and transitional categories equals each other when $\gamma_e = 0.25$, $\alpha_e = 1.0$, and $\gamma_t = 0.5$, $\alpha_t = 0.5$. In this case, we can say that the appropriation rate in the established category compensates for the low probability of full realization of the investment potential. Similarly, we can see that the firm may be indifferent between transitional and alternative categories when $\gamma_e = 0.5$, $\alpha_e = 0.5$, $\gamma_a = 1.0$, $\alpha_a = 0.25$. Again, here we can see that the certainty of full realization of investment potential compensates for the appropriation rate. This example showed that if the firm behaves as a value-maximizer, it may be indifferent between producing in different categories. If the firm expects to be limited in its ability to exploit all the available resources in the future, it may spend more on production.

If the firm expects the appropriation rate and probability of full realization together to be less than one, those effects multiply each other and decrease the firm's value. However, when the firm expects the appropriation rate and probability of full realization to move in opposite directions, those effects may cancel out each other. For example, suppose the firm expects productivity to improve in the transitional category, increasing the appropriation rate, while the probability of full realization goes down. In that case, it may still invest in this category and may even be indifferent between investments in the transitional or alternative categories. 2.1).

2.2.2 Firm's production as a function of emissions

In the paper, we assume that emissions are a linear or a polynomial function of the production volume. We use both forms of the emissions, and this relationship may be described by a function f_n for each project category n:

$$E_n = f_n(b_n, a_n, q_n), \tag{2.5}$$

where b_n stands for emissions associated with the installation of capacity needed to produce q_n, a_n is emissions per unit of production in category n. We assume that the function f_n is a polynomial that can be approximated by a linear function. For the sake of results tractability, we use a linear form of f_n in the theoretical part of the paper. However, we keep a polynomial form of the function 2.2 for the numerical simulations.

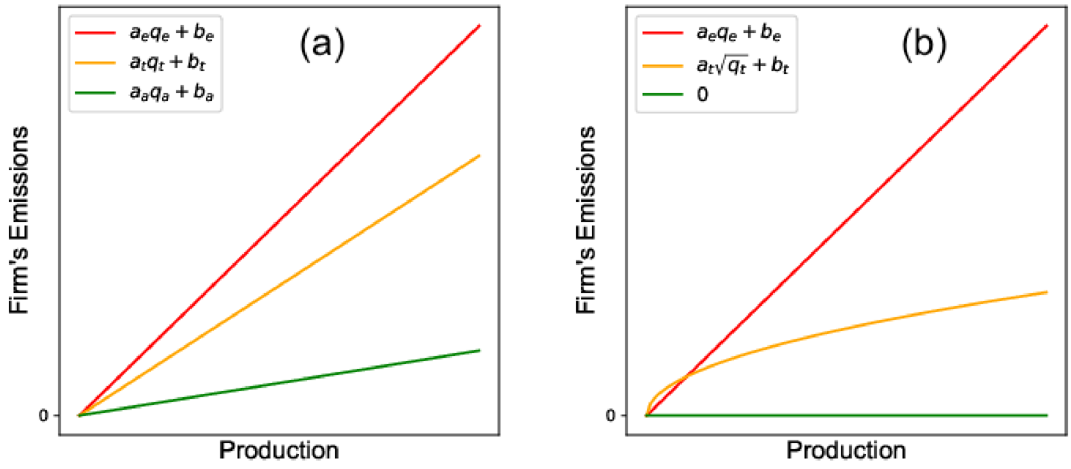


FIGURE 2.2: Firm's emissions as a function of production for every category for theoretical model (a), and for numerical simulations (b)

2.2.3 Constraints

Total emissions constraint In the model, we consider two types of emissions constraints. Under the first type, the firm is limited in the total amount of emissions $\bar{E}$ that it can produce regardless of a project's category: [7].

$$\bar{E} - \sum_{n \in \{e,t,a\}} E_n \geq 0. \tag{2.6}$$

Under this constraint, the firm may redistribute emissions allowances between categories. That being said, the firm may limit production from the transitional category while increasing production from the established category.

This constraint reflects the case when the firm is limited in the total amount of emissions. This constraint is closely related to the cap-and-trade policy with an inability to buy additional emissions allowances. The policy, known as cap-and-trade, combines a quantity-based limit on emissions with a price-based approach that puts a price on emissions. One example of implementation of this policy is the European Union's (EU) Emissions Trading System (ETS), launched in 2005 European Parliament, Council of the European Union (2003). Under the ETS,

[7]Here, we assume that we have an emissions budget until the end of a project's lifetime

the EU and national governments decide on the overall emissions cap – which is tightened every year. This policy gives a signal to firms from carbon-intensive sectors that they should limit their emissions or be prepared for additional expenses on emissions allowances.

Individual emissions constraints Under the second type of emissions constraints, the firm has individual constraints for each category [8]. However, we consider only a case when the emissions are associated with projects in established and transitional categories ($n \in \{e, t\}$). In this case, the firm can not redistribute emissions between categories:

$$\bar{E}_n - E_n \geq 0. \tag{2.7}$$

These constraints may be applied when a specific category is expected to be banned. For example, a car fleet operator may choose not to invest in vehicles with ICEs since they may be prohibited in the near future. Right now, California plans to achieve 100% zero-emission vehicles sales by 2035 Newsom (2022). A power-generating company may not invest in new coal power plants since they may also be prohibited. According to the new Coal Phase-out Act, Germany's last coal-fired power station is expected to close no later than 2038 Federal Ministry for Economic Affairs and Energy (BMWi) (2019).

2.2.4 Optimization problems

In total, we solve 6 optimization problems. Two for the firms operating under unconstrained emissions environment: one for the profit-maximizing firm (PMUC[9]), and one for the value-maximizing firm (VMUC[10]). The remaining problems are for constrained emissions environment (Table 2.2). There are two problems for the profit-maximizing firm under total emissions constraints (PMTC[11]) and under individual emissions constraints for every technology category

[8]We assume that the potential for future investments for alternative projects is limited as well. For example, the installation of wind turbines requires land and may cause deforestation and land erosion Enevoldsen (2018), Nazir et al. (2020)

[9]profit maximization unconstrained

[10]value maximization unconstrained

[11]profit maximization with total emissions constraint

(PMIC[12]). After that, value-maximizing firms are considered under total emissions constraint VMTC[13]), and under individual emissions constraints for every technology category (VMIC[14]).

Maximization	Total Emission Constraint	Emission Constraints by Project Type
Profit	$\pi + \lambda[\bar{E} - \sum_{n\in\{e,t,a\}} E_n]$	$\pi + \sum_{n\in\{e,t,a\}} \lambda_n[\bar{E}_n - E_n]$
Value	$V + \mu[\bar{E} - \sum_{n\in\{e,t,a\}} E_n]$	$V + \sum_{n\in\{e,t,a\}} \mu_n[\bar{E}_n - E_n]$

TABLE 2.2 Expressions for Lagrangian for the firm's optimization problems.

Here, λ and μ are shadow prices of imposing a total emission constraint on the profit- or value-maximizing firm correspondingly.

To solve a constrained maximization problem, we a the theorem of Kuhn and Tucker Sundaram (1996). First, we formulate the Lagrangian, which equals the sum of the objective function and constraints. Table 2.2 provides the Lagrangians for every case. For profit maximization, this may be written as:

$$L(q_e, q_t, q_a, \lambda) = \pi + \lambda[\bar{E} - \sum_{n\in\{e,t,a\}} E_n] \tag{2.8}$$

$$\frac{\partial L}{\partial q_n}(q_n, \lambda) = 0 \tag{2.9}$$

$$\frac{\partial L}{\partial \lambda}(q_n, \lambda) \geq 0 \qquad \lambda \geq 0 \qquad \lambda\frac{\partial L}{\partial \lambda}(q_n, \lambda) = 0 \tag{2.10}$$

The exact solutions for every constrained case may be found in Appendix A.1.

2.3 Numerical simulations

We present numerical simulations for two types of firms. The first type maximizes its profit, while the second type maximizes its value. For each type of firm, we consider several regimes of the regulatory environment when emissions are: 1) unconstrained; 2) constrained on the firm's level; 3) constrained on the individual category level.

[12]profit maximization with individual emissions constraint
[13]value maximization with total emissions constraint
[14]value maximization with individual emissions constraint

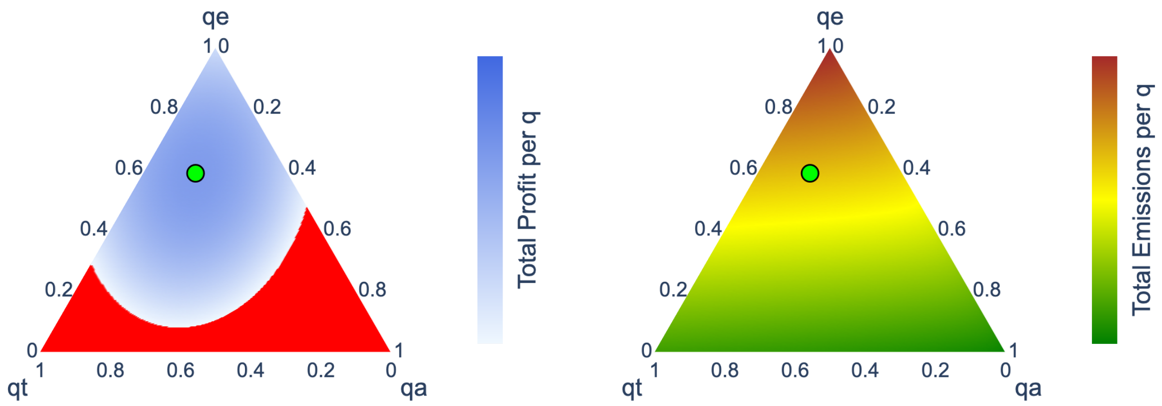
For all regulatory environments, we keep a set of parameters fixed and the same relationships between production and emissions. For the established category, we assume that the production linearly depends on emissions: $E_e = a_e q_e + b_e$, and for the transitional category, there are non-linear relationships between the firm's emissions and production: $E_t = a_t \sqrt{q_t} + b_t$. Finally, there are no emissions in the alternative group, meaning $E_a = 0$.

For all considered cases, we have assumed that $c_e < c_t < c_a$, and $v_e < v_t < v_a$. This assumption shows that the costs of production in the established category are the lowest, followed by the transitional and alternative categories. However, our model allows us to consider not only this case but also when $c_e > c_t > c_a$, and $v_e > v_t > v_a$. From a practical point of view, it means that the established category is the alternative one and vice versa.

We will present results as a ternary diagram showing relationships between a specific value (profit, value, emissions, etc.) and total production level, while keeping the sum of productions from each category constant: $q_e + q_t + q_a = q = Const$.

2.3.1 Profit-maximizing firm

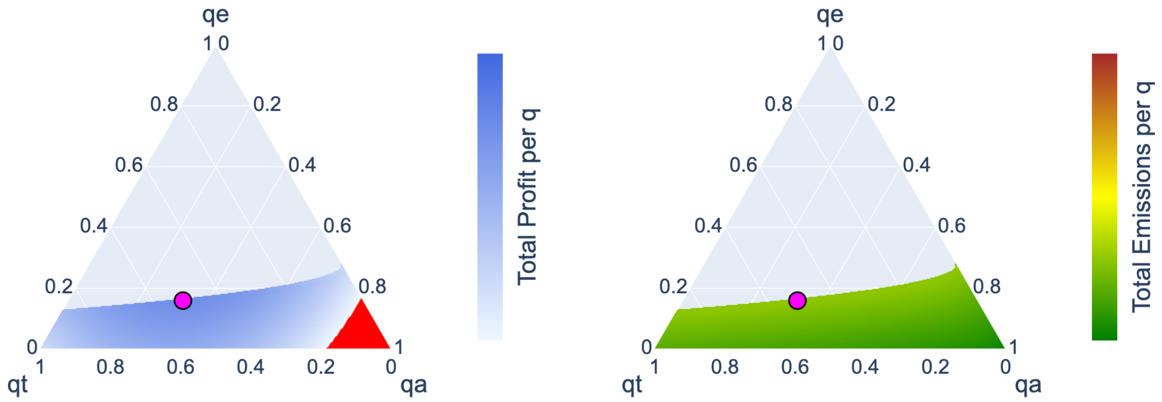
Firstly, we provide the solution for the profit-maximizing firm under an unconstrained emissions environment (2.3 (a)) and (2.3 (b)). The red area represents a case when the profit is less than zero. If we assume that the firm produces when its profit is greater or equal to zero, then the project combinations located in the red area are not attainable for the firm. The solution to the given optimization problem gives us the largest share of the production for the projects in the established category, followed by the project in transitional and alternative projects. Model parameters were selected in a way to mimic the share of investments of major oil and gas companies, according to report International Energy Agency (2020a), in projects that are related to each category.



(a) (b)

FIGURE 2.3: Solution for the profit-maximizing firm under unconstrained environment as a profit per unit of output (a), and as emissions per unit of output (b).

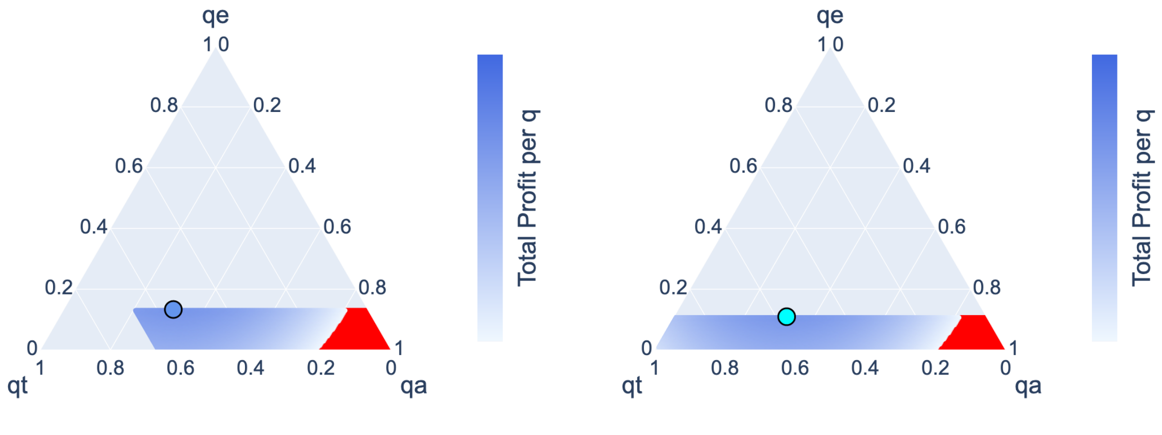
Under the total emission constraint, when the firm's total volume of emissions is constrained and equal to $\bar{E}$, the share of production in the established category goes down. The grey area shows unattainable combinations of categories shares since those combinations will generate more emissions than $\bar{E}$. Shares of the projects in the transitional and alternative categories increase (2.4 (a)) while the total volume of emissions decreases (2.4 (b)). The share of emissions from the established category is greater than the share of emissions from the transitional category.



(a) (b)

FIGURE 2.4: Solution for the profit-maximizing firm under total emissions constrain environment as a profit per unit of output (a), and as emissions per unit of output (b).

Then, we introduce individual emissions constraints for established $\bar{E}_e$ and transitional $\bar{E}_t$ categories while keeping the level of emissions at the same level as for the total emissions constraint, so $\bar{E}_e + \bar{E}_t = \bar{E}$. We start with introducing the emissions allowed equal to each category (2.5 (a)). Then we push the constraint on the emissions from the established category further, that $E_e < E_t$ (2.5 (b)). With this example, we can illustrate how constraints on the individual level reduce the production of the aimed category.



(a) (b)

FIGURE 2.5: Solution for the profit-maximizing firm under individual constraints in each category. For the case when the total level of emissions are equal to each other $\bar{E}_e = \bar{E}_t$ (a), and for the case when there is a stronger emissions constraint on the established category $\bar{E}_e > \bar{E}_t$ (a) (b).

From all the illustrative examples, we can see that the firm's profit per total output grows with the introduction of constraints. Despite the growth of the firm's profit from all categories, the total firm's output decreases due to the constraint on the emissions, and therefore production from the established category with the lowest costs compared to all the other categories (2.6).

(a)

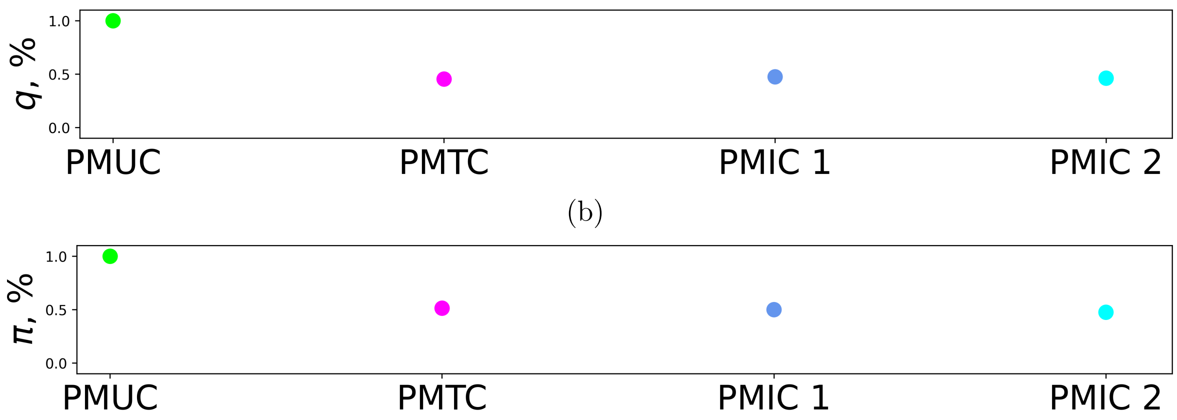


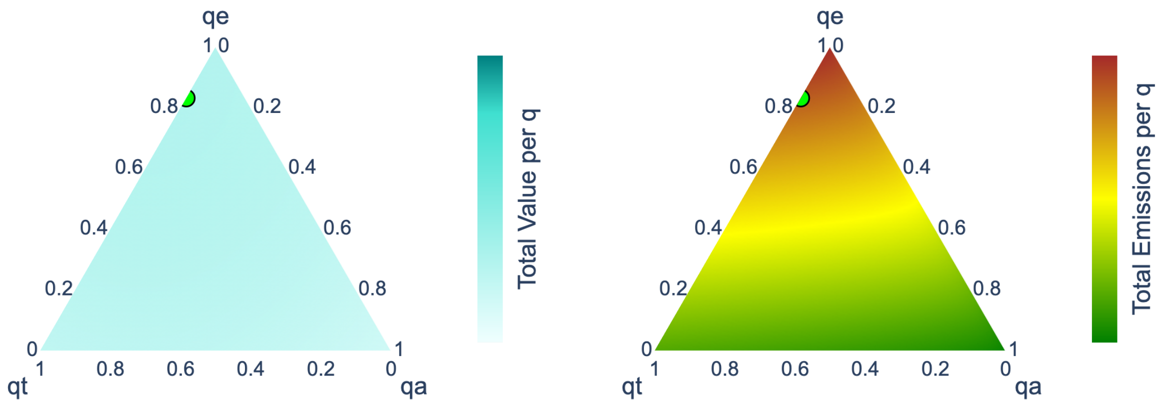
FIGURE 2.6: Optimal firm's total output (a) and profit (b) as a percent of optimal total output from unconstrained case

This section showed how constraints imposed on the firm's emissions decrease profit and total output. Total emissions constraint may encourage the firm to spend the majority of its emissions budget on a category of projects with the highest emissions per unit of output but with the lowest costs. In case when the projects in the established category have the lowest costs and highest emissions compared to other categories, the firm may limit its investments in other categories since all of them are competing for the same emissions budget. So, individual emissions constraints may be a better solution to control the firm's choice of projects than the total emissions constraint. However, individual emissions constraints may harm the firm's total output and profit more than the total emissions constraint.

2.3.2 Value-maximizing firm

For the value-maximizing firm we assume that $\gamma_e < \gamma_t < 1$ and $\alpha_e < 1$, $\alpha_t = 1$, and $\alpha_a > 1$. In this case, we may assume that the firm expects production costs in the established category to increase, and a regulator may impose constraints on the full realization of investment potential. For the alternative category, the firm expects an improvement in technologies and is sure of the ability to fully realize investment potential $\gamma_a = 1$.

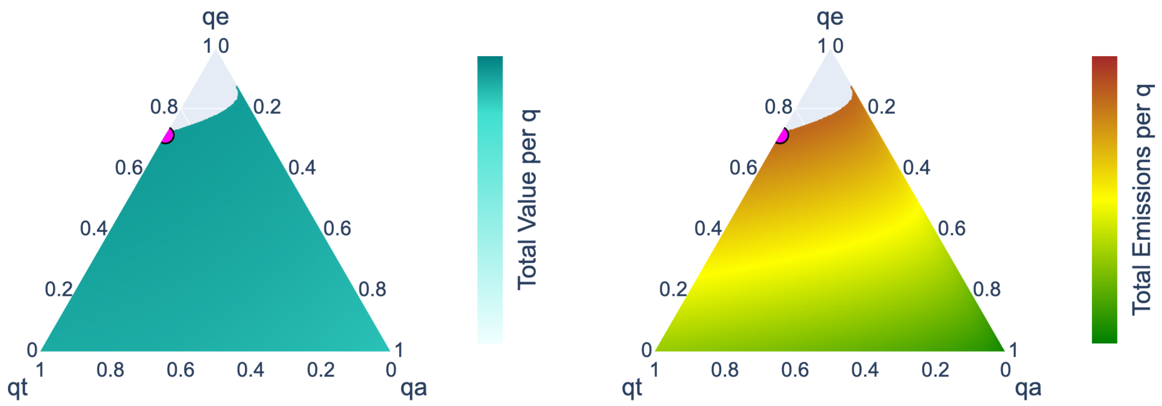
Firstly, we provide the solution for a value-maximizing firm under the unconstrained emissions environment. In this case, the share of the production in the established category is close to 100% 2.7 (a), and the volume of emissions would be the largest 2.7 (b) compared to all the other solutions.



(a) (b)

FIGURE 2.7: Solution for the value-maximizing firm under unconstrained environment as a profit per unit of output (a), and as emissions per unit of output (b).

Next, the total emissions constraint is applied to the value-maximizing firm. As a result, the firm still invests only in the established and transitional projects 2.8 (a). However, due to the total emissions constraint, there are some combinations of production from the established and transitional categories in the grey zone that the firm is restricted from realizing. In this case, the level of emissions is reduced 2.8 (b). The reduction is caused by the decrease in the firm's output and share of the projects in the established category, together with the growth of the share of the production from the transitional category.



(a) (b)

FIGURE 2.8: Solution for a value-maximizing firm with total emissions constrained. For profit per unit of output q (a), and the total emissions that are associated with this solution (b).

Finally, we have considered a case when individual emissions constraints are applied to the firm. Those emissions force it to expand its portfolio by adding production from the transitional category 2.9 (a). If the constraints that are applied to the established category become even stricter, the firm will enlarge the share of the transitional category further 2.9 (a).

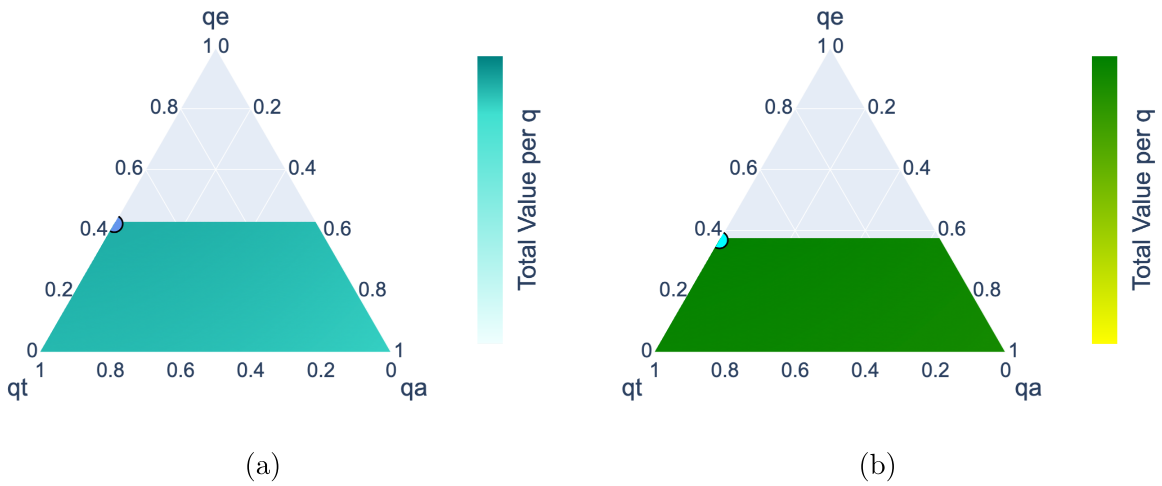


FIGURE 2.9: Solution for a value-maximizing firm under individual constraints in each category. For value per unit of output q (a), and the total emissions that are associated with this solution (b).

The reduction of the total firm's emissions or the reduction of the emissions on an individual level leads to a drop in the firm's production 2.10 (a). Even though the firm's value per unit of output is increasing, it still can not compensate for the loss of the firm's value 2.10 (b).

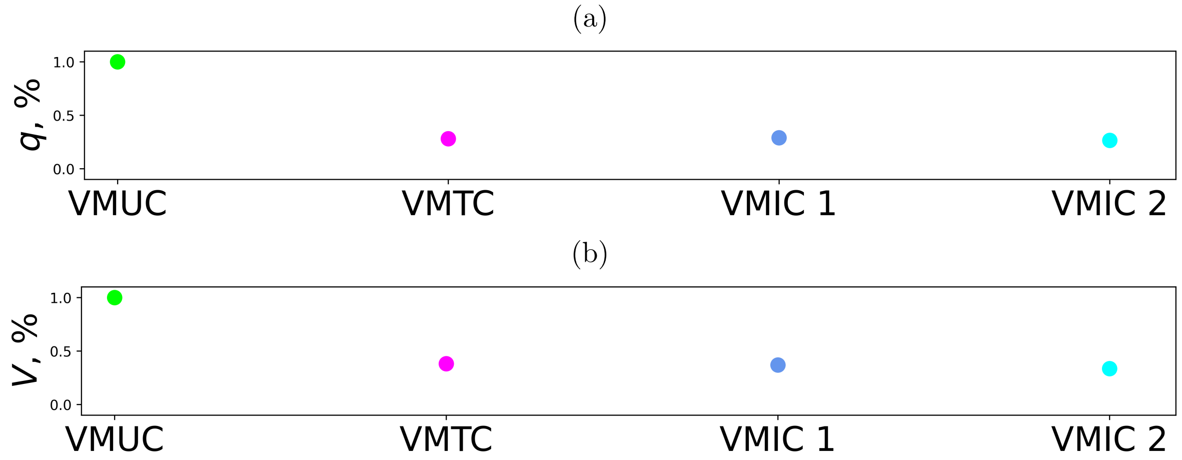


FIGURE 2.10: Optimal firm's production (a) and value (b) as percent of the total production and value that was for unconstrained, total emissions constraint, and individual constraints of emissions per category.

We compared solutions for the profit-maximizing and the value-maximizing firms under the same assumptions about prices and costs. We showed that in both cases, the optimal level of total production is reduced by introducing the emissions constraints of both types: that applied to the total emissions that the firm produces and the emissions that are produced in each category.

2.3.3 Comparison of profit- and value-maximizing firms behaviours

Now, we analyze how the firm's portfolio may change depending on the firm's objective (Figure 2.11). In order to do so, we investigate how the probability of full realization of investment potential influences the optimal mix of technologies in the firm's portfolio. We provide the results for the unconstrained emissions environment with the assumption that $c_e < c_t < c_a$, and $v_e < v_t < v_a$, and $\alpha_e < 1$, $\alpha_t = 1$, and $\alpha_a > 1$. In all considered cases, we assume that the $\gamma_e = \gamma_t = \gamma_a = \gamma$, and $p^0 < p^1$.

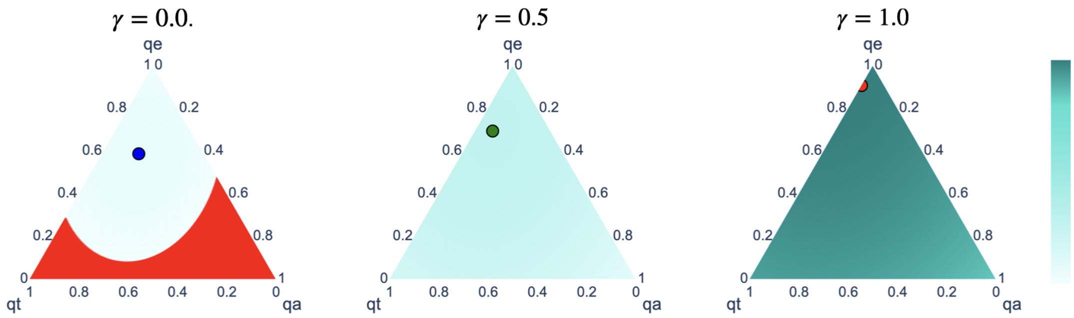


FIGURE 2.11: Firm's value for $\gamma = 0$, $\gamma = 0.5$, and $\gamma = 1$

If $\gamma = 0$, the firm's liquidation value equals 0, and the firm behaves as a profit-maximizer. In this case, the firm does not account for the depletion of its resources, and the share of the "clean" technology in the portfolio is the largest. With the growth of γ, the firm is confident in fully exploiting the investment potential associated with the "dirty" technology and takes into account that the appropriation rate is the lowest for the "dirty" technology and largest for the "clean" technology. It means that usage of "dirty" technology in the current period allows, on the one hand, to maximize profit because the costs attributed to the "dirty" technology are the lowest, and, on the other hand, since the appropriation value is the lowest for the "dirty", the value of the assets from "dirty" category is also the lowest. That is why under the considered set of assumptions, we see that if the firm aims to maximize its profit, it will invest the most in "clean" technology. In contrast, if the firm expects the appropriation rate to be the highest for the "clean" technology and currently it has the highest costs, the firm will invest in the "dirty" technology with the lowest cost and lowest appropriation rate.

2.4 Conclusions

Our goal was to build a model allowing for an understanding of how and why firms' strategies for energy transition vary under various environmental environments and to show that even under the same type of GHG emissions constraints, firms' behavior may differ depending on their size or stage of development. As a result, we showed under what conditions the firm may start an energy transition and what can accelerate the energy transition.

The developed model was used in numerical simulations under different scenarios. We showed the interplay between the firm's intrinsic probability of full realization of investment potential and the firm's appropriation rate using numerical and theoretical approaches. Depending on the relationships between those parameters, they might neutralize each other, or they may amplify the effect of each other. In the first case, the behavior of the value-maximizing firm may remain as if there were no changes in the probability of the full realization of the investment potential of projects that utilize the established technologies and the optimal mix of technologies in the value-maximizing firm's will be distinct from the profit-maximizing firm. In the latter case, the value-maximizing firm may behave as the profit-maximizing firm, while keeping all other parameters the same. If there is no external imposed constraint on emissions, both types of firms have no strong incentives to do the transition from the established technologies to alternative ones, while the alternative and transitional technologies costs are higher than the established. If, however, the emissions constraints are imposed, we find that firms' behavior is distinct depending on whether the emissions were constrained on the firm's level or the technology level used. In general, we find that the per-technology type constraint is more efficient in boosting the penetration of the alternative technologies that are associated with a lower level of emissions. When the constrained are imposed on the firm level, and there are no differences in the origin of the emission, we can see that the firm may be able to produce more; however, it is done at the expense of not investing in the "clean" technologies. We recognize that the results may suffer from a number of limitations, such as cost ranging. Another major limitation of the performed analysis is that we have not included the budget constraint, which is available to the firm when it invests. Also, we have yet to include the constraint on the firm's output, which may be necessary, especially if one looks at the power sector.

3 | Resiliency and shock propagation in interindustry trade networks: a global perspective

Berdysheva, S.; Ikonnikova, S.

This paper is based on and inspired by the international interindustry input-output (II-IO) and trade data from 2002 to 2018. To examine the effect of the short-term shocks stemming from the changes associated with the transition or other events affecting input or output flows, an enhanced model, combining elements of complex networks and international trade theories, is developed to capture II-IO dynamics. First, using the elements of the network theory, we analyze the relationships within the network and test its vulnerability to shocks of different origins, e.g. simulating an individual energy input (access) related shock. The proposed shock propagation algorithm helps develop projections for the first-, second-, and higher-order effects. The constructed model is further used to reveal how far an impact of the shock in an individual industry in a given country may spread (unless it is interrupted and interfered with) and how other industries and economies may become "infected" and experience economic losses. Thus, the study fills in the gap between the classical international trade literature, neglecting or minimizing the interindustry relationships complexity, and the IO works lacking the analysis of trade relationships. The developed model is also used to provide new arguments regarding the most effective sanctions on Russia, which would have a limited negative impact on the rest of the world and developing nations.

3.1 Introduction

The primary culprit behind rising temperatures is greenhouse gas (GHG) emissions, specifically carbon dioxide. The Paris Agreement, signed by 195 countries and the European Union (EU) in 2015, represents a worldwide agreement to combat climate change, and its primary goal is to limit global warming to well below 2°C above pre-industrial levels United Nations Climate Change (2015). GHG emissions reduction calls for energy transition, which is characterized by the decrease in fossil fuel usage through the growth of the share of energy generated from renewable energy sources and improving the efficiency of energy usage. According to statistics from 2021 EDGAR/JRC (2021), the power and transportation industries are the most significant contributors to global carbon dioxide emissions, accounting for more than half of the total, which is why those industries should be targeted first to reduce the production of GHG emissions.

In the electric power industry, coal power plants produce the most GHG emissions International Energy Agency (2021a), so accordingly the energy transition process targets them at first Jakob et al. (2020), causing coal power plants to phase out. During this process, they are replaced by a combination of natural gas power plants and renewable energy sources Safari et al. (2019), Bessi et al. (2021), International Energy Agency (2022a). This process has already started, and shares of renewables and natural gas power plants worldwide in the electricity generation mix from 2002 to 2018 increased by 3.3% and 7.1%, correspondingly International Energy Agency (2019). At the same time, the share of coal has shrunk worldwide by 1.3% International Energy Agency (2019). Even though the share of coal power plants in electricity generation reduced, the trade volume of coal increased Berdysheva and Ikonnikova (2021) due to the growth of total energy consumption International Energy Agency (2019). However, the number of coal suppliers that represent the top 95% of the global coal flow worldwide stayed almost the same and equaled 63 in 2002 and 62 in 2018 Berdysheva and Ikonnikova (2021).

Replacing internal combustion engine (ICE) cars with electric vehicles (EVs) could be a solution to the environmental challenges in the transportation industry. And this process has already started as well since the proliferation of electric vehicles (EVs) has been on the rise, as noted by Hardman et al. (2017), with the trend expected to continue Fachrizal et al. (2020). According to the International Energy Agency (2022b), global EV sales have doubled since 2019, with nearly 10% of all cars sold in 2021 being electric. This positive development is expected to decrease the world's dependence on oil-based products, leading to a more secure energy landscape for countries

Yuan et al. (2020). Nevertheless, achieving this energy security is contingent on meeting the increasing energy demand through energy production growth. An in-depth analysis is thus warranted, not only on oil dependency but also on other fossil fuels utilized for transportation purposes.

The energy transition, along with shifts in the global supply and demand balance, has an impact on global fossil fuels trade Zhong et al. (2017), and, consequently, on energy security of countries and various industries, as it alters the supply chain Yuan et al. (2020). In our work, we examine the global interindustry resiliency to shocks, particularly in relation to the effects of trade restrictions between fossil-related and other industries. Our analysis aims to track how such shocks propagate throughout the system over time.

Four groups of literature performed an earlier analysis of shocks in international trade. The first group focuses on input/output analysis developed by Leontief (1936). This approach allows for modeling the shocks on the supply or (and) demand sides Galbusera and Giannopoulos (2018). Depending on the goal, input/output analysis can be applied to a certain region Garcia-Hernandez and Brouwer (2020) or globally Contreras and Fagiolo (2014). A wide range of problems may be addressed using this framework. For example, it allows for solving the optimal resource distribution problem under an assumption that the shock may occur on the demand or supply side with various objective functions, such as minimization of gross domestic product or gross output disruptions Garcia-Hernandez and Brouwer (2020). To accomplish this, a technology matrix is calculated as interindustry monetary flows divided by the total output from each industry Kitzes (2013). Subsequently, the final demand or final production changes due to the shock while keeping the technology matrix the same while supply or demand in each industry transforms. The main drawback of this approach, if one evaluates the effect of the change on the industry's output, is that under this set of assumptions, even though the available inputs from the industry have changed, it does not influence the interindustry consumption. However, network analysis is rarely applied in this group of literature Cerina et al. (2015). We contribute to this group of literature as we provide a framework to analyze how actual interindustry trading relationships may be changed due to the changes in the actual interindustry trade in different countries.

The second group of literature emphasizes the importance of interindustry trade network structure and considers how a specific type of network may either amplify or compensate for the idiosyncratic productivity shock arising in a given industry Acemoglu et al. (2012a). This highlights the interconnected nature of industries and how shocks can have cascading effects throughout the system, specifically when there is a view of unique suppliers who are essential to other industries.

The third group of literature applies the network analysis framework for understanding how shocks can propagate through a system of physical or monetary flows of goods. Analyzing historical data on trade networks and how it has changed over time shed light on the effects that external factors such as energy transition Berdysheva and Ikonnikova (2021), or limitation of trade volumes may have the network dynamics. Another critical question that can be addressed using network analysis is what communities are in the network. By identifying clusters of countries that are closely connected in terms of their trade relationships, it is possible to gain insights into the structure of the network and how different regions of the world are interconnected Chen et al. (2018), Zhong et al. (2017). In addition to understanding the structure and evolution of the trading network, network analysis can also be used to estimate how the shock arising from a trade limitation may spread further and cause long-lasting Fair et al. (2017) or avalanching effects Lee et al. (2011).

Finally, international trade theory, and specifically gravity models presenting bilateral trade flows as a function of bilateral trade costs Costinot and Rodríguez-Clare (2014) are widely used to analyze the impact of trade barriers on the welfare Melitz and Ottaviano (2008), Dhingra et al. (2017). However, those models look only into the effects of the first order and do not allow tracking the impact of trade barriers on the third countries. The presented paper considers that effect on the interindustry trading network.

We can witness that after Russia invaded Ukraine in 2022, there were distortions in interindustry trade, including a considerable decrease in the natural gas trade between Russia and Germany at the end of August 2022 Eckert and Steitz (2023). This brings us to the question of how to model the effect of the shock propagation given both: 1) How the shock on the inputs may affect an industry's outputs; 2) How the reduction of outputs, if it takes place, may spread further, amplifying the initial effect of the shock.

The main contributions of this paper are the following: 1) We analyze the dynamic of interindustry global trade, and this will give us an understanding of how it evolved over time; 2)We develop a model that would allow us to track how the shock may propagate in the interindustry trade network further than the first-order neighbors; 3)We apply the developed model to the data on global interindustry trade and estimate the effects of the shock propagation arising from fossil-related industries.

The rest of the paper is organized as follows: we start with the discussion of the data, and we estimate the evolution of resiliency to shocks over time using methods from network analysis. Then, we present a model of shock propagation beyond the first-order neighbors. Finally, we apply the developed model to global interindustry trade data and present empirical results on how the shock arising in a fossil-related industry may propagate to its neighbors and how it evolved during the considered period.

3.2 Data and Framework

3.2.1 Data

To analyze the resilience of global interindustry trade to shocks and evaluate how they may propagate, we used data from Organisation for Economic Co-operation and Development (OECD) on Inter-Country Input-Output (ICIO) Tables. ICIO Tables contain information on trading relationships between 45 unique industries in 66 countries OECD (2021), including OECD countries, 26 other countries (including China, India, Russia, and Saudi Arabia), and the rest of the world grouped as one. However, to simplify the analysis, we grouped some of the industries, and the full list of available and considered grouped industries is presented in the appendix A.2.

The data on global interindustry trade is presented in the form of a square matrix with importers in columns and exporters in rows 3.1.

<table>
<tr><td colspan="3" rowspan="3">Output
Input</td><td colspan="7">Intermediate Use</td></tr>
<tr><td colspan="3">Economy 1</td><td rowspan="2">...</td><td colspan="3">Economy r</td></tr>
<tr><td>Ind. 1</td><td>...</td><td>Ind. i</td><td>Ind. 1</td><td>...</td><td>Ind. i</td></tr>
<tr><td rowspan="7">Intermediate input</td><td rowspan="3">Economy 1</td><td>Ind. 1</td><td colspan="7" rowspan="7">A</td></tr>
<tr><td>...</td></tr>
<tr><td>Ind i</td></tr>
<tr><td colspan="2">...</td></tr>
<tr><td rowspan="3">Economy r</td><td>Ind. 1</td></tr>
<tr><td>...</td></tr>
<tr><td>Ind. i</td></tr>
</table>

Table 3.1 Interindustry trade table scheme.

In the presented paper, we considered what happens if fossil-related industries, such as *Mining and quarrying energy producing products* and *Coke and refined petroleum products* are excluded from interindustry trade. This may happen due to shifts in the geopolitical situation or as a result of environmental concerns.

3.2.2 Network analysis

We base our analysis on an input-output matrix A with entries a_{ij}^{rs} showing relationships between industries $i \in \{1, 2, ..., S\}$ located in various economies $r \in \{1, 2, ..., R\}$. It may also be represented as a directed weighted graph with $S \times R$ nodes. Each node represents one industry in one country, and each directed link with weight $a_{ij}^{rs} > 0$ represents monetary flow from a industry i in a country r to a industry j in a country s. In other words, if $a_{ij}^{rs} > 0$, then a industry i in a country r supplies inputs to a industry j in a country s.

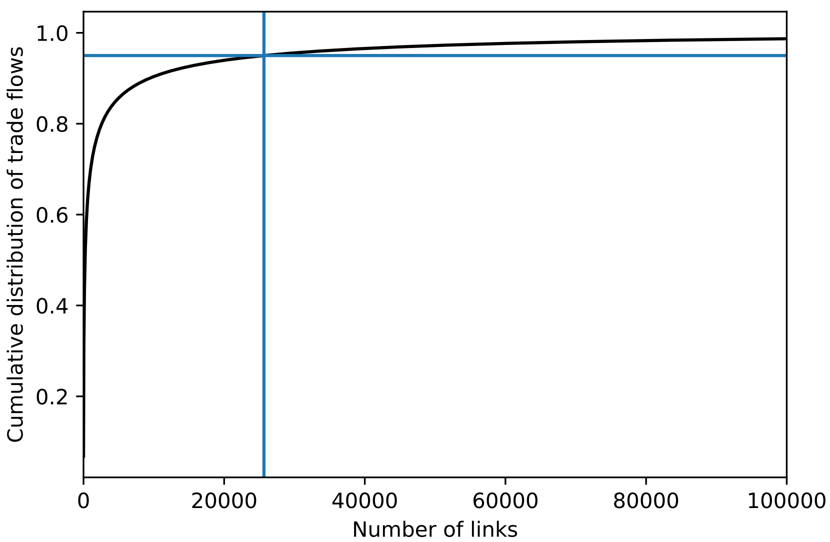


FIGURE 3.1: Commutative distribution of links in the input-output table for 2018.

We use interchangeably the notations between the input-output matrix and network representation of the interindustry trade. To define the network, we follow a standard approach of creating a "backbone" network. As a result, we keep only those links accounting together for only 95 % of the total trade volume for three years in a row. This approach allows us to reduce the size of the network while keeping the network structure the same 3.1. The same method was applied in the paper Fair et al. (2017), which analyzed the resilience of the wheat trade.

We use $|\cdot|$ notation to count non-zero elements, i.e. $|a_{ij}^{rs}| = 1$ if industry i in country r acts as a supplier for industry j in country s. Thus, $\sum_r \sum_i |a_{ij}^{rs}|$ equals to the number of trading partners of a industry j in country s that supply inputs, which is also called *in-degree* $d_{(s,j)}^{in}$ of the node (s, j). Similarly, $\sum_r \sum_i |a_{ji}^{sr}|$ equals the number of trading partners that buy inputs from a industry j in country s, which is also called *out-degree* $d_{(s,j)}^{in}$ of the node (s, j). This allows us to introduce a node's (s, j) degree that equals the sum of in- and out-degrees and may be given as follows:

$$d_{(s,j)} = d_{(s,j)}^{in} + d_{(s,j)}^{out} = \sum_r \sum_i (|a_{ij}^{rs}| + |a_{ji}^{sr}|). \tag{3.1}$$

Even though a node's degree allows us to get information about the number of trading partners, it neglects the flow volume between selected pairs of nodes. To that end, we use a node's strength that is calculated based on the volume that flows in and out of the node. Similar to the node's degree, the node's strength is calculated as a sum of *in-* and *out-strength* and equals to:

$$s_{(s,j)} = s_{(s,j)}^{in} + s_{(s,j)}^{out} = \sum_r \sum_i (a_{ij}^{rs} + a_{ji}^{sr}). \tag{3.2}$$

The shape of degree and strength distributions illustrate heterogeneity among various industries (Figure 3.2). Thus, in 2018 distributions approximate power-law pointing out that only a small number of industries have more than 25 trading partners and the most interindustry trade volume compared to the most extensive industries. The most connected industry with the highest trade volume is *Commercial and public services* in the USA, China, Germany, and Japan.

In addition, another important measure that characterizes the network is the average shortest path length. It is defined as the average number of steps along the shortest path it takes to get from one node to another across all nodes in the network. In other words, this measure shows how fast the signal (or the shock) may reach all the nodes in the network. For the considered reduced network, the average shortest path length was around three during the considered timeframe.

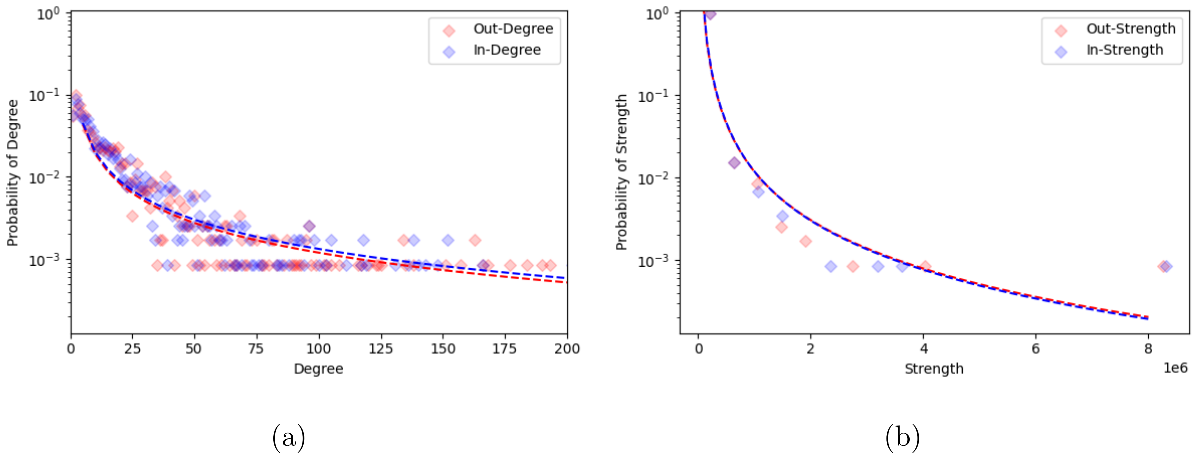


FIGURE 3.2: The degree (a) and strength (b) distributions.

3.2.3 Network resilience to shocks

In the current literature on network analysis, there are two main types of shocks based on their origin. The first type of shocks is errors; when it occurs, a random node is removed from the network. The second type of shocks is an attack; when it happens, a specific node with certain characteristics is removed. We estimate the shock's effect via the size of a giant strong component (GSC). The size of GSC equals the number of connected nodes in both directions, meaning one may approach the other nodes from the start node, and the start node can be reached from those other nodes Dorogovtsev et al. (2001).

To model the attacks, we use Page-In-Rank centrality, which shows how important a node is in terms of the importance of its predecessors in a connected network Page et al. (1999), and for the attacks, we will be removing the industries based on their Page-In-Rank centrality. This may illustrate the effect of trade restrictions from one country to another on a industry level.

The network is resilient to shocks if removing the node from the network reduces its giant component is reduced by one. Removing the node does not divide the network into two separate subnetworks. The equation in the form $y = 1 - x$ describes this process. Here y is the GSC's size after removing a portion of nodes x divided by the network initial size. When we remove the node, it means that a specific industry in a country is excluded from global interindustry trade Figure 3.3.

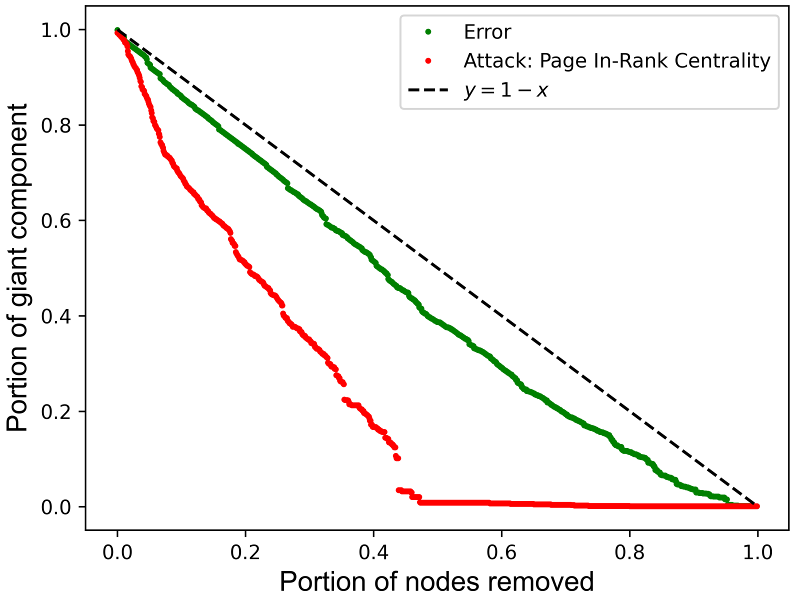


Figure 3.3: Giant component size in 2018.

As one may expect, the network is more vulnerable to attacks rather than to errors since the size of GSC divided by the initial size of GSC is closer to the -45° for errors than for the attacks. We can see that from 2000 to 2008, the network resiliency improved. When 10% or 20 % of the nodes were taken out, the size of GSC divided by the initial size of GSC was greater in 2008 than in 2002. However, after the global financial crisis in 2008, resiliency decreased.

3.2.4 Shock Propagation Model

In this section we introduce a framework for the analysis of multi-order shock propagation. The shock decreases trade volume between two industries (Figure 3.2 (a)). The cause of this reduction may be random, e.g., a natural disaster Garcia-Hernandez and Brouwer (2020), or a change in the regulation, e.g., imposing trade barriers Kinne (2012). Trade barriers may be in the form of sanctions or may be a consequence of the environment-oriented policies aiming at limiting imports of fossil-related industries. This may decrease inputs available for the industry's production. As a result, the affected industry will decrease its production, and the initial shock will have a avalanching effect. We limit our analysis to consideration of the shock effect only in the short term, meaning that we model how the shock may spread across industries. However, we leave the question of establishing new trading relationships behind the scope of this framework.

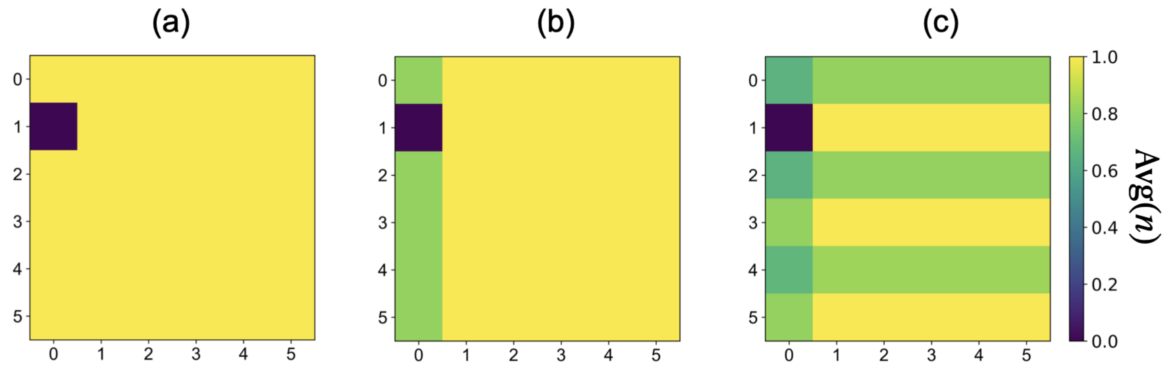


FIGURE 3.4: Interindustry monetary flows as the share of the initial state.

Let us assume that the trade volume from industry i in the country r to industry j in the country s is reduced. Then the monetary flow between given pair of industries and countries is reduced as follows:

$$a_{ij}^{rs}(n=1) = f_{ij}^{rs} \cdot a_{ij}^{rs}(n=0), \tag{3.3}$$

where n is the distance from the shock start; the intensity of the shock is given by $f_{ij}^{rs} \in [0,1]$. If $f_{ij} = 0$, the link from the country r and the industry i to the country s and the industry j is deleted. And if $f_{ij} > 0$, then a limitation on a total trade flow volume is imposed.

The shock propagates further from the affected industry j in the country s since the amount of the needed inputs is reduced due to the loss of a trade volume from industry i in a country r. In this case, the neighbors of the first order are said to be affected. As a result, a industry's j output may be reduced because of a lack of the inputs from the industry i in the country r if it is impossible to substitute for them in the short-term run. We assume that the industry j in the country s may resist the shock up to a threshold level t_j^s. Then, the indicator function may be given as:

$$\delta_j^s = \begin{cases} 0, & \text{if } w_j^s < t_j^s \\ 1, & \text{if } w_i^r \geq t_j^s. \end{cases} \tag{3.4}$$

To calculate the weights of shock propagation to the industry j, we first calculate how the shares of each country have changed because of the shock, keeping the industries fixed. Then, we calculate a product of those changed shares for each country for each industry that supplied inputs to the affected industry j in the country r:

$$w_j^s(n=2) = \prod_i \frac{\sum_r a_{ij}^{rs}(n=1)}{\sum_r a_{ij}^{rs}(n=0)}. \tag{3.5}$$

As a result, the weights in the interindustry trade matrix for the neighbors of order $n = 2$ will be equal to the product of the shock propagation indicator times the shock's weight times the weight of the link at the previous order:

$$a_{ij}^{rs}(n=2) = \delta_j^s \cdot w_j^s(n=2) \cdot a_{ij}^{rs}(n=1). \tag{3.6}$$

For the neighbors of order $n = 3$, we assume that the shock propagates even further since the output of the affected industry j in the region s will be reduced because of the initial shock. This leads to reducing the inputs of those industries that use inputs from industry j in the country s. Let us denote those industries as i and countries as r. In this case, the weights of the shocks will be given as follows:

$$w_i^r(n=3) = \prod_j \frac{\sum_s a_{ij}^{rs}(n=2)}{\sum_s a_{ij}^{rs}(n=1)}. \tag{3.7}$$

The resulting weights in the interindustry trade matrix at the order $n = 3$ can be as:

$$a_{ij}^{rs}(n=3) = t_i^r \cdot w_i^r(n=3) \cdot a_{ij}^{rs}(n=2). \tag{3.8}$$

This model could be illustrated with an example on Figure 3.4. In the first-order (a), flow from the start node 1 to node 0 stops $a_{01} = 0$. For the second-order (b), the flow that goes from node 0 is reduced proportionally to the input of node 1. Finally, for the third-order (c), the production from those nodes that used the output of the start node as input will also reduce production.

Those shocks may propagate even further to the neighbors of higher orders. In general, for orders $m = 2, 3, .., N$, the propagation of shocks may be written as:

$$a_{ij}^{rs}(m) = \begin{cases} t_p^k \cdot w_j^s(m) \cdot a_{ij}^{rs}(m-1), & \text{if } m \text{ is even} \\ t_p^k \cdot w_j^{sT}(m) \cdot a_{ji}^{sr}(m-1), & \text{if } m \text{ is odd.} \end{cases} \tag{3.9}$$

The average percentage change [15] due to the shock propagation of order m for the whole interindustry trade network with number of flows $(R \cdot S)^2$ equals to:

$$\text{Avg}(m) = 1 - \frac{1}{(R \cdot S)^2} \sum_{r,s} \sum_{i,j} \frac{a_{ij}^{rs}(n=m)}{a_{ij}^{rs}(n=0)}. \tag{3.10}$$

and it shows what portion of global interindustry trade is lost due to the shock propagation of order m. If $\text{Avg}(m) = 0$, the shock does not affect interindustry trade, while if $\text{Avg}(m) = 1$, the elimination of the industry destroys the global interindustry trade.

The outcome of the sanctions may vary significantly depending on the type of the economy's orientation, meaning what industry is the most crucial for the country domestic production and what industry is engaged in global trade the most. For example, the effect of imposing trade limitations on a target industry that depends little on export and is domestically oriented is different from the effect of the sanctions that are imposed on a target industry that is export-oriented and not so crucial for the domestic economy. As a result, in the first case, the target economy of the country under the sanctions will be affected more than in the second case, when the countries utilizing those exports from the target economy may be harmed more. That is why, together with average percentage change of the entire network, the average percentage change for the intermediate inputs and outputs should be estimated separately. We measure the impact of the shock as the average percentage change of the inputs available to the economy ($\text{Avg}_r^{in}(m)$). Similarly, we can define the average percentage change of the economy ($\text{Avg}_r^{out}(m)$) outputs after the shock . And it can be calculated as follows:

$$\text{Avg}_r^{in}(m) = 1 - \frac{1}{SR^2} \sum_{s} \sum_{i,j} \frac{a_{ij}^{sr}(m)}{a_{ij}^{sr}(0)} \qquad \text{Avg}_r^{out}(m) = 1 - \frac{1}{SR^2} \sum_{s} \sum_{i,j} \frac{a_{ij}^{rs}(m)}{a_{ij}^{rs}(0)}$$

[15] To calculate the average percentage change we have included only non-zero elements of the interindustry trade matrix.

Similarly, we define the average percentage change of inputs and output available to the industries as:

$$\text{Avg}_i^{in}(m) = 1 - \frac{1}{RS^2}\sum_j \sum_{r,s} \frac{a_{ji}^{rs}(m)}{a_{ji}^{rs}(0)} \qquad \text{Avg}_i^{out}(m) = 1 - \frac{1}{RS^2}\sum_j \sum_{r,s} \frac{a_{ij}^{rs}(m)}{a_{ij}^{rs}(0)}.$$

The average percentage change of intermediate inputs measures how the shock impacts the inputs needed by industries in a given country. When one assesses the impact of the shock arising from the limitations on a county's imports and, therefore, the lack of the intermediate inputs needed, the appropriate measure is Avg_r^{in}. Similarly, average percentage change due to shock of intermediate outputs Avg_r^{out} shows the reduction of intermediate outputs produced by this given country, and it may be used to measure the shock effect from the limitations on export from a given country.

3.3 Results

We present the results based on the proposed methodology, starting with the quantitative description of the interindustry trade network evolution. We provide evidence of the development of the network resiliency to the shocks arising from eliminating industries from the interindustry trade network. After that, we turn to the analysis of shock propagation, and how it may affect the interindustry trade if there are no substitutes for the inputs. Motivated by the Russian invasion of Ukraine in 2022 and subsequent sanctions imposed on Russia, we model how the termination of trade with Russia as an exporter or import may affect other countries. Furthermore, since Russia was the largest exporter of fossil fuels, including coal, oil, and natural gas, in 2018 International Energy Agency (2019), we analyze the propagation of shock originating from the termination of trading relationships with fossil-related industries in Russia. Finally, we look at the evolution of the dependency on fossil-related industries of the largest fossil fuel exporters worldwide.

3.3.1 Interindustry trade network evolution

Network resilience refers to the ability of the network to withstand and recover from disruptions or failures that may occur within the network. In our study, a disruption implies a node removal from the network. It means that the trade with the industry terminates in both directions. We have evaluated the network resiliency when 10% and 20% of the nodes are removed from the network. And, we evaluate the network resiliency to the targeted attacks based on a node's Page-In-Rank centrality (Figure 3.5).

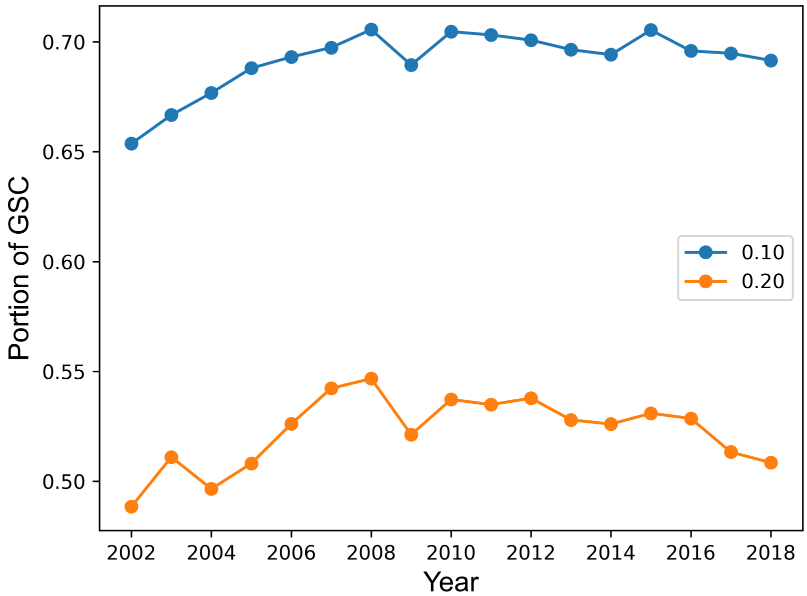


FIGURE 3.5: Evolution of global interindustry trade network resiliency when 10% a 20% of nodes are removed based on Page-In-Rank centrality.

Our findings demonstrate that the network ability to withstand disruptions has improved over the considered time frame, as evidenced by the increased resiliency observed when 10% of nodes were removed. However, no such improvement was observed when 20% of nodes were removed. In addition, our results suggest that the network response to the global financial crisis of 2008 was delayed by one year, resulting in a decrease in its ability to withstand disruptions.

3.3.2 Shock propagation modelling

We applied the developed model to the data on global interindustry trade to get further insights into how shock may propagate. In the section 3.2.2 we showed that the average shortest path length from 2002 to 2018 equals three. It means that, it takes three nodes on average to reach every other node in the network. That is why we consider shock propagation only to the third-order neighbors.

3.3.2.1 Excluding Russia from interindustry trade

After Russia invaded Ukraine, several countries, including the USA and European Union Members, imposed sanctions on Russia Minami Funakoshi and Deka (2022), including trade sanctions aimed at limiting trading relationships with Russia.

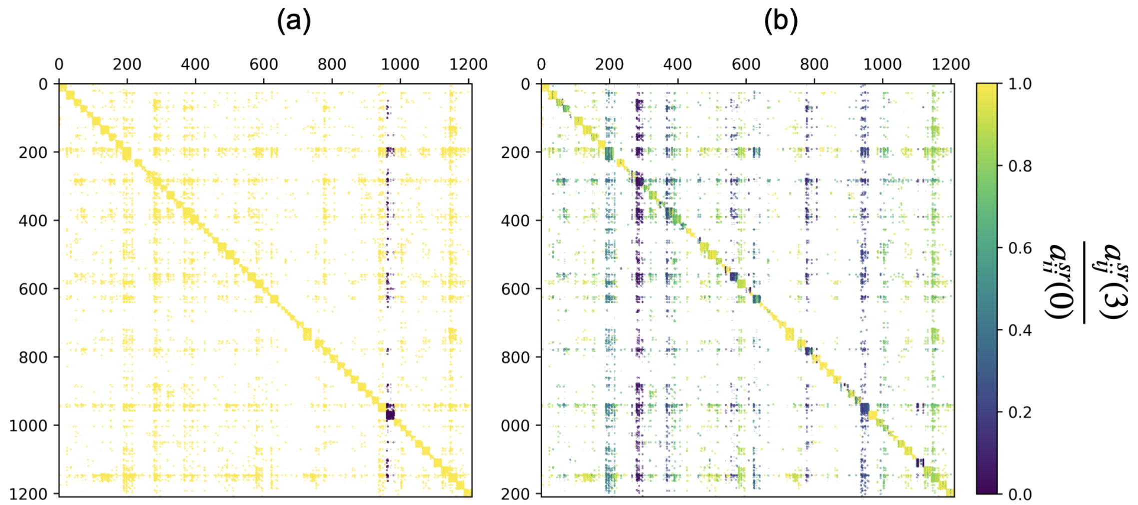


Figure 3.6: The average percentage change due to the shock propagation of third order when Russia is excluded as importer (a), and exporter (b) in 2018

So, we begin with a case where Russia is eliminated from the global trading network while keeping the trade within the country. We modeled what happens if every country terminates trade with Russia, where Russia behaves either as an importer Figure 3.6 (a) or an exporter Figure 3.6 (b) in 2018. Also, we simulated the shock propagation to the third-order neighbors, and the results are presented on the Figure 3.7.

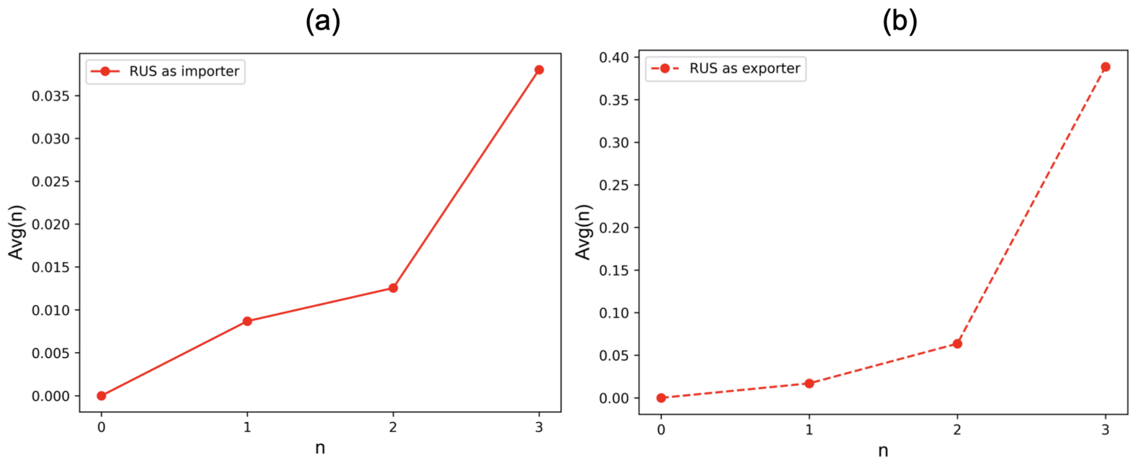


FIGURE 3.7: The average percentage change due to the shock propagation of order n when Russia is excluded as importer (a), and exporter (b) in 2018

For the zero-order neighbors, trading relationships are still the same since we did not consider any trading partners yet. Then, the shock occurs for the first-order neighbors, limiting or terminating trading relationships between a starting node and its nearest neighbors. It causes deficits in the inputs of the first-order neighbors resulting in decreased outputs serving as inputs for other industries. Those deficits cause the shock to spread to the second-order neighbors through the lack of inputs from the first-order neighbors. And the shock spreads further, causing avalanching effects. As shown on the Figure 3.7, we can see that the average percentage change in the trade relationships for the first-order neighbors is relatively small for imports and exports. As shown in Figure 3.7, when we remove Russia from the global interindustry trade, its volume changes by 0.9% and 1.8 % for the import and export correspondingly. Indeed, Russia's share in global trade, which includes added values as well, is larger than the volume of interindustry trade, and the share of Russia in total world import is only 1%, and in export, it is 2% WITS in 2018. However, when the shock propagates further, its impact on interindustry trade strengthens and accounts for 4% and 39% when the shock reaches the third-order neighbors, assuming there are no substitutes for the lost inputs.

In 2018, the share of the inputs from foreign countries in Russia equaled 5% on average in Russia, and the most dependent industries on the import are *Transport equipment* with 20%, *Textiles, textile products, leather and footwear* with 16%, and *Machinery* with 15%. However, when there are no imports to Russia, the average percentage change in its intermediate inputs equals 100%. At the same time, if there are no exports from Russia, the average percentage change in its intermediate outputs equals 23%. Comparing those two cases reveals that imposing sanctions on imports to Russia is more efficient and leads to minor losses in global interindustry trading relationships than when Russian export is sanctioned.

Excluding Russian fossil-related industries from interindustry trade Since Russia was the largest exporter of fossil fuels in 2018 International Energy Agency (2019), we also look into how the termination of trade with Russia as an exporter of products from fossil-related industries, including *Mining and quarrying, energy-producing products* (Figure 3.8 (a)) and *Coke and refined petroleum products* (Figure 3.8 (b)), influences other countries. The industry *Mining and quarrying, energy-producing products* includes non-cooking coal, crude oil, and natural gas. And the industry *Coke and refined petroleum products* includes processes products from crude petroleum and coal UN (2008).

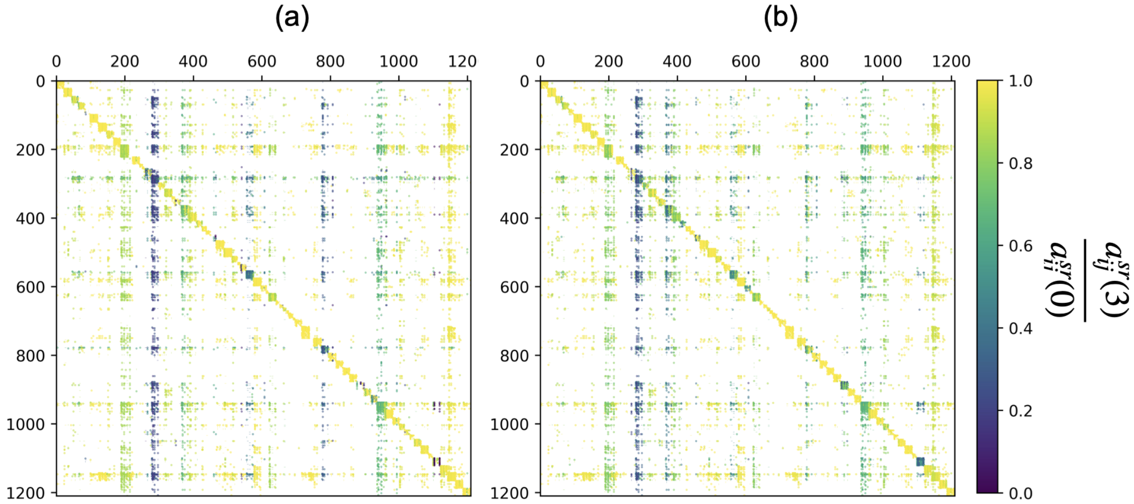


FIGURE 3.8: The average percentage change due to the shock of the third order when Russia is excluded as exporter of products from *Mining and quarrying, energy-producing products* (a) and *Coke and refined petroleum products* (b) industries in 2018.

Supposing that *Coke and refined petroleum products* industry is excluded from the interindustry trade, while it is maintained inside Russia. In this case, the average percentage change equals 20%. At the same time, the average percentage change in Russian intermediate outputs equals 15%. Similarly, suppose the *Mining and quarrying, energy producing products* industry is no longer integrated into the global interindustry trade network. In that case, the average percentage change equals 21% for the world, while for Russia, it equals 14 %.

Based on our findings, if we remove *Coke and refined petroleum products* industry from international trade, the most significant impact is on *Commercial and public services*, *Transport*, and *Electricity, gas, steam, and air conditioning supply* industries, with the average percentage change of inputs available to them 0.24%, 23%, and 23%, respectively. And the average percentage change of the inputs available to the economy is most considerable for Lithuania, Bulgaria, and Slovakia with 90%, 83%, and 82%.

Similarly, the results for *Mining and quarrying, energy producing products* are comparable to those when excluding the *Coke and refined petroleum products* industry, with the most affected industries being *Coke and refined petroleum products*, *Electricity, gas, steam, and air conditioning supply*, and *Commercial and public services* with the average percentage change of inputs available to them of 32%, 29%, 27%. According to our simulation, the average percentage change of inputs available is 100%, 99%, and 89% in Latvia, Bulgaria, and Hungary.

It's important to note that these numbers may not accurately reflect the current situation as they are based on data from 2018, and we assumed that there are no substitutes for the lost trade flows. Therefore, it's crucial to approach these figures with caution.

Evolution of reliance on fossil-related industries To evaluate the dependency of global interindustry trade on fossil-related industries, we selected the four largest fossil fuel exporters, including Australia (AUS), Canada (CAN), Russia (RUS), and Saudi Arabia (SAU). In addition to those countries, we also included the USA since its share in the global energy trade rapidly grows U.S. Energy Information Administration (2020). The average percentage change of the global interindustry trade network is biggest for *Mining and quarrying, energy-producing products* industry when Russia is excluded, followed by Saudi Arabia and Australia (Figure 3.9 (a)). In addition, we showed that the highest average percentage change of the global interindustry trade network for the *Coke and refined petroleum products* are caused by excluding this industry located in Australia, followed by Saudi Arabia and Canada (Figure 3.9 (b)). Over the considered period, the average percentage change of the global interindustry trade network caused by the exclusion of those industries in the given set of countries rose.

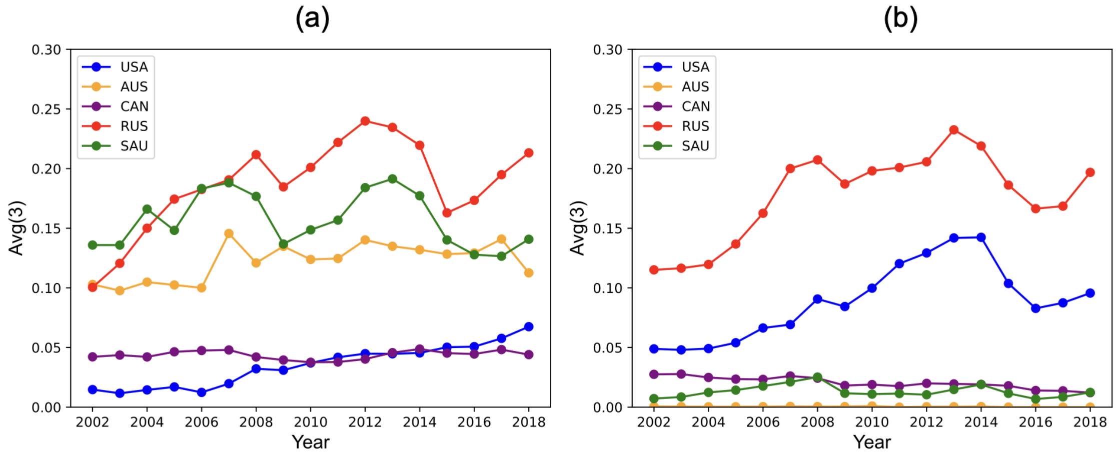


FIGURE 3.9: Evolution of the average percentage change due to the shock propagation of the third order when *Coke and refined petroleum products* (a) and *Mining and quarrying, energy-producing products* (b) industries in 2018 are excluded from the international interindustry trade.

We also explore the impact of excluding the *Mining and quarrying, energy producing products* industry from interindustry trade, with a focus on its location, based on data for 2018. The analysis reveals that the average percentage change in interindustry trade volume varies depending on the shock origin. Specifically, when the industry located in the USA is excluded from interindustry trade, the average percentage change in available inputs is highest in Mexico, Canada, and Chile, with values of 50%, 50%, and 23%, respectively. Similarly, excluding the industry in Canada results in the highest average percentage change in available inputs for Iceland, followed by the USA and Mexico, with values of 46%, 22%, and 19%. Likewise, excluding the industry in Saudi Arabia from trade leads to the most significant effects in South Africa, followed by South Korea and Taiwan, with values of 48%, 35%, and 32%. Finally, when the industry located in Australia is excluded from trade, the most affected countries are Argentina, Taiwan, and India, with the average percentage change in available inputs of 80%, 60%, and 60%.

The analysis indicates that among industries that may experience a drop in available inputs due to the withdrawal of *Mining and quarrying, energy producing products* from interindustry trade are most significant for *Coke and refined petroleum products*, followed by *Commercial and public services* and *Electricity, gas, steam, and air conditioning supply*. These findings suggest that the influence of excluding this industry from trade is consistent across the globe, but values of the average change in available inputs and the location of the industry are not crucial factors in determining which other industries will be "infected" around the world.

The impact of excluding the *Coke and refined petroleum products* from interindustry trade is contingent upon its location. Notably, when the industry is situated in the USA, its elimination leads to the most substantial percentage change in the available inputs in countries such as Costa Rica, Mexico, and Chile, with values of 90%, 58%, and 58%, respectively. Additionally, excluding the industry in Canada results in the most substantial percentage change in the available inputs for Iceland, followed by the USA and Mexico, with values of 14%, 7%, and 6%, respectively. Similarly, excluding the industry in Saudi Arabia from trade has the most significant impact on India, followed by France and the rest of the world, with values of 11%, 4%, and 3%, respectively. Analogous to the *Mining and quarrying, energy-producing products* industry, the effect on other industries worldwide does not exhibit significant disparities, and the obtained results suggest that the influence of excluding this industry from trade is consistent across the globe, with the most affected industries being *Coke and refined petroleum products* itself, followed by *Commercial and public services*, and *Transport*.

3.4 Conclusions

Our paper had two main objectives. Firstly, we aimed to investigate the evolution of resiliency to shocks in the global interindustry trade. Secondly, we aimed to create a model that considers the consequences of terminating trading relationships between industries, focusing on the limitations or terminations of trading relationships between fossil-related industries in countries that account for the largest share of the fossil fuels trade, including Russia, Saudi Arabia and Australia, and other industries in different countries.

Our analysis of the global interindustry trade network from 2002 to 2018 revealed that its resiliency to attacks had improved for thresholds of 10% and 20%. However, the global crisis of 2008 had a negative impact on the network resiliency, potentially due to the decrease in the number of participants and interindustry trade volume.

We also developed a framework to model the propagation of shocks through global interindustry trade up to order m, originating either from importers or exporters. This framework can be used for the normative or positive analysis of the termination or limitation of trading relationships due to trade barriers, which may be introduced due to a change in political or environmental agenda.

The developed model was employed to examine the scenario where Russia is eliminated either as an importer or exporter of goods in interindustry trade. The analysis revealed that the discontinuation of imports to Russia resulted in the most significant average percentage decrease in interindustry trade within its boundaries, as compared to the effect on global interindustry trade, which was relatively modest. Conversely, the elimination of Russia's export capacity was associated with substantial losses in the volume of global interindustry trade while having a minimal impact on interindustry trade within Russia.

The present study utilized the developed model to demonstrate that the average percentage change in the trade volume of international trade increased over time for fossil-related industries such as *Mining and Quarrying, Energy-Producing Products*, and *Coke and Refined Petroleum Products* located in the USA, Australia, Canada, Russia, and Saudi Arabia. This finding suggests that the global interindustry trade has become increasingly susceptible to disruptions arising from these industries. Additionally, the analysis revealed that the average percentage change in available inputs for economies is more reliant on the location of the eliminated industry than on the industry that is affected.

However, our analysis has several limitations. One limitation is that we assumed that any lost trade volume could not be compensated, meaning that our framework is only suitable for examining the short-term effects of shocks. Additionally, we did not consider how new trading relationships could be established, and incorporating this aspect could enable us to analyze both short-term and long-term effects. Finally, our analysis was conducted at a high level of industrial aggregation, which makes it impossible to track how trade restrictions on specific goods could impact the interindustry trade network. Nonetheless, our developed framework could be applied to a lower level of industrial aggregation in the interindustry trade model to examine these effects.

4 | The Energy Transition and Shifts in Fossil Fuel Use: The Study of International Energy Trade and Energy Security Dynamics

Berdysheva, S.; Ikonnikova, S.

The global energy mix is undergoing an accelerating transformation driven by new resources, novel technologies, and climate change-related commitments. Changes in the use and availability of energy resources have affected fossil fuel (coal, oil, and natural gas) trade patterns. Some economies enjoy increasing energy independence, whereas others become more dependent on imports to satisfy their energy needs. Using 2000–2018 United Nations Commodity trade and International Energy Agency energy- and monetary-flow data, we examine the evolution of the international network of energy flows to reveal new patterns and understand their energy security implications. We explore how the growth in US unconventional resources, European Union renewable energy, China's natural gas consumption, and changes in other energy flows affect individual economy positions and trade-network connectivity. Testing the small-world property helps us understand the diffusion of new technologies, including energy-demand electrification and renewable energy adoption. We introduce a modified energy-security index to highlight the interplay between fuel and import diversification and domestic supply and consumption. We conclude with insights about the projected energy transition and its effect on the future the international network of energy flows and energy security.

4.1 Introduction

The past two decades have brought dramatic changes to the energy landscape. Technological advances helped untap abundant unconventional natural gas and oil resources and led to nearly exponential growth in renewable energy production. The shares of unconventional resources in global natural gas and oil production have grown from less than 1% in 2000 to about 15% and 12%, respectively, in 2019 U.S. Energy Information Administration (2020). Over the same period of time, the supply of renewable energy has increased by about 50%, reaching 5% of global total primary energy consumption International Energy Agency (2018) . An increased number of countries have adopted the Paris Agreement and have introduced policies to encourage and accelerate deployment of low-carbon technologies. The process referred to as "the energy transition" aims to decrease carbon and other emissions, mitigating climate-change issues. The associated change in the energy mix would also help to achieve UN Sustainable Development Goals. The transition is underpinned by supply-side transformation along with demand-side reconfiguration. Developments in battery and other energy-storage technologies, adoption of circular economy principles, and employment of innovative materials are among the key drivers behind the decreasing energy intensity of global GDP.

Innovations and new energy-resource exploitation have been unevenly introduced and implemented among the countries. While many developed countries have been deploying clean-energy resources and reducing final energy consumption, fast-growing developing countries demand increasing volumes of energy, much of which are imported. Over the past two decades, the European countries have reduced their consumption by an average of 5%: this includes the Netherlands (-20%), Portugal (-16%), and Germany (-5%) BP. In the meantime, the leading Asian economy, Japan, has decreased its energy demand by about 15%; Canada has led the transition, reducing its energy intensity by almost 20%, whereas the United States has managed to decouple its energy consumption from GDP and has held its energy demand fairly flat International Energy Agency (2019). In contrast, primary energy use in China and central Africa has almost tripled, and in India, eastern Africa, and the Middle East, primary energy use has more than doubled, pushing global energy use to a 40% increase. Only partially satisfied by the increase in the renewable energy supply, the growing energy demand brings new disturbances to the status quo of fossil fuel trade Gonzalez-Salazar et al. (2018).

Those changes in the global and individual-economy energy-mix compositions have been enabled by and have impacted the international energy trade. The shifts in energy demand and supply have reshaped the network of fossil energy flows among countries Chen et al. (2018) . Energy is the critical resource for national economies and plays a pivotal role in economic development as well as the climate-change agenda. The structure of the energy supply has a profound effect on energy security and is an important factor in geopolitical decisions. Hence, understanding the effect of changes brought by the energy transition, especially the energy-trade evolution and its energy-security implications, is crucial for revealing new vulnerabilities and risks Finley (2019).

The purpose of this paper is to provide new insights about the effects of the energy transition and fossil-fuel use on the international energy trade and on energy security. First, we want to update and enhance the quantitative description of the INEF. By examining the evolution of fossil-fuel trade patterns, we intend to reveal whether energy and economic integration continues or the transition away from coal, substituted by natural gas and renewable energy resources, has weakened existing trade links and reduced network connectivity. Second, we aim to explore the changes in individual economy positions in natural gas, coal, and oil trade, which are crucial for understanding the competition and price dynamics. Particularly, we want to reveal whether the European Union's recent energy and environmental policies, China's strategies for carbon neutrality, and U.S. energy exports have affected the metaphorical systemic gravity of those regions and their suppliers. Finally, we tackle energy-security questions focusing on the effect of supply diversification under the changing (traded) energy mix, shifts in production capabilities, and domestic fossil-fuel demand shrinkage.

Economic integration, expansion of fuel transportation routes and infrastructure, demand electrification, and new energy and environmental policies have led to the surge in studies focusing on and emphasizing the geographical aspects of the energy transition Chen et al. (2018), Bridge et al. (2013). The large number of involved countries, the complexity of energy-network flows, and multidimensionality have induced scientists to step away from the traditionally used general equilibrium–based international trade models, turning instead to complex network- and graph-based models instead. Such models could be combined with input–output analysis or other economic approaches to investigate spatial and economic embeddedness of countries and their dynamics Chen et al. (2018). The increasing number of works applying network methods include but are not limited to the following: studies of international trade linkages, interdependencies, and energy communities Kali and Reyes (2007), Zhong et al. (2017); assessments of the carbon footprint, carbon leakage, and environmental impacts of the fossil-fuel trade Gan et al. (2020), Bernard and Vielle (2009), Aichele and Felbermayr (2015) ; and analyses of energy security, environmental regulations, and sustainability Chen et al. (2018), Zhong et al. (2014), Jamasb and Pollitt (2008).

While the diversity of the fast-growing body of literature tries to address the expanding number of relevant questions, several drawbacks call for further contributions. First, the revealed dynamics in the trade and security of supply suggests that the analysis should be regularly updated Finley (2019) . Second, the network models often separate energy and monetary flows, raising the question of how to compare them Sovacool (2011), Kruyt et al. (2009), An et al. (2014), Gao et al. (2015) . Third, with a few exceptions, analyses focus on one particular fuel (e.g., natural gas Chen et al. (2016), coal, or oil) or combine all energy sources together. Such approaches prevent researchers from understanding the role of individual fuels and the importance of their substitutability, which plays a key role in the energy transition Vivoda (2009). Finally, numerous studies on energy security, offering a wide range of security indexes and comparisons of them, traditionally limit their attention to one or two of the following aspects: (1) supply diversification, thus rarely considering the security or vulnerability of exporters; (2) one selected fuel or all fuels without insights about individual fuel contributions; and (3) individual energy-system component changes, namely interfuel substitution, or a change in the domestic demand or supply level Hughes (2009), Sovacool (2013) . However, understanding trade-offs among various energy-security components is essential in the time of the energy transition and developments of new production possibilities Podbregar et al. (2020), Narula and Reddy (2015), Gasser (2020). The study on the global security index study concludes that various measures are required to understand energy security, as countries vary in their capabilities, priorities, expectations, and preferences Azzuni and Breyer (2020).

Our analysis aims at updating the previous studies, filling in the gaps in the existing methodologies and providing an alternative, secure measure useful for all the economies and their diverse transition strategies. Hence, we contribute to this literature in several ways. First, we update the previous studies with recent data on energy production, consumption, and trade, expanding the previously investigated time frame to 2000–2018. We compare the two most-used publicly available databases, that of the IEA and UN Comtrade, linking our study to a large number of the earlier analyses. Furthermore, along with the energy-flow data, we compile the associated monetary flows, enabling deeper economic understanding. Our data analysis helps to enrich the intuitions provided by similar works and to support future studies.

Second, with the data on the individual fuel flows covering a period of two decades, we characterize individual-economy energy systems' evolutions, getting insights about the trade developments, and we relate variation in regional trade dynamics to the evolution of energy-system components. We pay special attention to the centers of gravity within the global energy trade system, including the European Union (EU) with its largest primary energy consumer, Germany, the United States, and China, by tracking the changes in absolute and relative strength of economies. We apply the complex-network method to examine the evolution of trade through the dynamics of strength and connectivity distributions. Then we test the small world property to reveal how the clustering and network distances for different fuels change over time. Commonly used for network description, the small world property indicates trade interconnectedness, tightness of competition, and diffusion efficiency. Hence, in the context of the global energy system, this property helps researchers understand how fast and far-reaching the transition to low-carbon fuels may be.

Finally, we suggest a modified energy-security index, capturing and reflecting developments in demand, supply, and trade. Exporting economies are often advised to diversify their economies, yet existing security indexes are not designed to suggest preferable diversification policies Ross (2019). Building on the classical Herfindahl–Hirschman Index, we offer a measure useful for energy importers and exporters alike. Our index is designed for consistency in discussions among international trade participants, informing them of energy-security implications of the energy transition and trade changes.

The rest of the paper is organized as follows: We start with the compiled data set description discussing the issues associated with the use of two different datasets. Then, we turn to the methodology for the trade and energy-security analysis. We highlight the similarities to and differences from the previous studies. Finally, we present the empirical results, including the conclusions about the overall trade-network development and shifts in energy security across all the considered economies. After that, we characterize dynamics related to the top exporters and importers, focusing on the role of individual fuel trade. We conclude with insights regarding the trends in trade and energy security for individual fuels and their contributions to international energy-system dynamics.

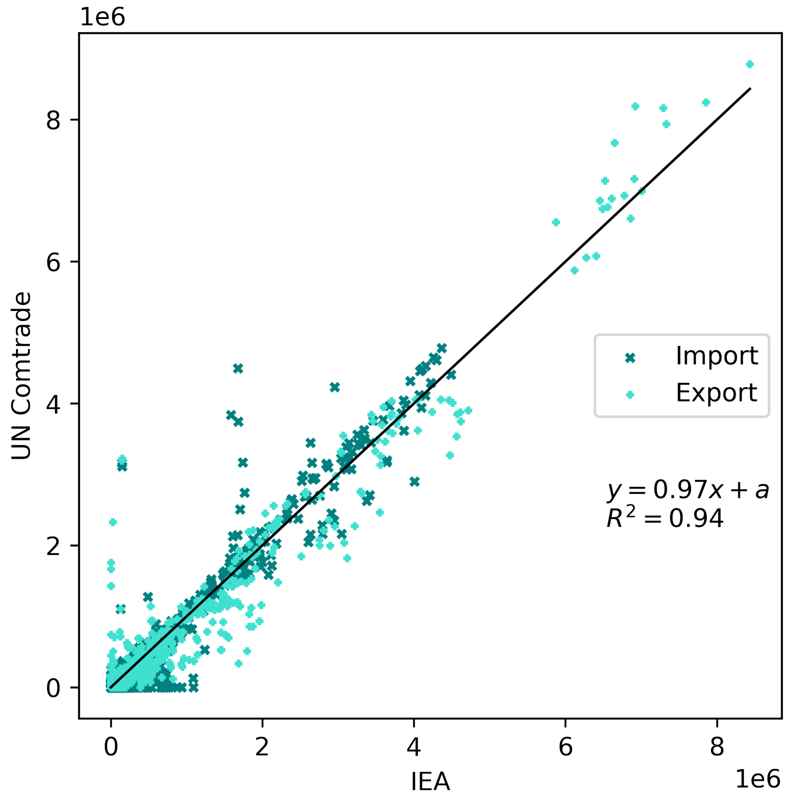


FIGURE 4.1: Comparison of the IEA and UN Comtrade datasets for natural gas data.

4.2 Data

To analyze the international energy trade evolution and its implications, we compiled a comprehensive dataset using the United Nations Commodity Trade (UNC) and IEA World Energy Balances databases International Energy Agency (2019). We retrieved the data describing historical production, consumption, and trade of oil, natural gas, coal, and renewable energy resources. This section describes the selected variables and provides details on the database construction, addressing issues including missing and erroneous data. Further technical details can be found in the Appendix A.3.

4.2.1 Dataset description

For 245 countries included in the UNC and IEA databases, we extracted data for the period of 2000 through 2019 on:

- Total primary energy consumption (TPEC) by energy type,
- Total final energy consumption,
- Domestic energy production for coal, oil, natural gas, and other sources of energy (including RE),
- Import of coal, oil, and natural gas, with economy of origin specified for each flow,
- Export of coal, oil, and natural gas with its destination.

Within and across the databases, different units of measurement are used. For instance, import and export flows are given in kilograms and the U.S. dollar value. For consistency and cross-comparison, we converted all energy units into Joules (J) based on the net calorific values, as described in appendix A.3. In what follows, we distinguish "energy flows" (in J) and "monetary flows" (in USD).

UNC database employs Harmonized Commodity Description and Coding Systems, or HS code, to classify goods and services. In our study, the following codes have been used: 2701 (oil), 271111 (natural gas in liquefied state) and 271121 (natural gas in gaseous states), and 2709 (coal) for correspondence with the previous analogous studies Chen et al. (2018), Gao et al. (2015), Hao et al. (2016).

4.2.2 Data processing and verification

With access to the two databases, we have an opportunity to fill in the gaps in data, detect erroneous data, perform a general verification, and comprise a more comprehensive database. The majority of data categories can be found in both databases; however, the UNC database contains more comprehensive bilateral trade information, whereas IEA has more granular data on produced and consumed energy United Nations Commodity Trade. To combine the data extracts and expand our dataset, in support of a more granular analysis, we checked the data for consistency.

the verification exercise was complicated by the occurrence of erroneous and missing data. So, we test the hypothesis of data compatibility by running a linear regression for the UNC against IEA data Gephart and Pace (2015). We perform this exercise for the entire dataset and for individual classes of data. Thus, the results for the natural gas data, cleaned of outliers, are represented in Figure 4.1. The results of the regression analysis do not allow to reject the hypothesis on the slope =1 for each individual fuel dataset. Hence, we confirm the similarity between the UNC and IEA data and conclude that the two datasets could be merged complimenting each other.

Combining the data allows us to fix various data issues and address problems such as bilateral asymmetry. We find that in some cases, the reported import quantity by economy i from economy j is not equal to the reported export quantity from j to i. We combat such a bilateral asymmetry by averaging over reported quantities or correcting it referring to the second dataset. Further detail on the comparison is provided in Appendix A.3.

We use the final dataset to map energy import and export data and grasp the radical changes in the world energy landscape analyzed in detail in the empirical analysis presented in Section 4.5 (Fig. 4.2).

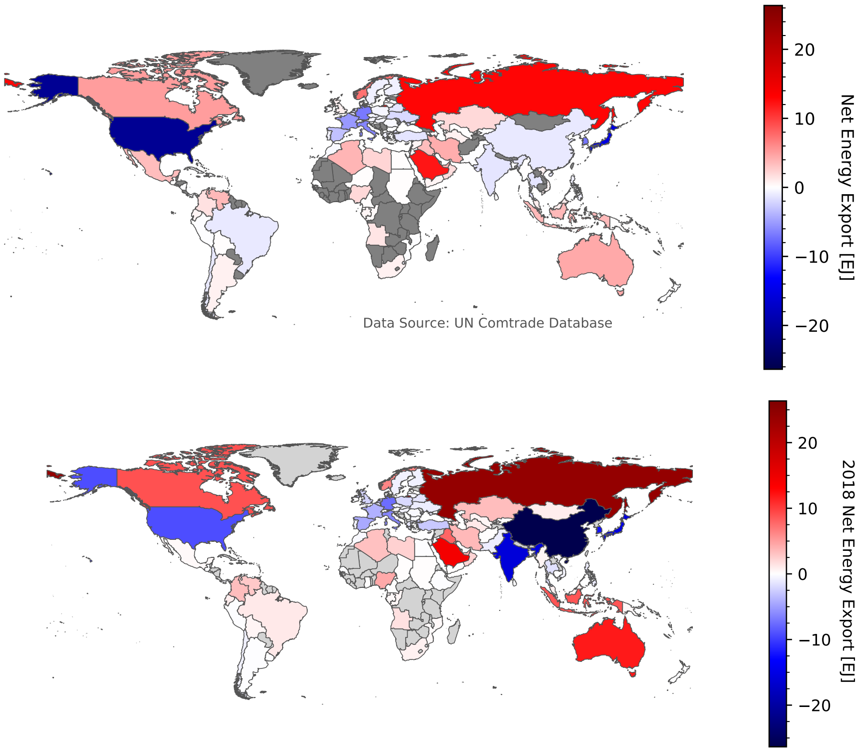


FIGURE 4.2: The maps of energy importers and exporters for 2000 (upper) and 2018 (lower) based on the net fossil fuels flows (in grey are the countries with no data).

4.3 Network analysis

The international energy trade, accounting for almost 90% of the total primary energy consumption, is described by the directed oil, natural gas, and coal flows and can be seen as a network U.S. Energy Information Administration (2020). Such a network, or INEF, is formed by nodes, countries, and links, import and export flows, connecting the nodes. Analyzing INEF as a complex network, we can characterize its structure, detect economically and environmentally relevant properties, reveal trade patterns, and monitor the dynamics. The methodology presented in this section was developed to answer questions relevant to the energy transition and shed light on the impact of shifts in fossil energy use. We introduce concepts to help answer questions such as: Does the regional integration continue or is it disrupted by the reduction in carbon-heavy coal consumption and production? Who are the most pivotal players on the energy market? How do the energy transition and adoption of new technology affect their positions? These and other relevant questions can be addressed. Our goal is to a provide quantitative description of the individual and total energy trade, reveal the channels of its evolution, and track the changes between 2000 and 2019.

To allow for different levels of aggregation, we specify a directed weighted network for individual fuels and all the flows combined. A network N^k for fuels $k \in \{C, G, O\}$ – coal, natural gas, and oil, respectively, is defined by the set of economies $E = \{1.., i, ..j, .., n\}$ and the set of flows $F^k = \{f^k_{ij}\}$ between all the pairs of economies i and j. The matrix, formed by f^k_{ij} elements, is called the adjacency matrix and has zeros on its diagonal. The elements of the adjacency matrix are net flows, so that:

$$F^k = \begin{cases} f_{ij} \geq 0, \text{ while } f_{ji} \equiv 0 \text{ when } i \text{ imports energy from } j \\ f_{ij} \equiv 0, \text{ while } f_{ji} \geq 0 \text{ if economy } i \text{ is exporter for } j \end{cases} \tag{4.1}$$

We use $|\cdot|$ notation to count non-zero elements, i.e. $|f_{ij}|$=1 for all exporters j of economy i and $\sum_j |f_{ij}|$ is the total number of exporters for i. Counting all the non-zero elements, we get the number of importers serving economy i, known as in-degree d^{in}. Summing up $|f_{ji}|$ over all the possible export destinations, we calculate out-degree d^{out}. Combined the two values determine the number of trade links or *net* trading partners, i.e. economy's degree d^k_i:

$$d^k_i = d^{k\,in}_i + d^{k\,out}_i = \sum_{j \in N^k} \left(|f^k_{ij}| + |f^k_{ji}| \right) \tag{4.2}$$

We analyze the evolution of trade connections by examining the dynamics in the number of links, namely looking at changes in individual economy degrees and the global degree distributions. Fig. 4.3 provides an example of the cumulative distribution reporting the number of links associated with a given percent of the total energy traded. The distribution reveals that in 2018, 95% of the total energy traded has been supplied by 22%, or 490 out of 2180, links. The trade links are arranged by the trade volume, with the smallest contributor standing last, depicting the concentration of flows. In what follows, we focus on the essential links falling into the 95th percentile, reducing the size of the network. Such a link cut-off is applied to each fuel separately and recalculated for every year.

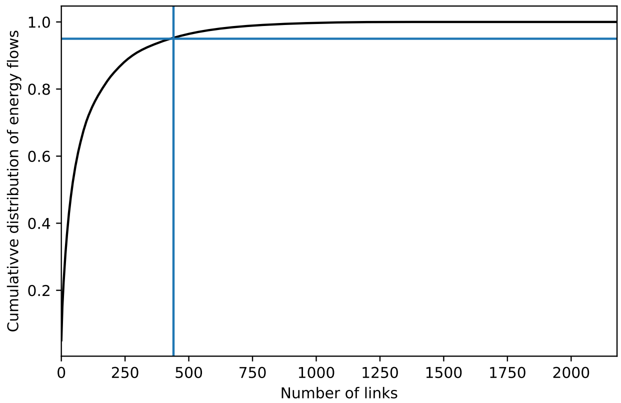


FIGURE 4.3: The cumulative distribution for the total fossil fuels trade in 2018.

The usefulness of the degree analysis is limited because it does not account for flow volumes. To that end, we use the link strength analysis characterizing the trade embeddedness or trade volume. Formally, economy's strength is the sum of its in- and out-strength and is equal to the total trade volume:

$$s_i^k = s_i^{k^{in}} + s_i^{k^{out}} = \sum_{j \in N^k} \left(f_{ij}^k + f_{ji}^k \right), \tag{4.3}$$

where $f_{i\cdot}$ accounts for the out-flows of economy i and $f_{\cdot i}$ measures the inflow volumes.

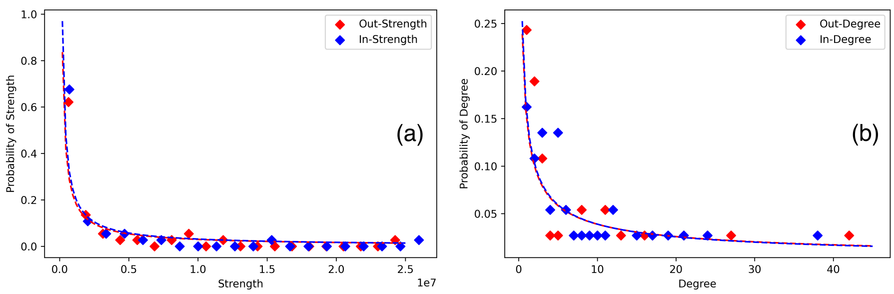


FIGURE 4.4: The degree and strength distributions for fossil fuels energy trade in 2018.

The shape of the degree and strength distributions helps demonstrate the heterogeneity among economies. Thus, the 2018 distributions exhibit the power-law character pointing out to a high dispersion in economies trade positions (Figure 4.4). The majority of economies have less than five trading partners, and only a handful have more than 20 trading partners. Among those highly connected are the major importers, including China, India, Korea, Japan, the U.S., European economies, and the largest exporters, such as Russia, Saudi Arabia, Canada, and Australia. In the results section, we pay special attention to them.

Finally, along with the degree and strength measures, networks can be characterized by density, D, telling us what portion of all possible links has been realized on a given network. For a directed network it is calculated as:

$$D = \frac{\sum_{i \in N^k} \sum_{j \in N^k} f_{ij}}{|E|(|E|-1)}. \tag{4.4}$$

We calculate the INEF density for individual fuels and total fossil energy flows to discuss the changes in the networks connectivity and globalization trends.

4.3.1 Testing the small world hypothesis

In addition to measuring degrees and strengths, we investigate whether the INEF possesses the "small-world" property. In a small-world network, most nodes are not directly connected, but, if needed, almost any node can be reached by every other through a small number of transitors. Therefore, a small-world network is characterized by (a) short average path length L, implying that trade between any pair of economies involves only a few transitors and (b) high clustering. The latter implies that some economies are highly interconnected in a way that makes them form a single market. The clustering coefficient quantifies how close the trade partners of a given economy from forming a completely connected sub-network. Hence, the small-world measure provides insights about regional network structure and the existence of "trade communities".

Clustering coefficient C is defined by the number of links m_i connecting trade partners of economy i and is averaged over the total number of economies $|E|$, as suggested by Watts and Strogatz (1998):

$$C = \frac{1}{|E|} \cdot \sum_{i \in N^k}^{n} \frac{2m_i}{d_i(d_i-1)}. \tag{4.5}$$

The small-worldness can be quantified with coefficient σ - a measure comparing the clustering and the average path length of a given network to an analogs of an equivalent random network. We choose the Watts-Strogatz (WS) approach to generate the random network with the same number of nodes, links, and the average degree, as proposed by Watts and Strogatz (1998), and calculate the small-world coefficient:

$$\sigma^k = \frac{C^k(N^k)}{C(N^{random})} / \frac{L^k(N^k)}{L(N^{random})}, \tag{4.6}$$

The network is said to possess the small-world property if the coefficient $\sigma > 1$ Humphries and Gurney (2008). Despite its sensitivity to network size, σ serves as a helpful measure showing the changes in the network connectivity. In reality, the small-world feature is often associated with networks consisting of several interconnected communities. The increase in the number of links or closer integration often results in higher σ or strengthening of the small-worldness. However, if the location of the new links does not shorten the average distance and/or coincides with the disappearance of links and decreasing clustering, the small-worldness may be weakened. Figure 4.5 demonstrates how the INEF has experienced a reduction in the small-worldness. To develop further understanding of the drivers behind the small-world measure reduction, in Section 4.5 we provide the clustering coefficients and the average shortest path lengths estimates for individual fuel networks.

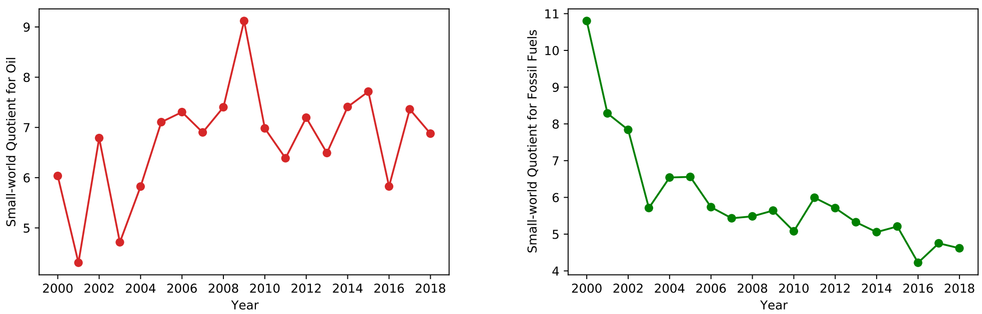


FIGURE 4.5: The evolution of small-world coefficient for oil (left) and the INEF (right).

The small-world effect has some crucial implications. First of all, the closer the small-world quotient to 1, the more interconnected the economies and the faster diffusion processes are expected to be. Thus, the small-world coefficient dynamics may explain the spread of new technologies, price signals, or the effects of regulation. Furthermore, recent research has been focusing on the link between the network robustness or shock-resiliency and small-worldness

Peng et al. (2016). Those implications call for special attention to the small-world property in the context of the energy transition.

4.4 Energy Security Analysis

Energy security is a complex concept brought in the context of geopolitical and policy discussions, highlighting risks of physical availability of energy. The energy transition has led to an expansion of the security notion to embrace other elements critical for the energy supply. The enhanced definition includes the following aspects of energy security Kruyt et al. (2009), Asia Pacific Energy Research Centre (APERC) (2007):

- Availability – geological existence of a resource in some location.
- Accessibility – geopolitical aspect of the access to energy.
- Affordability – economical aspect of energy availability.
- Acceptability – environmental and societal preference.

Approaches to energy security vary and may focus on a single or multiple elements of the above-provided definition. In our study, we consider energy security indicators based on bilateral energy exchange between economies, neglecting the issues of availability and acceptability.

The network analysis, presented in the previous section, provides insights into the changes in the overall network and reveals economies' embeddedness in trade. The degree and strength analysis also points to economies with central and peripheral positions and diversification of trade. However, to understand the security implications of the network evolution, additional measures are required. Various energy security indexes, calculated with the datasets used for the network analysis, are commonly applied to quantify and compare energy security among the economies or changes over time Gasser (2020). We start this section by reviewing the widely known HHI-based indexes. We discuss their weaknesses and introduce new modified measures, namely consumption security index (CSI) and production security index (PSI). To develop intuition and highlight the advantages of the proposed indexes, we construct an illustrative example with interpretations linked to the energy transition strategies of some economies. We conclude with insights employed in the next section, where we present our empirical results.

4.4.1 Traditional HHI-based indexes

Various indexes, public and commercial, have been developed to quantify energy security. Several previous studies focusing on the INEF have estimated the classical Herfindahl-–Hirschman Index (HHI), also known as Simpson index, relating security to supply concentration Chen et al. (2018), Gao et al. (2015), Gasser (2020). However, the obtained results have not been addressing security concerns raised in the energy transition discussions, suggesting the need for improvements in the index or the use of different measures.

Traditionally, the HHI index quantifies trade concentration and is calculated, solely, based on the trade flows of type $l \in \{C, G, O, FF\}$ for coal, natural gas, oil and aggregation over fossil fuels, correspondingly, as:

$$\mathrm{HHI}^{l}_{imp:i} = \sum_{j \in N^l} \left(\frac{f^l_{ij}}{\sum f^l_{ij}} \right)^2 \qquad \mathrm{HHI}^{l}_{exp:j} = \sum_{i \in N^l} \left(\frac{f^l_{ij}}{\sum f^l_{ij}} \right)^2 \tag{4.7}$$

To analyze the import competition, the summation over all the import sources j is used. The same expression is applied to quantify economy's j export concentration $\mathrm{HHI}^{l}_{ex=j}$, in which case the summation shall be done over all export destination i.

The expression (4.7) reveals that HHI does not account for any changes in domestic production or fuel consumption mix. If an economy decreases its energy import, e.g., thanks to the growth in domestic energy production, it is likely to limit the number of trading partners. In this case, HHI might increase, suggesting the worsening energy security situation. While this, indeed, leads to the higher *import* vulnerability, the overall economy security may improve with the energy self-sufficiency. Hence, the HHI index would lead to misleading conclusions. Another situation in which HHI could result in erroneous conclusions is when an economy serves as a hub.

Those and other related considerations have led to the development of another class of security index, including consumption into consideration, and hence, resolving "hub" situations. It has also been realized that energy security shall account for fuel substitutability and energy mix. These arguments have led the International Energy Agency to develop the HHI-based energy security index (ESI), combining the concentration index for individual fuels with supplier-economy risk weights, r_j, and fuel shares in the supply:

$$\mathrm{ESI}_i = \sum_{k\in\{C,G,O\}} \frac{Qc_i^k}{Qp_i^P} \cdot \left[\sum_{j\in N^k} \left(r_j \frac{f_{ij}^k}{\sum f_{ij}^k} \right)^2 \right], \tag{4.8}$$

Here Qc_i^k is the primary energy consumption of fuel k, whereas (Qp_i^P) is the total primary energy supply in economy i. ESI has been designed to measure energy security from an importer perspective and does not provide an appropriate measure for energy export risk exposure. Changing weather conditions, global crises, and fuel preferences make exporting economies face acute supply risks and speak of supply security. Thus, the COVID-19 pandemic has resulted in a sharp drop in oil use, having a detrimental effect on the oil exporters. Besides, economy-specific import constraints are a commonly used instrument for political and economic pressure Ikonnikova and Zwart (2014). Among the most well-known examples are financial and trade sanctions on Iran that were imposed starting 1970, reintroduced by the U.S., the E.U. several times. Iran suffered from the curtailed export, forced to search for new buyers for its oil and develop new supply routes, Katzman (2021). Under the energy transition, some exporters become especially vulnerable, facing changing fuel preferences and shrinking supply opportunities. The carbon neutrality targets adopted by the increasing number of economies suggest changes in the future coal production and trade possibilities, calling for coal export security analysis.

Hence, the enhancements that make ESI superior to HHI are not sufficient to address exporters' concerns. ESI captures the changes in the consumption mix but is ignorant to possible changes in the production mix, determining exporters' supply risk exposure under the energy transition. To tackle that issue, we introduce modified security indexes distinguishing exporter and importer perspectives.

4.4.2 Importer and exporter perspective on energy security

It is logical to assume that just as exporters may mitigate their supply risk by managing their trade flow concentration. However, we have already established that concentration of trade flows alone, is not sufficient to reflect the security. One have to consider the weight of the trade in economy's energy balance. In other words, the concentration index shall be modified to account for total energy. Importers improve their security by becoming self-sufficient, for instance, decreasing the share of consumption imported. Therefore, importer index shall be consumption-based measure, we call it consumption security index (CSI). In contrast, the exposure of exporters stem from the share of the total producition traded. So exporters would be less vulnerable the more of their produciton is consumed domestically or spread among a larger number of buyers. Hence, exporter or production security index (PSI) shall weigh the export concentration against the fuel produciton.

We incorporate the above thinking into our analysis and modify the traditional HHI and HHI-derived indexes normalizing the trade concentration to the total production of fuel $k \in \{C, G, O\}$, Qp_i^k, and total fuel consumption, Qc_i^k, deriving the security index for exporters and importers as:

$$\mathrm{PSI}_i^k = \sum_{j \in N^k} \left(\frac{f_{ji}^k}{Qp_i^k} \right)^2 \qquad \mathrm{CSI}_i^k = \sum_{j \in N^k} \left(\frac{f_{ij}^k}{Qc_j^k} \right)^2, \tag{4.9}$$

Note that the presented indexes allow to identify hub economies with index values > 1. For economies that import or export energy for own utilization CSI_i^k and PSI_i^k values are in the range $[0, 1]$.

It is important to recall that the difference between the domestic production and consumption, for any given fuel type, is determined by the sum of net flows, or strength in a particular direction:

$$Qc_i^k - Qp_i^k = \sum_{j \in N^k} (f_{ij}^k - f_{ji}^k) \tag{4.10}$$

Although developed with importer and exporter perspectives in mind, both indexes may be applied by the economy serving as a hub or have strong export and import trade connections. An excellent example of such an economy is the U.S., strengthening its trade position with the growing domestic production of renewable energy and unconventional oil and natural gas resources, increasing exported volumes. The fossil energy resource depletion in the past has made the U.S. rely on energy import, a substantial portion of which is reserved despite its own growing supply.

The modified indexes help distinguish between in- and out-flow related risks informing economies, like the U.S., on the security management needs in different directions. Yet, as suggested by ESI, an aggregate index evaluating the total energy portfolio security is needed for the economy-wide analysis. The IEA approach is valuable but, as noted, suffers from the production mix ignorance and inability to isolate the role of the consumption versus production mix changes. We try to address those issues with our total consumption and total production security indexes, CSI_i^P and PSI_i^P, respectively.

Formally speaking, different types of fossil fuels are not perfect substitutes. If economy i imports f_{ij}^G from economy j, while economy j exports energy type O from economy i, such that $f_{ij}^O = f_{ij}^G$ in energy value, the loss of a trade partner would require both economies to make additional investments to compensate for the energy supply losses. This issue is often addressed by introducing of the conversion efficiency, η, or degree of substitutability. Thus, for any two energy types k and $m \in \{C, G, O\}$:

$$f_{ij}^P = \sum_k \sum_m (\eta_{km} \cdot f_{ij}^k - \eta_{mk} \cdot f_{ij}^m). \tag{4.11}$$

The change in energy generation and utilization technologies makes η a dynamic variable whose value may change across the economies. Without loss of generality, we leave the technical details outside the scope of our paper and, in what follows, assume perfect substitutability, i.e. for $\forall$ $k, m:\ \eta^{km} \equiv 1$. In this case, $f_{ij}^P = \sum_k f_{ij}^k$ and the flow of fossil fuels between any two economies i and j is equal to the sum of net flows of coal, natural gas, and oil and equation (4.10) is rewritten as:

$$Qc_i^P - Qp_i^P = \sum_{j \in N^k} \sum_k (f_{ij}^k - f_{ji}^k) = \sum_{j \in N^k} f_{ij}^P. \tag{4.12}$$

Then, we can estimate an economy's aggregate energy security calculating security for individual fuels and combining those values based on the fuel shares in the total consumption share and production:

$$\text{CSI}_i^P = \sum_k \frac{Qc_i^k}{Qc_i^P} \left[\sum_{j \in N^k} \left(\frac{f_{ij}^k}{Qc_i^k} \right)^2 \right] \qquad \text{PSI}_i^P = \sum_k \frac{Qp_i^k}{Qp_i^P} \left[\sum_{j \in N^k} \left(\frac{f_{ij}^k}{Qp_i^k} \right)^2 \right]. \tag{4.13}$$

The derived aggregate indexes are able to account for the changes in consumption and production mixes. Notably, the indexes will show whether the growth in domestic production and the resulting increase in self-sufficiency is compensated or outweighed by the change in the trade flow concentration stemming from the drop of some trade-partners, e.g., for political or environmental reasons.

4.4.3 Illustrative example

To develop the intuition behind the introduced security indexes and ease their comparison to the established HHI-based measures, we construct an illustrative example. Consider an economy, named A, consuming two fuels, c and g. Let there be two exporters, supplying A, called B and C. Assuming all the economies have similar political risk, we normalized it to one: $r_A = r_B = r_C = 1$. We evaluate the changes in energy security caused by the energy transition, e.g. changes in teh fuel use, and the growth in the domestic production, resulting in the energy trade evolution.

Focusing on the import-oriented indexes, we calculate CSI, PSI, ESI, and HHI. We start by considering the indexes for one fuel, *Case* 1 ((Table 4.1). The consumption of that fuel is set to be fixed $Qc^P = 6$; we drop the superscript to save on notations. We distinguish four possibilities for trade and production to develop. In cases 1.1 and 1.2, economy A imports more than half of the consumed energy, whereas in cases 1.3 and 1.4, the economy reduces its import in half, raising own energy production. In all the cases, the economy may either import the required energy from one exporter or split the export equally between B and C, but the volume of import is twice as high in the first two cases. The situation described can be associated with the developments in Germany and the U.S., reducing their natural gas imports and growing domestic energy production.

TABLE 4.1 Energy Security indexes for economy A, the case of one fuel.

Case	**Import to A**	Qp^P	Qc^P	**HHI**	**CSI**$_i^P$	**ESI**
1.1	$f_{AB} = 2$; $f_{AC} = 2$	2	6	0.5	0.22	1.5
1.2	$f_{AB} = 4$; $f_{AC} = 0$	2	6	1.0	0.44	3.0
1.3	$f_{AB} = 1$; $f_{AC} = 1$	4	6	0.5	0.05	0.75
1.4	$f_{AB} = 2$; $f_{AC} = 0$	4	6	1.0	0.11	1.5

The results presented in Table 4.1 provide two important insights. First, we see that the HHI values have been affected only by export distribution and not by the change in the domestic production, as discussed earlier in this section. Second, ESI has the same values in cases 1.1 and 1.4, suggesting that the increase in own production balances out the loss associated with the increased import concentration. Hence, the substitution of an import flow with the own production has no impact on the security. In contrast, our CSI shows that domestic production strengthening the security of supply. The latter argument is frequently brought in political debates. Furthermore, comparing the ESI and CSI estimates, we find that both have the highest values in case 1.2 and the lowest in 1.3. Hence, we confirm IEA insights about the role of diversification and the total import size.

Next, we turn to *Case* 2 to explore the role of the energy mix and its effect on security under the energy transition. Here, we assume again that the total consumption level remains unchanged and distinguish five possible scenarios with respect to domestic production and import diversification. In cases 2.1-2.3, economy A keeps the domestic production unchanged, whereas in cases 2.4 and 2.5, it is increased by 25%. Case 2.1 is a business-as-usual situation, with all other cases representing the situation when carbon-heavy C fuel has to be substituted by G in the consumption profile. The substitution leads to the changes in trade, i.e. introduction of $f^G_{AB} = 2$ or $f^G_{AB} = 1$ and $f^G_{AC} = 1$ in cases 2.2 and 2.3 accordingly. Hence, in cases 2.2 and 2.5, the economy diversifies its imports for both fuels. Case 2.4 corresponds to the situation, when the economy loses one of its trading partners and starts to import more from the remaining partner. We associate this situation with the developments in China; the country has been reducing its coal consumption, increasing natural gas use and trade.

TABLE 4.2 Energy Security indexes for economy A, the case with two fuels.

Case	**Import to** A	Qc^k_A	Qp^P_A	Qc^P_A	$\mathbf{HHI}_A$	$\mathbf{CSI}^P_A$	$\mathbf{ESI}_A$
2.1	$f^C_{AB} = 2$; $f^C_{AC} = 2$ $f^G_{AB} = 0$;$f^G_{AC} = 0$	$Qc^C_A = 6$ $Qc^G_A = 2$	4	8	0.5	0.17 0	0.75
2.2	$f^C_{AB} = 2$; $f^C_{AC} = 0$ $f^G_{AB} = 2$;$f^G_{AC} = 0$	$Qc^C_A = 4$ $Qc^G_A = 4$	4	8	0.5	0.17	0.75
2.3	$f^C_{AB} = 1$; $f^C_{AC} = 1$ $f^G_{AB} = 1$;$f^G_{AC} = 1$	$Qc^G_A = 4$ $Qc^G_A = 4$	4	8	0.5	0.06	0.50
2.4	$f^C_{AB} = 1$; $f^C_{AC} = 0$ $f^G_{AB} = 1$;$f^G_{AC} = 0$	$Qc^C_A = 4$ $Qc^G_A = 4$	6	8	1.0	0.03	0.67
2.5	$f^C_{AB} = 0.5$; $f^C_{AC} = 0.5$ $f^G_{AB} = 0.5$;$f^G_{AC} = 0.5$	$Qc^C_A = 4$ $Qc^G_A = 4$	6	8	0.5	0.02	0.33

The estimation results of all the situation reported in Table 4.2. Examining the multi-fuel situation, the weakness of HHI becomes even more apparent, as the index takes only two values. The ESI estimates, however, reveal some similarity to our CSI, but we first discuss the differences to make the rationing behind our modification more transparent. First of all, one may notice that the largest ESI value is assigned to case 2.1, whereas CSI reaches its maximum in case 2.2. This result implies that our security index values fuel diversification more than supply concentration. In other words, the more balanced the energy mix is, the better it is for energy security. Second, it appears that ESI is loses its sensitivity to supply diversification, as the volume of import decreases, as follows from the minor difference between the values in cases 2.4 and 2.5. In comparison, our index continues to show the benefit of the supply diversification boosted by the increased fuel variety. Lastly, CSI value in case 2.3 is lower than in 2.4, with the opposite true for EIS. Similar to the one fuel case, it highlights the greater importance of the domestic production boost over the import concentration.

Hence, we conclude with several essential insights supported by our modified indexes. First, without changes to the total consumption and production levels, fuel diversification would have a greater impact on energy security than import diversification. Second, a boost in domestic production brings more security benefits than fuel or supply diversification. Hence, the investments in renewables improve the energy security of any economy, along with the increase in domestic production of other energy sources. The transition away from coal would help improve energy security in countries, with coal outweighing other fuels in the energy mix. For instance, countries like China would benefit from a more balanced consumption mix. However, reducing the equality among fuels due to the transition and witnessing new dominant fuels, like natural gas, economies may experience worsening of their security situation. With those insights, we proceed to the empirical analysis to test and verify the usefulness of our network description and developed security indexes.

4.5 Results

Following the developed methodology, we start the presentation of results with the quantitative description of the INEF. We provide insights about the evolution of individual fuel and altogether fossil energy trade, paying particular attention to the changes associated with the production and consumption energy mix changes accompanying the energy transition and adoption of technologies. We discuss the global trends and country-specific developments and trends, reporting the estimates for the top 10 global economies, which are also the largest energy consumers. Then, we proceed with the results for energy security, focusing on the interplay between fuel and supply diversification and changes in energy mixes. We select the most noticeable results, keeping further observations and results in Appendix A.4.

4.5.1 Energy transition and trade network evolution

To put the observed developments into context, it is worth recalling that the world population and the global GDP continue to grow, explaining the increase in the global primary energy consumption. Although fossil energy continues to be the dominant energy source, the share of renewable and nuclear energy steadily increases. For the analyzed period of 2000 – 2019, RE generation has grown by $\sim 50\%$; yet, despite the accelerated installations of RE capacities, about $\sim 95\%$ of energy demand is covered by fossil fuels BPS (2020). Hence, the world increasingly relies on fossil energy, and almost 85% of it is delivered through the international trade network.

4.5.1.1 Flow analysis

The compiled dataset allows us to see how the volume of energy trade has witnessed an almost 50% increase between 2000 and 2019. This trade growth has not been even across the fuels: the coal trade has risen by about 150%, natural gas – by close to 70%, whereas oil has increased by less than 30% (Figure 4.6). The changes in coal and natural gas trade have roughly coincided with the changes in the monetary flows. In contrast to the mild growth in trade, monetary flows associated with oil have undergone dramatic perturbations over the last two decades.

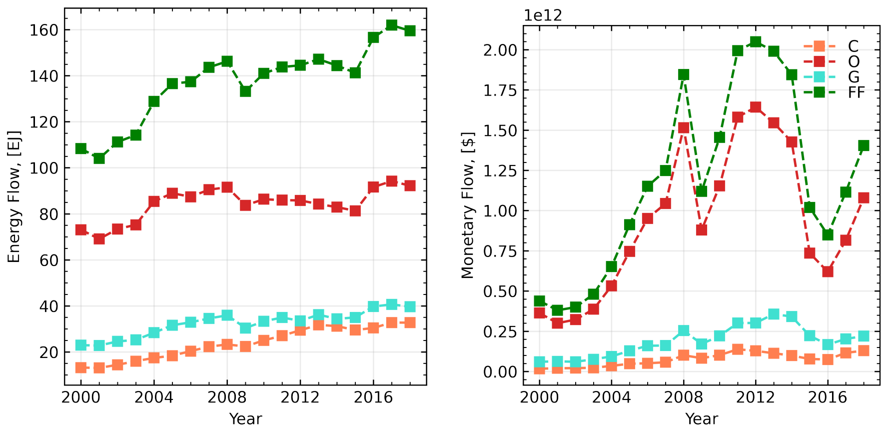


FIGURE 4.6: The evolution of fossil fuel trade in energy (Exajoules $= 10^{18} J \simeq 10^{15} Btu$) and monetary (USD 10^{12}) terms.

To understand such uneven developments, we turn to the network analysis and explore the changes in the number of links and the associated flows, namely degrees and strength distributions. First, we observe that the increase in the trade volume has been accompanied by the increase in the number of economies involved (Figure A.1). Yet, looking into the truncated network, applying 95% cut-off, we find that the scope of the network has hardly changed. But the number of trade destinations for natural gas has increased by 55%, for coal by mere 10%, and for oil went down by almost 10%.

While the number of nodes for coal remained fairly stable, the percent of links responsible for the 95% of flows dramatically decreased, suggesting the market concentration related to the changes in China's and India's consumption, as we discuss next. The expansion of the liquified natural gas trade and the emergence of new gas spot markets stands behind the upward trend or decrease in flow concentration. Finally, we see a possible explanation for the fluctuations and the rise in oil monetary flows in the oil trade concentration as depicted by the statistics on the links.

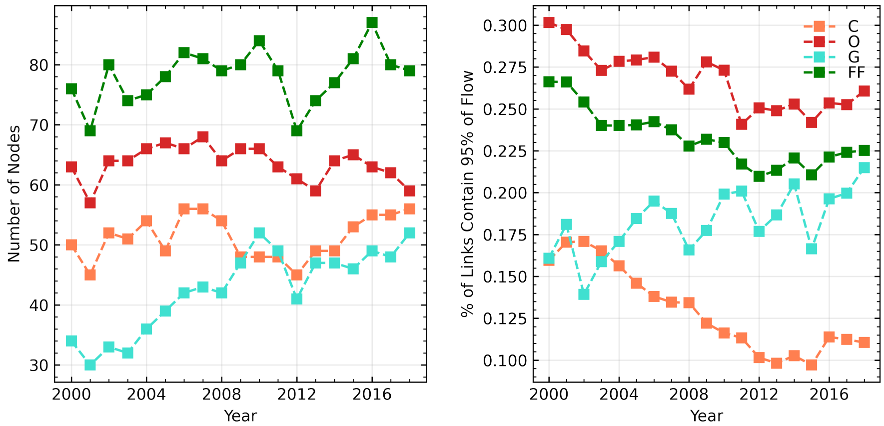


FIGURE 4.7: Changes in the number of nodes and links accounting for 95% of INEF.

As marked in the methodology section, we have to check the distribution of strengths for a better understanding of the trade dynamics. We focus on the results for China (CHN), Europe (EU) and Germany (DE), the United States (USA), Russian Federation (RUS), and Australia (AUS). The results shall give us insights into whether the concentration has increased or the reduction in the number of links has led to the unification of flows. The shape of cumulative energy flow distribution has already suggested that there are only a few major players in the network (Figure 4.3). Investigating the changes in country strengths, we, therefore, turn to the top ten economies. We estimate and report the in- and out-strengths for the largest importers and exporters (Figure 4.8). The presented plots reveal that two main results. First, we find that the total energy strength distribution is driven by the oil (Figure 4.9) flows surpassing other fuels by volume and monetary values by far. Second, we see that oil importers have increased in size and become more homogeneous. In other words, the number of large consumers increased, and those consumers became more comparable in size. Thus, China has grown its oil consumption, while the U.S. and EU have been slowly decreasing its demand. The changes on the export side have been less dramatic, with the exception of the emergence of a new exporter – the U.S.. Such evolution in strength helps explain the oil price dynamics, highlighting the role of buyer vs. seller competition.

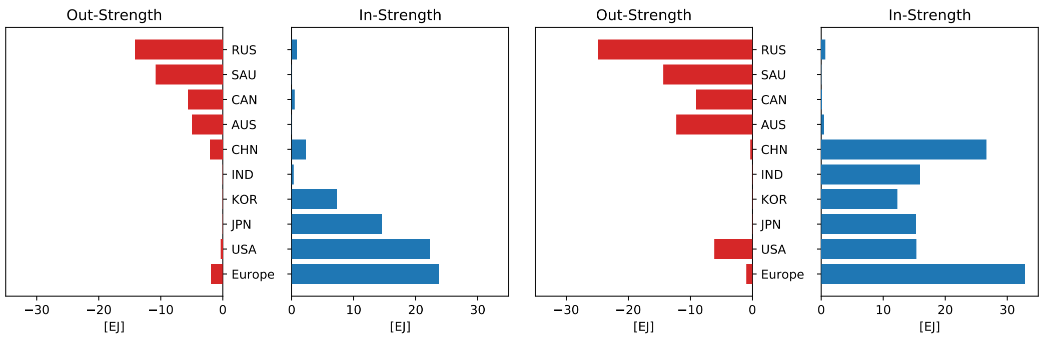


FIGURE 4.8: The change in the fossil fuels trade concentration from 2001 (left) to 2018 (right).

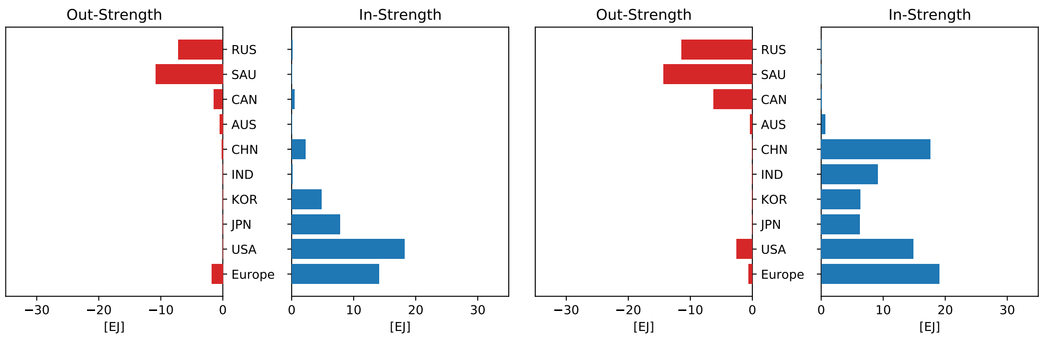


FIGURE 4.9: The change in the oil trade concentration from 2001 (left) to 2018 (right).

Similarly, we examine the distributions and their dynamics for natural gas and coal networks. We confirm the original intuition that the development of the liquefied natural gas trade has resulted in the increased natural gas network density and connectivity (Table 4.3). Intensified electrification worldwide and the energy transition have contributed to the homogenization of natural gas import flows. The enhanced ability to grow domestic production, owing to the unconventional resources, has mitigated the increase in absolute strength of natural gas compared to oil. Transition away from coal for environmental reasons, like in China and Germany, or economic, like in the U.S., has coincided with the growth in coal power generation in Asia. As a result, both in- and out-flows have become more uniformly distributed. The densities of coal, natural gas, and oil networks decrease, fluctuate, and grow, correspondingly, with the overall the INEF density going up.

TABLE 4.3 The evolution of networks densities for coal, natural gas, oil and fossil fuels networks.

Year	D^C	D^G	D^O	D^{FF}
2000	0.045	0.026	0.033	0.038
2010	0.050	0.026	0.037	0.039
2015	0.044	0.029	0.036	0.041
2018	0.040	0.028	0.041	0.042

The concentration of oil and coal flows is often linked to their price dynamics, e.g. as discussed by Fattouh (2007). Yet, the energy network literature rarely includes monetary flows data. We address that weakness of the previous studies, like Chen et al. (2018), reporting on the monetary flows associated with individual fuels as well as the total energy trade (Figure 4.6). Combining the strength and degree analysis with the monetary observations, we find that the inequality in import and export are responsible for the observed monetary flow dynamics. But the pressure or boost to the prices may also stem from the inter-fuel network developments. Thus, we highlight the reduced weights of oil flows coupled with the homogenization of imports and exports. These findings justify our equal attention to import and export concentration and consumption and production mixes in the energy security analysis.

4.5.1.2 Small-worldness

Networks for different types of fossil fuels provide the grounds for the analysis of trade communities and trade structure dynamics. The characteristic feature used in such analysis is small-worldness. The higher the small-world coefficient is, the larger is the size of communities in the network and the smaller the characteristic path between them. We describe the trade evolution addressing the question on whether the developments in consumption and fuel transportation infrastructure boosted the energy integration and trade globalization. We calculate the clustering coefficients and the average path lengths for individual fuels and plot the evolution of the small-world coefficient for natural gas and coal (Fig. 4.10).

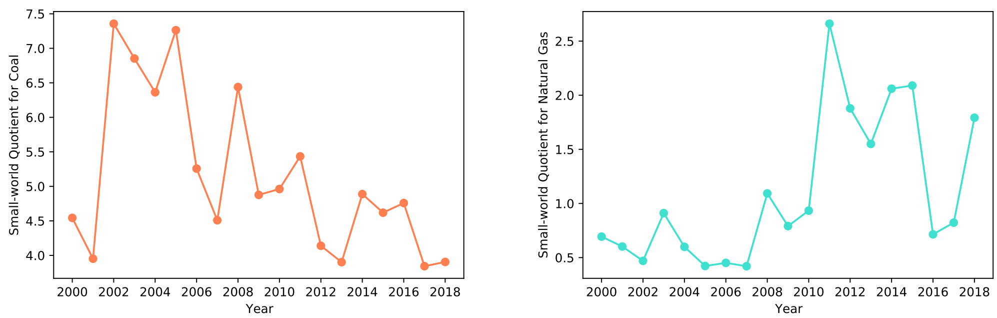


FIGURE 4.10: The evolution of small-world coefficient for coal (left) and natural gas (right).

Figure 4.5 reveals that during the considered period, small-worldness σ is decreasing for the fossil fuels network. This decrease is primarily driven by the developments in the coal trade. Pressure on establishing new coal trade relationships, the decrease in demand, and the removal of some destinations lead to the strengthening of distanced regional communities. At the same time, the growth of the LNG trade has turned the natural gas trading network into a small-world network with an increasing number of destinations and links. Before the LNG trade expansion, the size of communities was smaller, while the distance between them was larger when compared to the present-day natural gas network. However, this growth of the small world coefficient for the natural gas network has not compensated for the lost trading relationships in coal networks.

The network analysis helped us to reveal the following significant trends. First, we established that the number of network participants had been slowly increasing. The trade embraces almost the entire world; yet, only a small number of economies continue to hold the position of gravity centers, including China, the U.S., the European Union, India, Australia, and a few others. We revealed that the transition away from coal by the major consumers had a weakening effect the trade integration leading to increased trade regionality. The development of natural gas resources and technologies, in contrast, has led to the increased global integration and the emergence of new trade channels. Finally, we notice the redistribution in oil trade flows resulting in the unification among the major oil importers and the emergence of the U.S. as the new exporter. The homogenization in the buyer market is likely to explain the monetary flow fluctuations. With those observations, we proceed with the energy security analysis. Further details are represented in appendix A.3, Table A.4.

4.5.1.3 Energy security overview

To get a general picture of how energy security evolves, we start by presenting the estimated aggregate CSI and PSI indexes distributions for the entire network (Figure 4.11). We show the violin plots depicting the change in CSI and PSI distributions over time and allowing for their cross-comparison. Hence the PSI and CSI help to find detect a small number of energy hubs, for instance, the Netherlands, with index values over 1. Along with that, we the results for the HHI, calculated based on the energy and monetary flows (Figure 4.12).

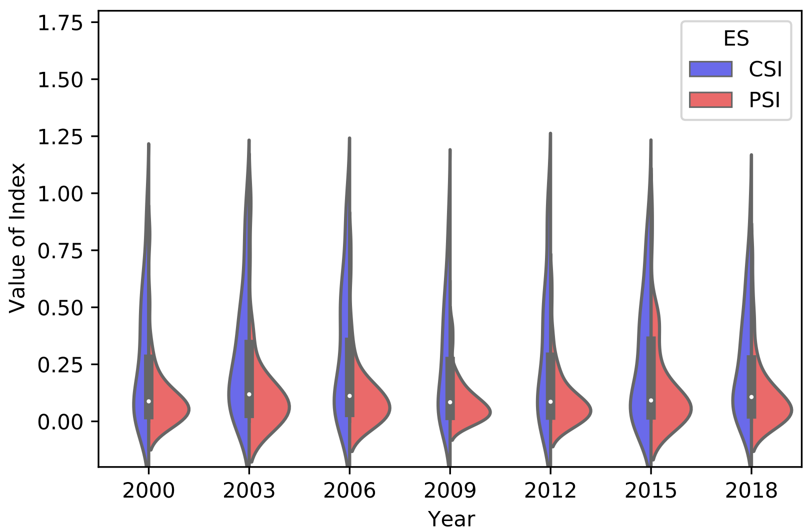


FIGURE 4.11: Distributions of country PSI and CSI based on the aggregate fossil energy trade.

Examining the modified index estimations, we make two interesting observations. First, see that CSI has a longer distribution tail and features of a log-normal distribution. It implies that a larger number of consumers have supply-related concerns. In contrast, the smaller number of net exporters tend to be reasonably well secured with much lower exposure to supply risk. That suggests other than environmental reasons for the energy transition by the net energy importers. Thus, over the past two decades, the mean value of CSI has decreased by 7%, indicating that the overall position of energy-importing economies has improved, whereas the mean value of PSI has gone up by 13%, implying weakening of the energy-exporting economies positions. Second, we see the impact of the negative oil price drop impact on exporters' security in 2015, which is likely to be seen in the recent COVID-19 time data once it becomes available.

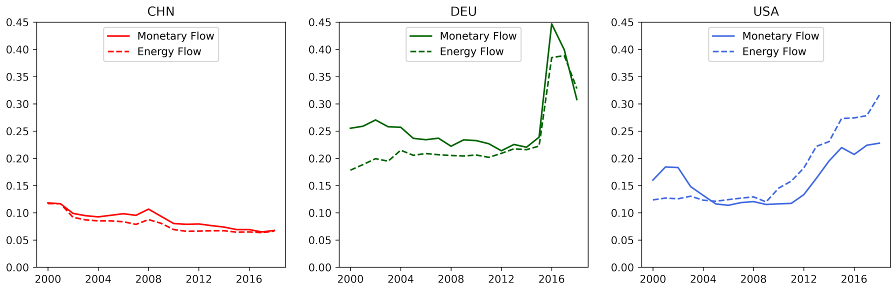


FIGURE 4.12: The evolution of individual country HHI for the fossil energy import.

Turning to HHI results, we confirm that HHI has low sensitivity to the on-going developments associated with the energy transition and changes in energy use. However, the exercise using energy and monetary flow helps to answer sometimes brought critique, showing the close correspondence in the values calculated with the two flows. For comparison, we present the HHI based on monetary and energy flows for natural gas (Figure 4.13). It enables us to show how the differences in price for a single type of energy are less than for all fossil fuels.

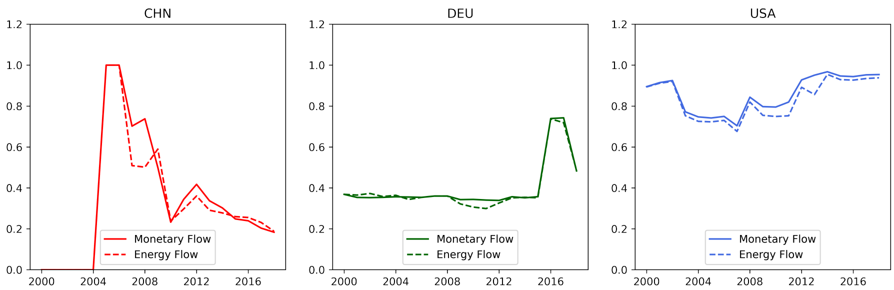


FIGURE 4.13: The evolution of individual country HHI for natural gas.

4.5.1.4 Energy security: Individual country analysis

To get further insights about changes in energy security, we turn to the security assessments for the largest importers and exporters, China, Europe, and the U.S. (see Figure 4.8). Most of the countries play either a net importer or exporter roles in the considered period of time. However, thanks to the unconventional resource production growth, the U.S. has become the net fossil fuels exporter in 2019 U.S. Energy Information Administration (2020)). We use the unique opportunity and examine the U.S. security development in the course of its conversion, including the country into the set of importers and exporters.

To start our discussion with the description of the total primary energy consumption, TPEC, focusing on the shares of fossil fuels in the energy mix. Figure 4.14 shows how China's TPEC has been continuously increasing, supporting its fast GDP growth. However, aggressive investments in nuclear and renewable energy, including hydro, have helped the country break the increasing trends. And since 2011-2012, China has been slowly decreasing the share of fossil fuels in TPEC. In 2019, before the COVID-19 disruption in power generation and consumption coal accounted for 59% of China's total energy consumption, about 1.5 percentage points down on the previous year. So, for almost a decade China has been gradually reducing the share of coal in its energy mix and decreasing its consumption in absolute terms too. That transition has been supported by the growing share of low-carbon and energy, including natural gas, hydro, solar, and wind, which accounted for 23% of the total energy consumption. This trend has been mainly supported by the transition away from coal (Figure 4.16). That led to slow down the rising vulnerability in coal import, as indicated by CSI.

It is crucial for energy security analysis to recognize that the substitution of fossil fuels boosted the country's reliance on domestic production. However, the limitations in coal use could not be compensated solely by renewable and nuclear energy production. Since 2011, China has been increasing its natural gas production, consumption, and import. In total, the dependence of China's economy on natural gas has soared along with its security index, implying the increased exposure to supply risk (Figure 4.22). With a somewhat similar situation around oil, China's aggregated energy security index is going up, confirming and explaining the concerns raised in the country's energy transition and development strategy. Hence, our index and analysis go in line with the current observations and reflect real-world developments. In contrast, IEA's measure has hardly captured the dynamics and cannot provide a clear explanation to the standing concerns. China's ESI shows minor fluctuations around a relatively constant level (Figure 4.15).

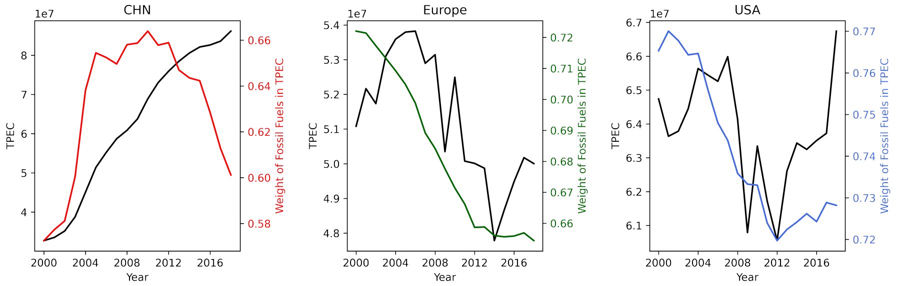


FIGURE 4.14: The evolution of the TPEC and the share of fossil fuels in TPEC.

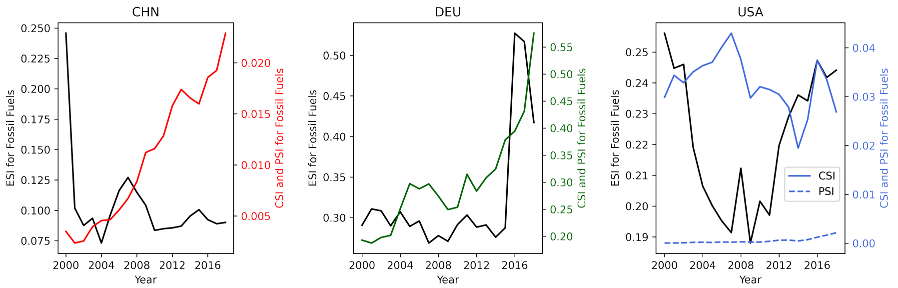


FIGURE 4.15: Comparison of ESI and CSI dynamics.

Analyzing the energy mix dynamics for Europe and Germany specifically, we first confirm the widespread image of the region as the pioneer in the energy transition. Energy efficiency measures and carbon-reduction commitments result in Europe's decreasing TPEC and the share of fossil energy, with some weather-driven fluctuations. Yet, looking at the transition in detail, we reveal that the electrification and the drop in domestic coal production have induced the country to import more coal, even though the total coal consumption decreased. Furthermore, substituting coal consumption, Germany has been increasing the share of natural gas in primary energy imports and consumption. Based on the insights from our illustrative example, the decrease in total domestic energy production, combined with the re-balance in the fuel consumption and import mix, translates into the increasing aggregate and individual fuel CSI. This result goes against the common belief that an increase in RE would inevitably lead to an improvement in energy security. Hence, our analysis informs policy-makers of the importance to account for the changes in domestic production, i.e., whether RE compensates for the lost coal production, consumption mix, monitoring for the dis-balance, and shift towards high reliance on one fuel, and supply diversification.

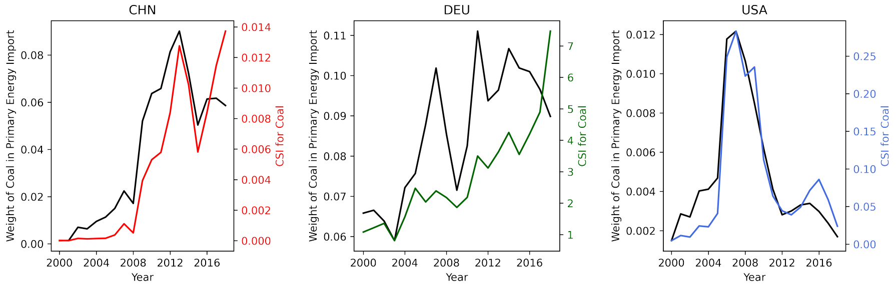


FIGURE 4.16: The evolution of CSI for coal importers.

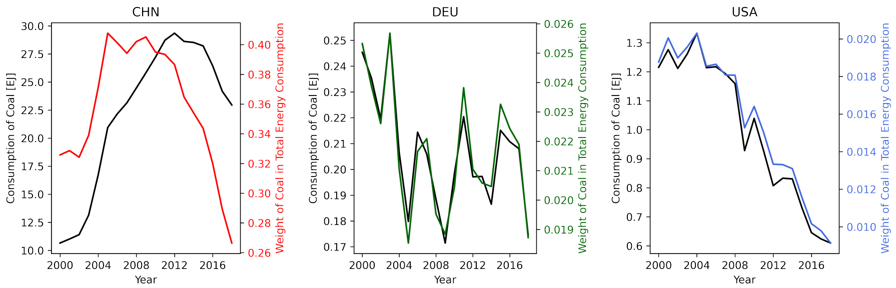


FIGURE 4.17: The evolution of coal consumption and its share in the total energy mix.

Looking into the U.S. security and energy trade dynamics, we must analyze its importer and exporter positions in parallel. Driven by resource availability and market demand, the U.S.'s use of fossil energy has undergone dramatic changes over the past two decades. At the beginning of the millennia, the country faced the depletion of economically recoverable fossil fuel resources and grew energy imports under relatively stable TPEC. After 2005, the shale revolution has enabled the country to elevate domestic energy production, surpassing the depletion of conventional fossil fuels. Thus, the surge in domestic production has led to dramatic natural gas and then oil price drops. With minimum policy support, the U.S. squeezed out coal, substituting it with natural gas. In the last years, the drop in coal demand and flooding of the market with natural gas and oil turned the country into an exporter.

Those developments are reflected in CSI and PSI. The increase in imports in the early 2000s is captured by the increasing aggregate and individual fuel CSI. At that time, PSI has been negligible. The rise in energy-sufficiency has dropped CSI, whereas PSI has been slowly growing, reflecting the export developments. In the last years, CSI eliminating security of supply concerns from the government's agenda. However, the expansion in exports shall soon bring increasing PSI concerns. The COVID-19 situation has demonstrated that the U.S. is already exposed to the export supply risks, calling for fuel or export destination diversification to mitigate future risks.

We shall highlight that while for China ESI demonstrated limited dynamics, the estimates for Germany and the U.S. appear to be misleading. In the time of the domestic production uplift, the U.S.'s ESI has fallen markedly, suggesting the security improvements, which ignore the increasing coal import exposure. In the last few years, the ESI values have been going up without indicating that the vulnerability stems from the export this time. Germany's ESI had remained fluctuating around the same level until 2016 when the conflict with Russia led to the necessity to use other suppliers affecting the concentration component of the index. Hence, we confirm our earlier observation that ESI is limited use in the case of production mix change.

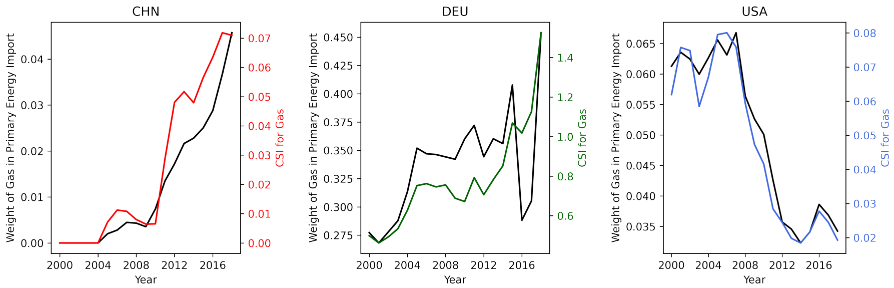


FIGURE 4.18: The evolution of CSI for natural gas importers.

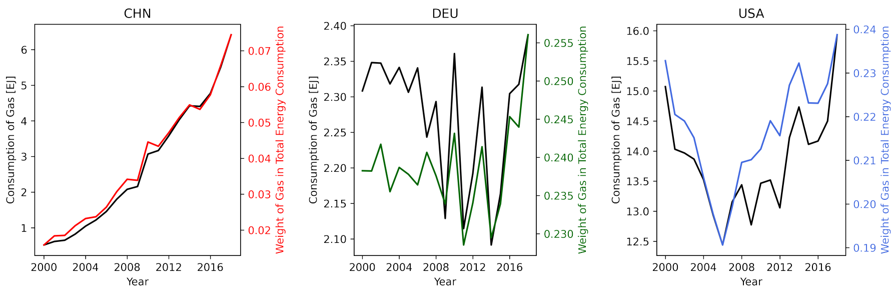


FIGURE 4.19: The evolution of natural gas consumption and its share in the total energy mix.

For the individual exporter analysis, we choose Russia, Australia, and the U.S., highlighting their increasing role in the INEF. Examining the coal production dynamics for those countries, observe a striking correlation with the changes in coal share in the total energy production for all the three exporters. As a result, the PSI dynamics mimics the change in the weight of coal in primary energy export. Thus, the increase in the coal's share results in the increased risk and elevated PSI values. This linkage is only slightly broken in the case of the U.S. due to the natural gas development described above.

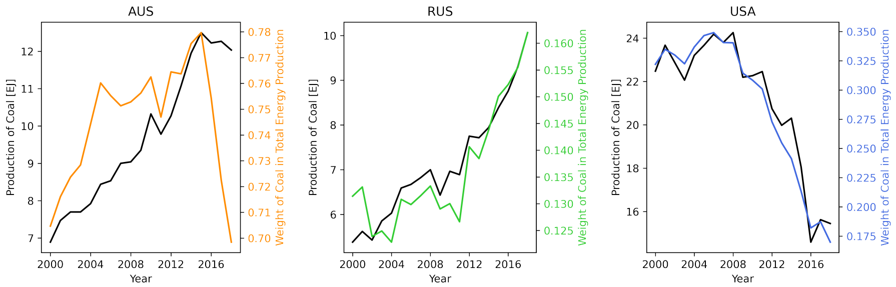


FIGURE 4.20: The evolution of coal production and its share in the total energy mix.

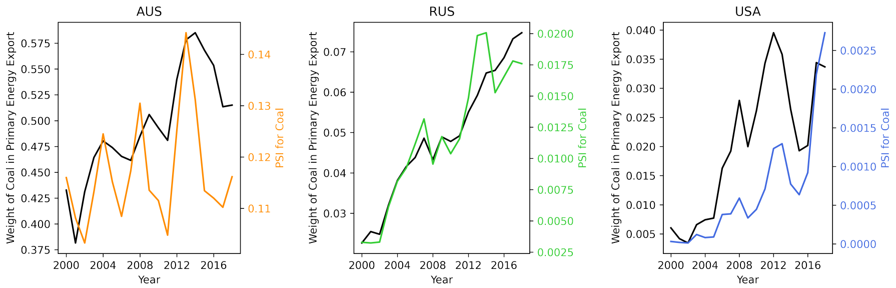


FIGURE 4.21: The evolution of PSI for coal exporters.

The situation is quite similar for the natural gas export. The increase in resource production coincides with export growth. Higher reliance on the trade translates into an upward trend in PSI. Some deviation can only be found in the case of Russia. Growing coal production and export to Asian and European regions surpass natural gas leading to a downward trend in the natural gas share in the total energy production. This dis-balance benefits natural gas security, harming PSI for coal. Hence, the intuition used in the case of importers applies to the exporter's risk assessment. Namely, the disproportional shift in one fuel export would translate into an increased supply, just as the overall increasing reliance on export.

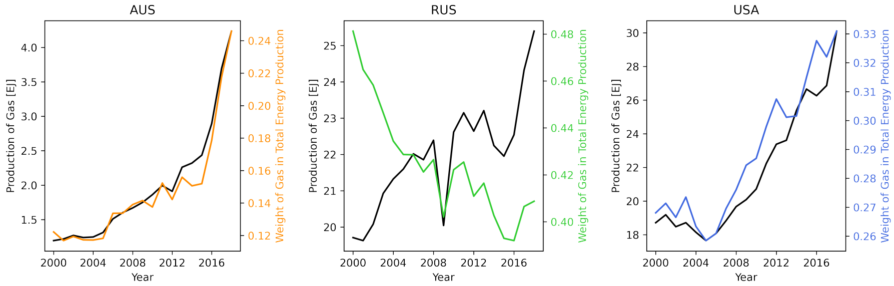


FIGURE 4.22: The evolution of natural gas production and its share in total energy mix.

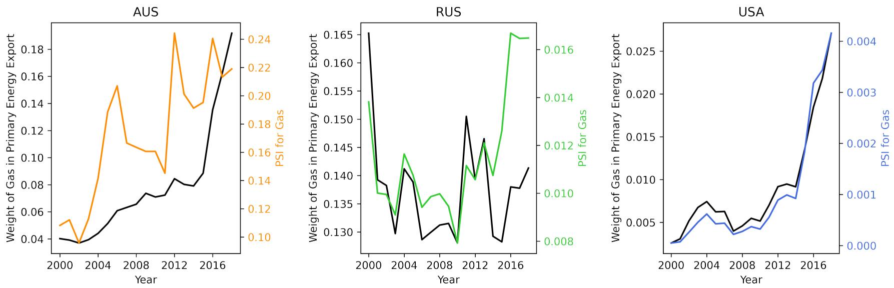


FIGURE 4.23: The evolution of PSI for natural gas exporters

In summary, we find that the increasing number of net energy importers adopt climate goals and implement the energy transition affecting the international trade of fossil energy. Despite the common belief that investments in RE improve countries' energy security, we find that most countries either saw little change in their security or experience its worsening. In line with the developed intuition, we find that reduction in coal consumption shifts the balance in fuel diversification, weakening the security. The increased reliance on natural gas could have had a stronger negative impact on energy security, but the expanding LNG trade, spot trade, and entry of new exporters, such as the U.S., reduce the negative impact. Finally, we find that the growth in the global energy demand induces the major energy exporters to produce more, exposing them to supply risk. But the symmetry in the situation with importers helps keep the global average security close to a constant level.

4.6 Conclusions

Motivated by the observed changes in the global and individual country energy mixes, we aimed at updating the earlier studies describing the effect of the energy transition and shifts in energy use on the international energy trade. To account for the global developments, we had to enhance previous studies, including all the fossil energy sources and all the countries with energy statistics. To embrace the complexity of the trade, we paid attention to dynamics associated with imports as well as exports. Finally, realizing that political concerns regarding energy security often shape trade, we included it in our analysis. While we followed the existing methodology on complex network analysis for the trade network description, we found that the traditionally used HHI-based security indexes are ill-suited for the transition analysis. As a result, we developed modified security indexes useful for importers and exporters alike and applicable to individual fuel analysis or aggregate energy supply description.

Our methodology for energy security analysis and the accompanying illustrative example helped us develop the intuition, which we later verified with the real data analysis. First, our indexes suggest that energy security is highly sensitive to the ability to produce energy resources domestically. Second, (import or export) supply concentration may be outweighed by the dis-balance in fuel (consumption and production) mix. Third, the interplay of these three factors shall be seen in the global interdependency perspective.

In the empirical analysis, we have confirmed the importance of the increasing impact of the energy transition and new technology adoption, translating into the shifts in production and consumption mixes, on the international trade. Thanks to the most up-to-date energy data, we have been able to describe the consequences of China's coal consumption reduction, Germany's boost in renewable energy, and the U.S. export growth. Among the most interesting results, we revealed the homogenization among the major energy importers of oil and natural gas, and continuous regional integration. In contrast for coal, we find the tightening of the regional communities, as the increasing number of countries limits its coal trade.

We find that the transition away from coal pushes energy importers to rely more on natural gas. Countries for which this leads to a reduction in fuel diversification have a negative energy security impact. But the regions for which this implies a transition to a more balanced fuel portfolio and/or ability to boost the domestic production strengthen their security. Hence, we reveal that RE as an instrument to increase domestic energy production improves the energy security situation, but the policies constraining the use of coal, resulting in the decrease in the total energy production and increase in the share of natural gas, shall be warned.

We see several prospective venues for future research. First, we believe that the evolution of energy communities for individual fossil fuels should be analyzed to gain further understanding of coal-related developments and discuss the issues such as carbon leakage. Second, one shall focus on energy conversion and substitutability, accounting for the dynamics related to the introduction and adoption of new technologies. Finally, we find that further insights may be developed about the linkage between importer and exporter energy security.

5 | Conclusion

The energy transition is a complicated process engaging individuals, firms, industries, and countries. On each level, challenges need to be addressed to achieve a sustainable energy transition that would not threaten the security of already existing firms, industries, and countries. On the firm level, it is crucial to understand what regulatory regime could initiate a firm's transition from established, "dirty" technology to an alternative or "clean" technology. On the level of an industry, it is essential to understand how different industries across the globe may react to a limitation or termination of trading relationships between industries, especially if a shock originates from an energy-related industry, and how this shock may propagate to other industries. Finally, on a country's level, it is crucial to understand how introducing renewable capacities to its electricity-generating portfolio may affect its energy security. This dissertation sheds light on energy transition from those perspectives and suggests frameworks for analyzing energy transition effects. This chapter provides an overview of the key results, implications, and limitations.

The first paper presents a model and tool designed to aid firms undergoing an energy transition and how it selects a portfolio of technologies and the production level with each technology. The optimal production levels for different categories of emissions and costs were determined both numerically and theoretically, using both profit and value as the firm's objective function. The study considered three environmental regimes: unconstrained emissions, emissions constrained at the firm level, and emissions constrained by origin. Results demonstrated that emissions and total production levels decreased under constrained regimes. Firms pursuing value-maximization invested more in low-cost, high-emission projects if they expected these projects to be prohibited in the future. The study's findings highlight the importance of tailoring policies to suit different firms' objectives and show that the method of emissions regulation has a significant impact. Total emissions constraints may lead to heavy investment in high-emission projects, while category-specific constraints rule out this outcome. However, the more constrained the emissions are, the lower will be the total firms' output. This research contributes to the literature on the optimal production choice and closes the existing gap by adding emissions constraints of various types when the optimal mix of production is determined given a set of available technologies. In addition, our research contributes to the literature on the energy transition as well since it considers the individual firm going through transition instead of an industry or a country. In this paper, further improvements may be made. Firstly, one may also consider emissions constraints together with budget constraints. Thus, we can ensure that newly installed capacities are within budget constraints. Secondly, if we consider a realistic firm, the minimum production level that a firm is required to produce may be introduced. For example, suppose an energy-generating company goes under an energy transition. In that case, it is crucial that facilities dependent on its electricity steel could deliver the needed electricity to either houses or plants.

The second paper discusses how the evolution of energy systems influenced resiliency to shocks of a global interindustry trade network and how a shock originating from a limitation or termination of trading relationships between fossil-related industries, such as *Mining and quarrying, energy producing products* and*Coke and refined petroleum products*, and other industries may propagate in a global interindustry network. The paper includes two parts. In the first part, we evaluate the development of interindustry trade relationship resiliency to shocks and attacks. In the second part, we suggest a framework to assess how a shock originating in one industry in a specific country may propagate to other industries and countries. The suggested framework may be applied to estimate the effect of sanctions that are imposed on a country, and it allows to provide insights on the effects of the sanctions not only on the bilateral trade relationships but also to have a better understanding of how other countries may be affected as well. We showed that even though resiliency to attacks decreased, the effect of shock propagation originating in energy-related industries increased. This means that the damage caused by cutting off one energy-related industry in the country to other industries and countries has increased. This way, we could highlight the importance of interindustry linkages on the global level that brings awareness that policy or sanctions introduced on specific countries or industries may echo across the globe in other industries that use the products produced by sanctioned countries and industries. The second essay contributes to the literature on the analysis of global trade networks since it assesses the resiliency of the global interindustry trade networks rather than focusing on a single product. In addition, it also contributes to the international trade literature since it allows us to estimate how a change in trading relationships between a pair of industries may also influence other trade relationships. However, the proposed framework has limitations, such as the absence of substitution for lost trade volume, limiting its usefulness to short-term effects only, and the high level of aggregation of global interindustry trade data, which makes impossible to track the effects of eliminating a specific good instead of a specific industry.

We conclude this dissertation by considering the impact of the energy transition and changes in energy use on international energy trade. We updated previous studies on energy security by bringing up the question of not only the net energy importers but also net energy exporters, who also may suffer from a highly concentrated market. We developed modified security indexes for net energy importers and exporters and found that energy security is highly sensitive to the ability to produce energy domestically; supply concentration may be outweighed by the disbalance in the fuel (consumption and production) mix. Our empirical analysis confirmed the impact of the energy transition and new technology adoption on international trade. It showed the consequences of China's coal reduction, Germany's boost in renewables, and the US's export growth. We found that transitioning from coal increases reliance on natural gas, which can have negative or positive energy security impacts depending on fuel portfolio diversification and domestic production. We suggest future research on energy communities for individual fossil fuels, energy conversion and substitutability, and the linkage between importer and exporter energy security.

Appendix

A.1 Firm's Portfolio Transition to Carbon Neutrality: Financial and Environmental Trade-offs

Equilibrium for the profit-maximizing firm under emissions constrained applied on the firm level:

$$q_e^{*,PMT} = \frac{\bar{E}a_e c_a c_t + (a_a^2 c_t + c_a a_t^2)p_e^0 - a_a a_e c_t p_a^0 - a_e a_t c_a p_t^0 - c_a a_e c_t b}{a_a^2 c_e c_t + a_e^2 c_a c_t + a_t^2 c_a c_e} \tag{A.1}$$

$$q_t^{*,PMT} = \frac{\bar{E}a_t c_a c_e + (a_a^2 c_e + a_e^2 c_a)p_t^0 - a_a a_t c_e p_a^0 - a_e a_t c_a p_e^0 - a_t c_a c_e b}{a_a^2 c_e c_t + a_e^2 c_a c_t + a_t^2 c_a c_e} \tag{A.2}$$

$$q_a^{*,PMT} = \frac{\bar{E}a_a c_e c_t + (a_e^2 c_t + a_t^2 c_e)p_a^0 - a_a a_e c_t p_e^0 - a_a a_t c_e p_t^0 - a_a c_e c_t b}{a_a^2 c_e c_t + a_e^2 c_a c_t + a_t^2 c_a c_e} \tag{A.3}$$

$$\lambda = \frac{(a_a/c_a)p_a^0 + (a_e/c_e)p_e^0 + (a_t/c_t)p_t^0 + b - E}{a_a^2/c_a + a_e^2/c_e c_t + a_t^2/c_t} \tag{A.4}$$

Equilibrium for the value-maximizing firm under emissions constrained applied on the firm level:

$$q_e^{*,VMT} = q_e^{*,PMT} + \frac{\alpha_a\gamma_a a_a a_e c_t + \alpha_t\gamma_t a_e a_t c_a - \alpha_e\gamma_e(a_a^2 c_t + a_t^2 c_a)}{a_a^2 c_e c_t + a_e^2 c_a c_t + a_t^2 c_a c_e} \cdot p^1 \tag{A.5}$$

$$q_t^{*,VMT} = q_t^{*,PMT} + \frac{\alpha_a\gamma_a a_a a_t c_e + \alpha_e\gamma_e a_e a_t c_a - \alpha_t\gamma_t(a_a^2 c_e + a_e^2 c_a)}{a_a^2 c_e c_t + a_e^2 c_a c_t + a_t^2 c_a c_e} \cdot p^1 \tag{A.6}$$

$$q_a^{*,VMT} = q_a^{*,PMT} + \frac{a_a c_e c_t + \alpha_e \gamma_e a_a a_e c_t + \alpha_t \gamma_t a_a a_t c_e - \alpha_a \gamma_a (a_e^2 c_t + a_t^2 c_e)}{a_a^2 c_e c_t + a_e^2 c_a c_t + a_t^2 c_a c_e} \cdot p^1 \tag{A.7}$$

Condition, under which the optimal level of new capacities for a profit-maximizer equals to the value of value-maximizer:

$$q_e^{*,VMT} - q_e^{*,PMT} = 0 \tag{A.8}$$

$$\frac{\alpha_e \gamma_e}{a_e} = \frac{\alpha_a \gamma_a a_a c_t + \alpha_t \gamma_t a_t c_a}{a_a^2 c_t + a_t^2 c_a} \tag{A.9}$$

And if we set the emissions from the established category to zero:

$$\frac{\alpha_e \gamma_e}{a_e} = \frac{\alpha_t \gamma_t}{a_t} \tag{A.10}$$

$$\mu = \lambda - \frac{\alpha_a \gamma_a (a_a/c_a) + \alpha_e \gamma_e (a_e/c_e) + \alpha_t \gamma_t (a_t/c_t)}{a_a^2/c_a + a_e^2/c_e + a_t^2/c_t} \cdot p^1 \tag{A.11}$$

Equilibrium for the maximization problems with individual emission constrains

$$q_e^{*,PMI} = \frac{\bar{E}_e - b_e}{a_e} \qquad \lambda_e^* = \frac{a_e p_e^0 - c_e(\bar{E}_e - b_e)}{a_e^2} \tag{A.12}$$

$$q_t^{*,PMI} = \frac{\bar{E}_t - b_t}{a_t} \qquad \lambda_t^* = \frac{a_t p_t^0 - c_t(\bar{E}_t - b_t)}{a_t^2} \tag{A.13}$$

$$q_e^{*,VMI} = \frac{\bar{E}_e - b_e}{a_e} \qquad \lambda_e = \lambda_e^{*,PMI} - \frac{p^1 \alpha_e \gamma_e}{a_e} \tag{A.14}$$

$$q_t^{VMI} = \frac{e_t - b_t}{a_t} \qquad \lambda_t^{*,VMI} = \lambda_t^{*,PMI} - \frac{p^1 \alpha_t \gamma_t}{a_t} \tag{A.15}$$

A.2 Resiliency and shock propagation in interindustry trade networks: a global perspective

Industry	**ISIC Rev.4**	**Grouped Industries**
Agriculture, hunting, forestry	01, 02	Agriculture, hunting, forestry
Fishing and aquaculture	03	Fishing and aquaculture
Mining and quarrying, energy producing products	05, 06	Mining and quarrying, energy producing products
Mining and quarrying, non-energy producing products	07, 08	Mining and quarrying, non-energy producing products
Mining support service activities	09	Mining support service activities
Food products, beverages and tobacco	10, 11, 12	Food products, beverages and tobacco
Textiles, textile products, leather and footwear	13, 14, 15	Textiles, textile products, leather and footwear
Wood and products of wood and cork	16	Wood and products of wood and cork
Paper products and printing	17, 18	Paper products and printing
Coke and refined petroleum products	19	Coke and refined petroleum products
Chemical and chemical products	20	Chemical and chemical products
Pharmaceuticals, medicinal chemical and botanical products	21	Pharmaceuticals, medicinal chemical and botanical products
Rubber and plastics products	22	Rubber and plastics products
Other non-metallic mineral products	23	Other non-metallic mineral products
Basic metals	24	Basic metals
Fabricated metal products	25	Machinery
Computer, electronic and optical equipment	26	Machinery

Electrical equipment	27	Machinery
Machinery and equipment, nec	28	Machinery
Motor vehicles, trailers and semi-trailers	29	Transport equipment
Other transport equipment	30	Transport equipment
Manufacturing nec; repair and installation of machinery and equipment	31, 32, 33	Manufacturing nec; repair and installation of machinery and equipment
Electricity, gas, steam and air conditioning supply	35	Electricity, gas, steam and air conditioning supply
Water supply; sewerage, waste management and remediation activities	36, 37, 38, 39	Commercial and public services
Construction	41, 42, 43	Construction
Wholesale and retail trade; repair of motor vehicles	45, 46, 47	Commercial and public services
Land transport and transport via pipelines	49	Transport
Water transport	50	Transport
Air transport	51	Transport
Warehousing and support activities for transportation	52	Commercial and public services
Postal and courier activities	53	Commercial and public services
Accommodation and food service activities	55, 56	Commercial and public services
Publishing, audiovisual and broadcasting activities	58, 59, 60	Commercial and public services
Telecommunications	61	Commercial and public services
IT and other information services	62, 63	Commercial and public services
Financial and insurance activities	64, 65, 66	Financial and insurance activities
Real estate activities	68	Commercial and public services
Professional, scientific and technical activities	69 to 75	Commercial and public services
Administrative and support services	77 to 82	Commercial and public services

Public administration and defence; compulsory social security	84	Commercial and public services
Education	85	Commercial and public services
Human health and social work activities	86, 87, 88	Commercial and public services
Arts, entertainment and recreation	90, 91, 92, 93	Commercial and public services
Other service activities	94,95, 96	Commercial and public services
Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	97, 98	Residential

A.3 The Energy Transition and Shifts in Fossil Fuel Use: The Study of International Energy Trade and Energy Security Dynamics

The appendix is an optional section that can contain details and data supplemental to the main The data for the total primary energy consumption (TPEC) and energy production by type were also taken from the IEA database International Energy Agency (2019). In the UNCT database, the volume of trade is measured both in dollars and in kilograms Table A.2.

Table A.2Used Databases and corresponding data units.

Database	**Units**
UN Comtrade	kilograms; US dollars
IEA Gas imports by origin	Terajoules (TJ); Thousands of British thermal unit (MBtu)
IEA World Energy Balances and statistics	

However, since the goal of the presented paper is to investigate the energy flow, kilograms were converted into terajoules (TJ) to have the ability to compare the amount of energy Hao et al. (2016), UN2 contained in oil, natural gas and coal. For the conversion, net calorific value, which shows what amount of heat is realised by burning one kilogram of fuel, was used. In reality, depending on fuel's type and quality net calorific values may vary significantly. Used values of net calorific values may be found in Table A.3.

TABLE A.3Note: In our data source, the unit of commodities is kilogram. Net calorific value was used for every type of fuel International Energy Agency (2020b). Net calorific value shows what amount of energy is contained in one kilogram of resource.

Fuel	**Net Calorific Value (MJ/kg)**	**Relative Error**
Coal	25.75	10%
Oil	43.05	3%
Natural Gas	45.86	9%

To compare two databases (Comtrade and IEA) we sum over all imports for every economy and region that is contained in both databases for each type of fuel. This approach was also used in the paper by Gephart et. al Gephart and Pace (2015). It was revealed that UN Comtrade contains some out layers for natural gas trade which was corrected by IEA database where possible based on IEA Gas imports by origin. The largest out layers correspond to the flow between USA and Mexico for the period of 2014 to 2018. Another out layer was import of natural gas from Myanmar to China in 2016. This out layer was corrected based by BP database BP. Due to that correction the portion of the variability in UN Comtrade database that can be explained by IEA database for natural gas has increased from 0.016 to 0.99 for export and from 0.007 to 0.96 for import. For coal and oil, the portion of variability in UN Comtrade database that can be explained by IEA database is greater than 0.97 for both: import and export. After the correction of UN Comtrade database all slope coefficients are close to 1.

A.4 Evolution of global fossil fuels network in 2000–2018

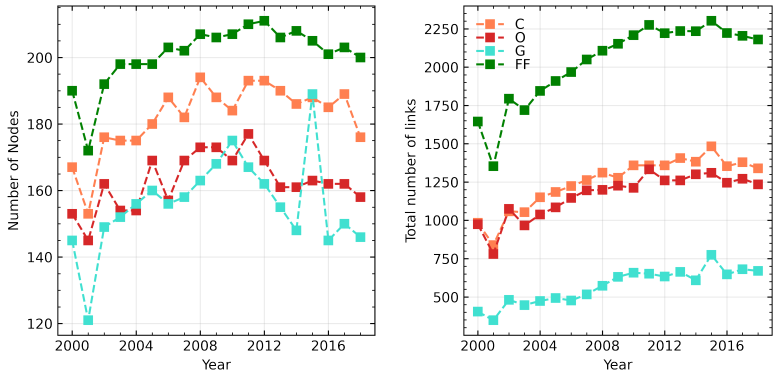


FIGURE A.1: The evolution of networks characteristics (number of nodes and number of links) for coal (C), oil (O), natural gas (G) and fossil fuels (FF).

TABLE A.4The evolution of small-worldness of the INEF.

Year	C^C_{actual}	C^G_{actual}	C^O_{actual}	L^C_{actual}	L^G_{actual}	L^O_{actual}	σ^C	σ^G	σ^O
2000	0.09	0.06	0.09	0.08	0.13	0.08	4.54	0.69	6.03
2010	0.11	0.07	0.08	0.10	0.21	0.07	4.96	0.93	6.98
2015	0.12	0.07	0.10	0.10	0.09	0.07	4.61	2.09	7.71
2018	0.11	0.06	0.09	0.10	0.10	0.08	3.90	1.79	6.88

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