The German Hydrogen Sector in Global Production Networks

Structures, Agency, and Uneven Development

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Abstract

The hydrogen sector is considered crucial for the energy transition. In Germany, the national government supports domestic companies in their plans to export hydrogen technologies and import green hydrogen to replace fossil fuels. However, these efforts face significant challenges: green hydrogen remains economically uncompetitive and its transportation is more expensive than that of fossil fuels.

This study examines the structural challenges the green hydrogen sector faces, the agency of different actors in enhancing its competitiveness, and the uneven developments the German hydrogen sector fosters. Conceptually and empirically, the thesis contributes to understanding the economic implications of energy transitions and contemporary economic policies, especially regarding state agency in defossilizing global production networks. The thesis is based on two years of qualitative data, incorporating interviews, documents, and participant observations.

The central argument is that hydrogen raises high expectations in Germany, as it appears to support both the energy transition and industrial development. Therefore, a broad alliance of companies, labor unions, and environmental organizations advocates for state support, even when it diverges from neoliberal ideas. However, the sector's development falls short of expectations due to the material properties of green hydrogen – specifically, its transportation costs, which will remain higher than those of fossil fuels. This poses a competitive disadvantage for energy-import-dependent countries like Germany and its energy-intensive industries.

Despite this, the German state and other actors primarily use their agency to facilitate the import of green hydrogen and hydrogen derivatives rather than supporting the relocation of energy-intensive industries from Germany to regions with abundant renewable energy. While the state currently covers the costs of replacing fossil fuels with green hydrogen, regulations will shift this burden to companies in the future. In turn, companies will pass on additional costs to consumers through higher prices, risking a decline in public support for the energy transition. An alternative hydrogen strategy could enable German companies to produce energy-intensive intermediate goods abroad, thus maintaining participation in global production networks while contributing to international development.

Cumulative Articles, Manuscripts, and Author Contributions

Article I:

Walker, B., 2022. Governance der deutschen Wasserstoffwirtschaft. Standort 46, 265–270. https://doi.org/10.1007/s00548-022-00789-z. The article is licensed under the CC BY-NC-ND 4.0 license.

Article II:

Walker, B., Klagge, B., 2024. Infrastructure Bottlenecks as Opportunity for Local Development: The Case of Decentralized Green-Hydrogen Projects. Tijdschrift voor Economische en Sociale Geografie. https://doi.org/10.1111/tesg.12633. The article is licensed under the CC BY-NC-ND 4.0 license.

Contribution: I led the development of this article, identifying the research gap, designing the research approach, and acquiring and analyzing the data. The conceptual framework and article structure were jointly developed with Britta Klagge. The writing and revisions were conducted collaboratively throughout the review process.

Article III:

Walker, B., 2024. Place-based allocation of R&D funding: Directing the German innovation system for hydrogen technologies in space. Environmental Innovation and Societal Transitions 52, 100878. https://doi.org/10.1016/j.eist.2024.100878. The article is licensed under the CC BY-NC-ND 4.0 license.

Article IV:

Kalvelage, L., **Walker, B.**, 2024. Strategic coupling beyond borders: Germany's extraterritorial agency in Namibia's green hydrogen industry. Journal of Economic Geography lbae036. https://doi.org/10.1093/jeg/lbae036. The article is licensed under the CC BY-NC-ND 4.0 license.

Contribution: I shared the development of this article with Linus Kalvelage. We collaboratively developed the theoretical and conceptual approach, co-wrote the article, and revised it together. While we were jointly responsible for data acquisition and analysis, Linus Kalvelage conducted some interviews in Namibia independently.

Manuscript I:

Walker, B., Coulomb, F. Climate action driving competitive dynamics and recoupling? Why cement lead firms plan to produce jet fuels in Germany. Unpublished manuscript, under peer review at Progress in Economic Geography. The article is intended to be licensed under the CC BY-NC-ND 4.0 license.

Contribution: This manuscript is based on my work, with Frederick Coulomb contributing by collecting and analyzing a quarter of the interview data and providing critical feedback on article drafts.

Manuscript II:

Walker, B., Coulomb, F. The de-risking state in global production networks: Why and how the German state de-risks investments in synthetic aviation fuels. Unpublished manuscript, under peer review at Advances in Economic Geography (ZfW). The article is intended to be licensed under the CC BY-NC-ND 4.0 license.

Contribution: Manuscript II is based on my work, with Frederick Coulomb contributing by collecting and analyzing data for one of the three case studies and providing critical feedback on article drafts.

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List of Abbreviations

AFD – Alternative für Deutschland (Alternative for Germany, a right-wing political party)
BMWi – Bundesministerium für Wirtschaft (Ministry of Economic Affairs, legislature 2018-2021)
BMWK – Bundesministerium für Wirtschaft und Klimaschutz (Ministry of Economic Affairs and Climate Protection, legislature 2021-2025)
BRICS – Intergovernmental organization of emerging economies, named after its founding member states (Brazil, Russia, India, China, South Africa)
C – Carbon
CARM – Competitive Adjustment and Risk Mitigation Mechanisms
CBAM – Carbon Border Adjustment Mechanism (European CO_2 border adjustment system)
cf. – compare (Latin confer)
CH_4 – Methane (natural gas or synthetic gases)
CH_3OH – Methanol
CO_2 – Carbon dioxide
CRC – Collaborative Research Center
DAC – Direct Air Capture (of CO_2)
e.g. – for example (Latin exempli gratia)
EU – European Union
EU ETS – European Emissions Trading System
EWI – Energiewirtschaftliches Institut an der Universität Köln (Institute of Energy Economics at the University of Cologne)
eSAF – synthetic aviation fuel derived from renewable electricity
FID – Final Investment Decision
GDP – Gross Domestic Product
GPE – Green Planet Energy
GPN – Global Production Networks
H – Hydrogen (Hydrogenium)
IEA – International Energy Agency
IPCEI – Important Project of Common European Interest
IRENA – International Renewable Energy Agency
LNG – Liquid Natural Gas
MW – Megawatts
MOIP – Mission-oriented Innovation Policy
MOIS – Mission-oriented Innovation System
N – Nitrogen (Nitrogenium)
NH_3 – Ammonia
SOE – State-owned Enterprise
TRR – Transregional Program
US – United States (of America)
WTO – World Trade Organization

1. Introduction

In economic and political geography, the hydrogen sector has only recently gained attention, primarily due to its potential role in climate action and economic development. Green hydrogen, a renewable energy carrier produced through water electrolysis using renewable electricity, holds promise for reducing emissions across various industries (IEA 2019). The hydrogen sector thus encompasses a diverse range of firms already involved in the production, transport, or use of hydrogen and its derivatives, firms that plan to do so in the future, and firms that develop technologies for these purposes, from fertilizer plants to refineries and the aviation industry.

With the publication of national hydrogen strategies assigning significant importance to the hydrogen sector for global economic development and the energy transition, geography has begun to recognize its relevance (Kalvelage and Tups 2024; Njøs et al. 2024). In this vein, the overarching aim of this dissertation is to explore a sector that could play a pivotal role in the global energy transition yet could also turn out to be an expensive mirage, measured against current expectations.

This dissertation is situated at the intersection of economic and political geography, within the field of geographical political economy (Hudson 2016; Bridge and Gailing 2020). Geographical political economy is concerned with the spatial co-evolution of economic, political, and biophysical processes, exploring how this co-evolution reproduces uneven geographical development (Sheppard 2011). It provides the macro-theoretical background and guidance for how I use and combine different mid-range theories and concepts, primarily the materiality concept (Bridge and Bradshaw 2017), the global production networks approach (Coe and Yeung 2015), relational state theory (Jessop 2016) and research on (post-)neoliberalization (Brenner, Peck, and Theodore 2010).

The thesis examines several aspects of the hydrogen sector along three thematic axes, along which the thesis contributes to the aforementioned theoretical and conceptual literatures. The first axis investigates the structures underpinning the development of the German hydrogen sector. In my view, structures refer to past economic developments that have materialized as sunk costs in the built environment (Sheppard 2011). In addition, structures also refer to the materiality of different energy carriers (K. Bakker and Bridge 2021; 2006; Balmaceda et al. 2019), including the unequal physical-geographical distribution of renewable energy sources and the chemical-physical properties of different energy carriers that influence their economics (IEA 2019). The production of green hydrogen is energy-intensive, which – among other reasons – is why green hydrogen is still far more expensive than hydrogen produced from fossil fuels (so-called gray hydrogen) or fossil fuels themselves. Therefore, some authors are skeptical about green hydrogen's potential to become a widely used energy carrier (Brauers, Braunger, and Jewell 2021; Szabo 2021; Wright, Nyberg, and Bowden 2024). Moreover, the transportation of hydrogen is costly due to its material properties, posing competitive disadvantages for industries relying on imported green hydrogen (Samadi, Fischer, and Lechtenböhmer 2023; Verpoort et al. 2024). I contributed to these debates by researching the following question:

- How do the uneven geographical distribution of renewable energy, the material properties of hydrogen, and the sunk costs of the fossil-fuel-based economy influence the development of the German hydrogen sector?

The second axis focuses on the agency of various actors in making green hydrogen competitive with gray hydrogen and fossil fuels. While structures present "differential constraints and opportunities that vary by agent", actors possess different capacities to shape development in their interest within these structures (Jessop 2016, 55). The governance of the hydrogen sector is particularly influenced by state involvement, as many actors in Germany advocate for strong state support to address the sector's economic challenges (Löhr, Markard, and Ohlendorf 2024). However, many firms are part of global production networks that span state borders, potentially limiting state agency, as firms may relocate to avoid regulations (Bataille et al. 2018). Conceptualizing the agency of state institutions in improving the competitiveness of green hydrogen in global production networks constitutes the core conceptual contribution of this dissertation, addressed by the following research question:

- How do state institutions and other actors try to make green hydrogen competitive with fossil fuels?

Moreover, the extent to which contemporary state interventions deviate from neoliberal ideas and whether this represents a shift in economic policy (Mazzucato 2018b; Alami and Dixon 2020; Gabor 2021; Gerstle 2022) or a process of variegated post-neoliberalization is debated (Brenner, Peck, and Theodore 2010). Hydrogen policies present an opportunity to gain empirical insights into this debate. Therefore, the dissertation addresses the question:

- To what extent do hydrogen policies reflect neoliberal ideas?

The third axis investigates the implications of the hydrogen sector for Germany's economic development and energy transition. While the literature on how the energy transition reproduces uneven developments is extensive (Bridge et al. 2013; Balta-Ozkan, Watson, and Mocca 2015; Walker 2022), the role of the green hydrogen sector in these developments remains underexplored. According to Germany's National Hydrogen Strategy (BMWi 2020), the hydrogen sector is crucial for both the energy transition and industrial development. The strategy supports firms that want to import green hydrogen and derivatives, like ammonia, methanol, and synthetic fuels, for energy-intensive industries in Germany. Conversely, hydrogen technologies are to be exported to sustain Germany's export-oriented economic development model. However, critics argue that this strategy may perpetuate historical uneven developments or even represents neo-colonial dynamics, especially in the context of importing green hydrogen from Namibia, a former colony (Gabor and Sylla 2023; Müller 2024; Tunn et al. 2024). Conversely, Samadi et al. (2023) argue that renewable energy-rich regions in the Global South could attract investments from energy-intensive industries, creating new development opportunities. Economic geography has yet to fully grasp these transformative implications for the locations of energy-intensive industries (While and Eadson 2022). This leads me to the final research question:

- To what extent does the hydrogen sector propel economic developments that align with or differ from historically uneven economic developments?

To answer these questions, I single-authored two articles, co-authored another two, and co-authored two unpublished manuscripts, which are attached to this framing paper (see author's contributions, page II, and summary, page 64). The following, second section of the framing paper contextualizes, relates, and summarizes the theoretical and conceptual perspectives used in the articles, highlighting their conceptual contributions. The third section explains the overarching research design and methodology. The fourth section presents the empirical findings and references the respective articles for detailed explanations. The fifth section discusses the findings, theoretical approach, and limitations, offering suggestions for future research. The framing paper concludes with a summary of the contributions and core findings, along with an outlook on persisting research gaps not addressed by this thesis.

2. Theoretical and Conceptual Debates, Literature Review

The following sub-sections lay out the theoretical approach of the thesis. In brief, it investigates structures that provide opportunities for and constraints on the agency of different actors. Based on the interplay between structures and agency, I explain economic development. To conceptualize structure, agency, and development, this dissertation draws on a range of theoretical and conceptual debates, which will be introduced.

2.1. Structures: The Materiality of Green Hydrogen and the Development of the Hydrogen Sector

To understand how the uneven geographical distribution of renewable energy, the material properties of hydrogen, and the sunk costs of the fossil-fuel-based economy influence the development of the German hydrogen sector, I use the materiality concept. Materiality can be defined as "the (biological, chemical, physical) qualities of materials [that] shape strategies for value capture" (Bridge and Bradshaw 2017, 221). This concept has been applied in social science research on energy and resources (K. Bakker and Bridge 2021; Balmaceda et al. 2019). More recently, it has also been used in economic geography research on the Norwegian hydrogen sector, specifically to understand material dependencies that constrain human agency. This includes "human-made material dependencies" related to infrastructures and the sunk costs of past investments, as well as "natural material dependencies" tied to the geographical distribution of renewable energy sources, the chemical properties of hydrogen, and the physics of hydrogen production from various feedstocks (Njøs et al. 2024, 8).

2.1.1. Natural Material Dependencies of (Green) Hydrogen Production, Transport, and Use

Hydrogen is predominantly produced from natural gas today, although other fossil energy sources are also used. The production and use of hydrogen is geographically concentrated, as hydrogen's low volumetric density makes transportation expensive (Wang, Swinbourn, and Li 2023). As a result, hydrogen is seldom transported. However, a few hydrogen pipelines exist worldwide that distribute hydrogen over several hundred kilometers between industrial sites. Moreover, hydrogen is delivered in small quantities by truck (IEA 2019).

Hydrogen can be converted into ammonia (NH_3) through reaction with nitrogen (N). Hydrogen is also part of various carbon-containing (intermediate) products, such as methanol[1] (CH_3OH), synthetic gases[2] (CH_4), and synthetic liquid fuels[3]. These products are primarily produced by the (petro-)chemical industry from natural gas and coal. Compared to pure hydrogen, ammonia, methanol, synthetic gases, and synthetic liquid fuels have higher volumetric densities and are thus globally traded (IRENA 2022).

To indicate the emission-intensity of different production methods, a range of hydrogen "colors" are being distinguished (Ajanovic, Sayer, and Haas 2022). The production of gray hydrogen and its derivatives from fossil fuels is responsible for about 2% of global CO_2 emissions (IEA 2019, 17). To reduce these emissions, the sector can rely on alternative, lower-emission production methods, which are currently underutilized. Of particular significance for climate protection will arguably be yellow and green hydrogen, produced in electrolyzers by splitting water (H_2O) into hydrogen (H) and oxygen (O) using electricity from the grid[4] or renewable energy sources (Figure 1).

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[1] Methanol is currently used as a fuel as well as a chemical feedstock for the production of adhesives, plastics, textiles, and insulation materials (Fortune Business Insights 2024).

[2] Synthetic gases are similar to natural gas (i.e. methane) and are primarily produced from coal and biomass through chemical synthesis. Hence, they can be used in conventional natural-gas technologies, such as gas turbines (Gao et al. 2021). Biogas can also be referred to as synthetic gas, but it is mostly produced using biological decomposition processes (da Silva Pinto et al. 2022).

[3] Synthetic liquid fuels, also called power-to-liquid fuels or eFuels are liquid fuels made by synthesizing green hydrogen and renewable carbon (see page 5) using renewable electricity. These liquid fuels have similar material properties as fossil gasoline, diesel, or kerosene, and, hence, can be used by conventional liquid-fuel technologies, such as combustion engines (Gao et al. 2021).

[4] The share of green electricity in many electricity grids around the world is still limited, so the carbon footprint of hydrogen production depends on the CO_2 intensity of the electricity used during electrolysis (Palmer et al. 2021).

Figure 1: The hydrogen color spectrum (the author, based on: Ajanovic, Sayer, and Haas 2022)

Electricity costs are the primary cost factor in green hydrogen production. The costs of renewable electricity generation, in turn, depend on the full load hours[5] renewable energy plants can achieve, as these hours define the plants' utilization rate. Access to renewable energy plants with high full load hours is also crucial for maximizing the utilization rate of electrolyzers, thereby reducing the specific capital investment costs of electrolyzer plants per kilogram of hydrogen (IRENA 2020b). Therefore, access to globally competitive renewable energy sources is key to producing competitively priced green hydrogen. However, such renewable energy sources are not available in Germany (IEA 2019).

Due to the lower infrastructure throughput, transmission losses, and higher capital intensity of transporting electricity and green hydrogen, techno-economic studies show that their transport will remain more expensive than the transport of fossil fuels. Transporting methanol, synthetic gases and synthetic liquid fuels instead of green hydrogen and ammonia will not alleviate the increased transport costs of renewable energy carriers. Whereas the transport costs of the former equal the transport costs of fossil fuels, their production is even more energy-intensive and, hence, more expensive than green hydrogen production. Moreover,

[5] Full load hours are the hours that a renewable energy power plant would have to produce at its nominal power in order to generate the same annual yield that it achieves in real operation with frequent partial load and nighttime shutdown (Wirth 2020, 82).

methanol, synthetic gases, and liquid fuels require renewable carbon, which is similarly expensive to transport as renewable energy (Fink et al. 2025).

Renewable carbon originates from a carbon cycle, meaning it must have been extracted from the atmosphere either technologically (via so-called Direct Air Capture systems, DAC) or biologically (via biomass growth) before its emission (C. Schmid and Hahn 2021). Since DAC systems are economically uncompetitive, access to biogenic carbon sources, which, like renewable energy, are unequally distributed globally, is required to produce competitive synthetic gases and liquids (Chireshe et al. 2025). However, it is already foreseeable that Germany will not be able to produce enough biogenic carbon on its territory to satisfy the expected demand, stemming particularly from its (petro-)chemical industry (C. Schmid and Hahn 2021).

2.1.2. Human-Made Material Dependencies

The key spatial challenge in defossilizing[6] existing places of energy-intensive production and energy use more generally is that their locations often do not align with places offering sufficient, globally competitive renewable energy supply. Besides the higher transport costs of green hydrogen and renewable electricity compared to fossil fuels, transporting renewable electricity is often constrained by infrastructure bottlenecks (IEA 2023; Walker, Becker, and Klagge 2021). Likewise, large-scale hydrogen transport is constrained in most regions globally by the lack of hydrogen pipelines. While natural gas pipelines could be repurposed for hydrogen transport, this would still result in higher transport costs for hydrogen compared to natural gas (Paul Martin et al. 2024).

To avoid paying for high transport costs, countries and regions can aim to maximize their energy sufficiency. However, the production of green hydrogen can be limited by the available land for renewable electricity generation, particularly in densely populated areas (van de Graaf et al. 2020). Renewable energy sources are characterized by a lower (volumetric) energy density than fossil fuels, meaning that, for a given surface area, a renewable energy plant produces less energy than a fossil power plant (Smil 2016). Consequently, regions with a high energy demand relative to their surface area, such as cities or areas hosting energy-intensive industries, cannot produce sufficient renewable electricity and green hydrogen to meet their energy demand (Walker 2022). In international comparison, Germany has one of the highest energy demands per unit of surface area (MacKay 2013). Hence, if Germany's energy demand remains unchanged, the country will be particularly dependent on costly renewable energy imports to reach climate neutrality.

[6] Since the replacement of carbonaceous materials, such as carbonaceous fuels or minerals, is still technologically unfeasible in industries from cement to aviation, I use the term defossilization instead of decarbonization in this study. Whereas decarbonization implies the substitution of carbonaceous materials, defossilization refers simply to the replacement of fossil fuels (Tilsted 2024, 75).

The aforementioned findings highlight the increasing importance of energy as a location factor in an economy based on renewable energy sources (IRENA 2022, 21; Lambert 2023; Samadi, Fischer, and Lechtenböhmer 2023; Verpoort et al. 2024). As renewable energy becomes increasingly critical for location decisions, companies are incentivized to relocate production to areas offering cost-effective renewable energy. This phenomenon, known as the "renewables pull" (Eicke, Kramer, and Quitzow 2024; Samadi, Fischer, and Lechtenböhmer 2023; Verpoort et al. 2024), has yet to be integrated into economic geography, even though the field has highlighted that (renewable) energy is a location factor for energy-intensive industries (Michielsen 2013; While and Eadson 2022).

Peer reviewed research on where green hydrogen will be needed for defossilization, especially regarding the existing (gray) hydrogen industry in Germany or globally, was sparse at the start of this dissertation (see for early agenda-setting articles: Scott and Powells 2020; van de Graaf et al. 2020). Only a few studies from innovation research offered insights into the interest of German automobile and heating system producers in green hydrogen, exploring past hypes and failed expectations (S. Bakker and Budde 2012; Budde, Alkemade, and Weber 2012; Hekkert et al. 2005).

Gray literature could offer some insights into the market for pure hydrogen, which – as part of the industrial gas market – is globally dominated by an oligopoly consisting of Linde, Air Liquide, and Air Products (Böhm 2020). Pure hydrogen (H_2) is mainly used materially in its gaseous[7] form, not yet as an energy source as is envisioned for the future, in refineries (petroleum processing) and the chemical industry (mainly in ammonia for fertilizers and explosives), as well as in smaller quantities for various production processes (e.g., metal processing, food industry) (IEA 2019).

The significance of the hydrogen sector for climate change mitigation arises not only from its own greenhouse gas emissions but also from the expectation that green hydrogen will be used in new applications in the future (Figure 2). In some applications, the use of hydrogen derivatives competes with the direct use of renewable electricity. Therefore, I have stopped using the popular term 'hydrogen economy' (Wasserstoffwirtschaft) in later works, as it implies a future ubiquity of hydrogen production and use, which is contested, and instead refer to the hydrogen sector (Clarke 2022).

[7] Hydrogen only becomes liquid at very low temperatures (-259°C). In comparison, methane (natural gas) becomes liquid at -162°C, which is why the transport of liquefied natural gas is technologically easier and more energy-efficient than the transport of liquefied hydrogen (Wang, Swinbourn, and Li 2023).

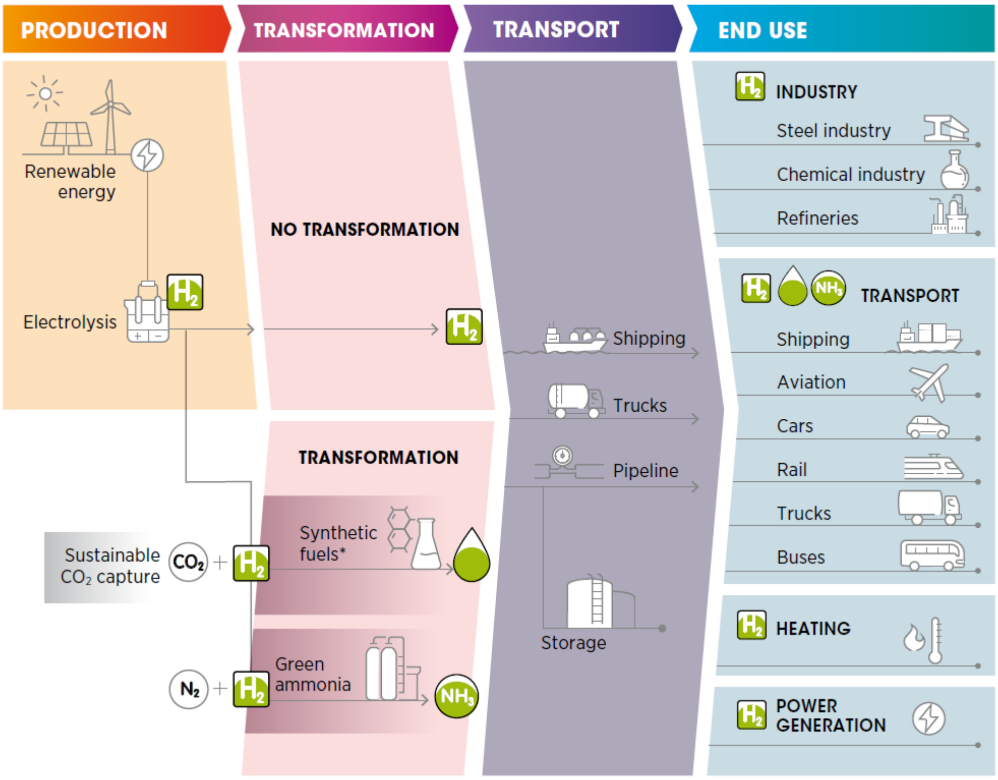

Figure 2: Production, transformation, transport, and possible applications of green hydrogen (derivatives) (Source: the author, based on IRENA 2020a, 7)

To differentiate between the direct use of green electricity and its indirect use following transformation and intermediate storage as hydrogen, a distinction is made between direct and indirect electrification (Figure 3, Philibert 2019). Since hydrogen derivatives share the chemical properties of their fossil equivalents, they can be utilized in existing infrastructures and technologies, like combustion engines, without technological adaptations (Ravi et al. 2023). Consequently, stakeholders whose capital is tied to these technologies and infrastructures, such as the natural gas (distribution) industry and parts of the automotive industry, advocate for indirect electrification (Brauers, Braunger, and Jewell 2021; Szabo 2021). Proponents of direct electrification, however, argue that it offers higher energy efficiency. Therefore, they consider the use of renewable electricity to produce green hydrogen inefficient as long as the electricity can be used directly (Giovanniello et al. 2024).

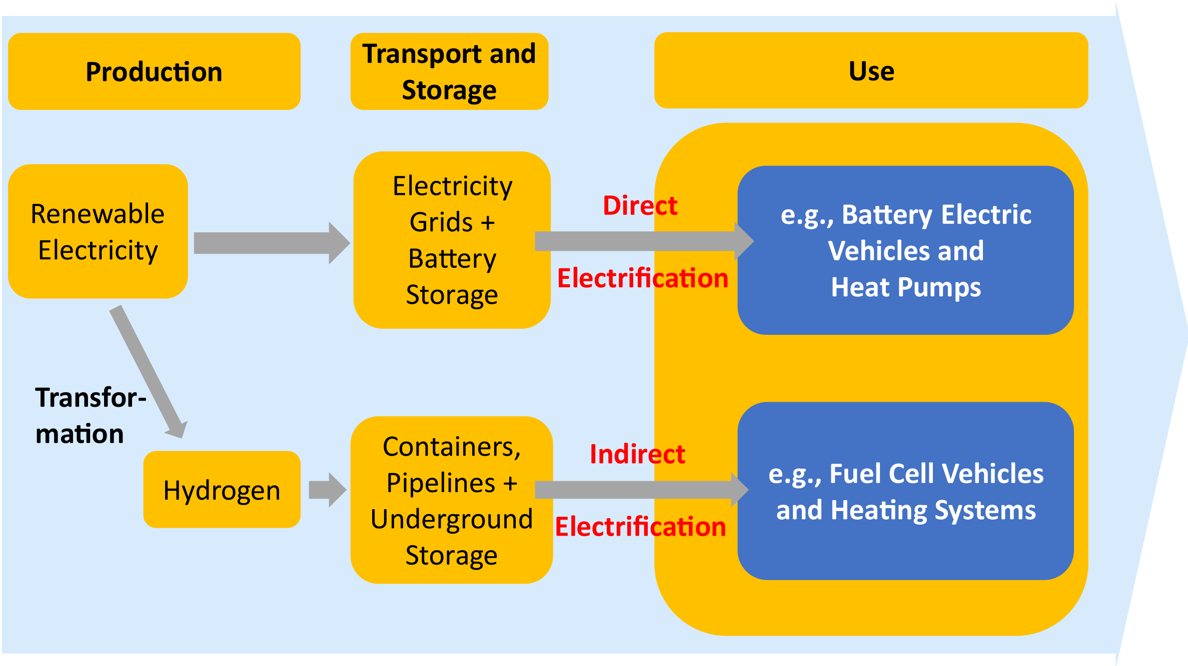

Figure 3: Comparison of direct versus indirect electrification pathways (Source: the author, article I)

Firms usually adopt climate change mitigation measures when they offer economic co-benefits, such as production cost savings (Wesseling et al. 2017). Therefore, green hydrogen's low energy efficiency constitutes an important techno-economic obstacle as its use does not offer energy cost savings. As a result, and because some technologies required for green hydrogen production – such as electrolyzers – are not produced at scale yet, substituting fossil fuels with green hydrogen would lead to significant increases in production costs (Table 1).

Sector	**Expected Rise of Production Costs**	**Source**
Pure hydrogen for steel production in Sweden	20-30%	Vogl, Åhman, and Nilsson 2018
Methanol and ammonia use in oversea shipping	30-40%	BCG 2024
Synthetic aviation fuels	At least four times more expensive	Dahal et al. 2021

Table 1: Expected rise of production costs when using green hydrogen (derivatives) across different sectors

The cost disadvantages of adopting green hydrogen are particularly challenging for industries where green hydrogen and its derivatives represent the only defossilization option. Specifically, industries that already use gray hydrogen depend on the transition to green hydrogen (Figure 4, Row A). In addition, certain industries require energy carriers with high volumetric energy density or access to vast amounts of renewable energy, for example, for storage purposes (Figure 4, Row B).

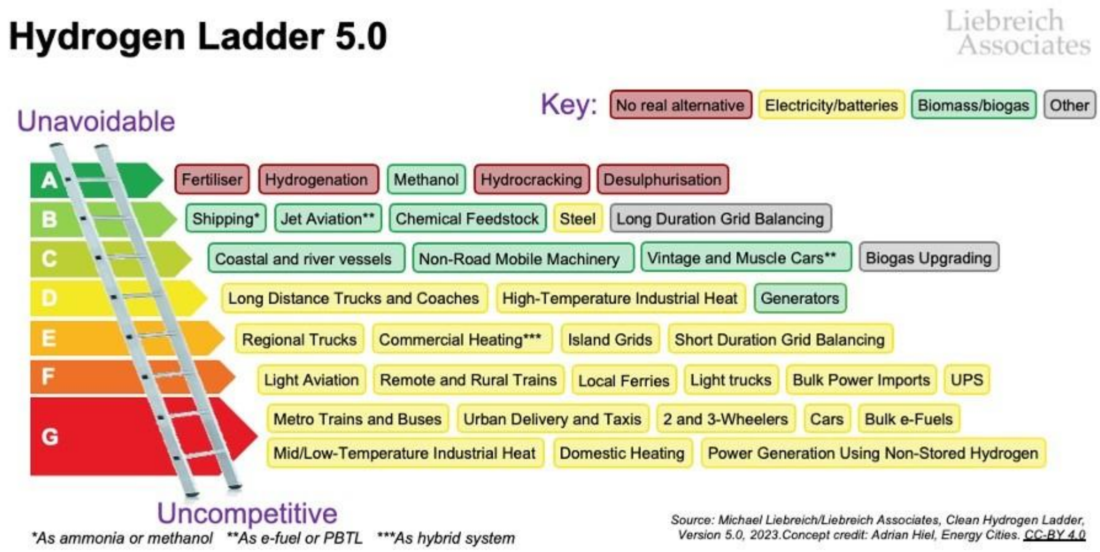

Figure 4: Unavoidable as well as (likely) uncompetitive areas for green hydrogen adoption (Source: Michael Liebreich/Liebreich Associates, [Clean Hydrogen Ladder, Version 5.0, 2023](). Concept Idea: Adrian Hiel, Energy Cities. [CC-BY 4.0]())

Economic geography provides little empirical insights into industrial defossilization efforts, often focusing instead on renewable energy technology producers (Afewerki, Karlsen, and MacKinnon 2019; Coe and Gibson 2023; Dawley 2014). In comparison, potential users of green hydrogen (derivatives), particularly energy-intensive industries, have received little attention. For example, research on the industries that constitute the empirical focus of this dissertation, namely the cement, aviation, and refining industries, is dated (Melamid 1955; Odell 1963; Hay 1971) or does not take the issue of climate change into account (Bowen Jr. and Leinbach 2006; Bowen 2010; Niewiadomski 2017). However, economic geography could provide theoretical frameworks for analyzing the challenges that industries confront in regard to their defossilization.

2.1.3. Materially Induced Economic Challenges of Green Hydrogen

From a theoretical perspective, it is crucial to avoid a monocausal explanation of the challenges hindering the uptake of green hydrogen derivatives. For example, Christophers (2022; 2024) argues that firms are driven by profits not costs. Consequently, the high cost of green hydrogen is not the only barrier to its competitiveness and uptake. However, existing analytical approaches, which utilize various indicators to explain competitive dynamics, such as the Global Production Networks (GPN) 2.0 approach, have not yet been applied to the energy transition (Coe and Gibson 2023). Hence, these approaches require adaptation and operationalization to analyze the development of the green hydrogen sector.

To gain a comprehensive understanding of green hydrogen’s competitiveness, I applied the GPN 2.0 approach (Coe and Yeung 2015). Other analytical frameworks, such as the multi-level perspective in transition research (Christophers 2022) or the green industrial path development literature (Sotarauta et al. 2021; Trippl et al. 2020), are more advanced in analyzing energy transitions. However, I argue that the advantage of the GPN approach lies in its comprehensive consideration of (global) competitive dynamics along multiple indicators.

The GPN 2.0 approach evaluates competitive dynamics through four key indicators: cost-capability ratio, market development, financing, and risks. Applying these variables to green hydrogen provides insights into the sector's economic challenges. In essence, the lack of cost parity with fossil fuels affects all the other GPN 2.0 variables, offering new insights into their interrelations (G. Yeung 2016). Specifically, using green hydrogen would lead to higher production costs, since green hydrogen is often multiple times more expensive than gray hydrogen or fossil fuels. These cost increases either endanger profits or market growth, if producers increase prices, which face uncertain demand (Nazarenko and Saleh 2024; Oerlemans, Chan, and Volschenk 2016). Therefore, investors associate risks with investments in cost-ineffective, climate-friendly technologies, which can make financing difficult (Karltorp and Maltais 2024). However, cost parity is a necessary but insufficient condition for green hydrogen's competitiveness. Even if cost parity is reached, technological risks, unfavorable financing conditions, or insufficient demand may persist.

While the GPN 2.0 approach offers a comprehensive understanding of the economic challenges associated with green hydrogen, it primarily explains firms behavior based on the four variables (MacKinnon, Dawley, Pike, et al. 2019; Neilson et al. 2018). Therefore, additional theoretical work was necessary to understand how different actors – particularly governments – can influence the variables to enhance green hydrogen's competitiveness. In other words, conceptualizing agency in shaping competitive dynamics and mitigating risks was imperative.

2.2. Agency of the State and other Actors in Global Production Networks

Given limited research on agency in regard to the GPN 2.0 approach, this section first develops a conceptual understanding of how actors can enhance the competitiveness of commodities – such as green hydrogen – relative to competing alternatives. In addition, I present a theoretical and conceptual perspective on the political economy of the German hydrogen sector and distinguish between neoliberal and post-neoliberal policy approaches. This distinction serves as a basis to addressing the research question of to what extent hydrogen policies reflect neoliberal ideas.

2.2.1. Competitiveness Adjustment and Risk Mitigation Mechanisms (CARM)

The GPN 2.0 approach was expanded by conceptualizing how different actors, particularly the state, can influence the various dimensions of competitiveness. To this end, I synthesized existing mechanism-based approaches in GPN research with related strands of literature (Binz, Truffer, and Coenen 2016; MacKinnon, Dawley, Pike, et al. 2019), introducing the notion of competitiveness adjustment and risk mitigation mechanisms (CARM). I distinguished between four mechanisms: (1) cost-capability transformation, (2) market creation, (3) climate financing, and (4) risk mitigation. Each mechanism addresses one of the four competitive dynamics and the risk dimension of the GPN 2.0 approach (Table 2). Through these mechanisms, actors can increase the competitiveness of certain products or technologies, such as green hydrogen, relative to competing alternatives.

Whereas Articles IV and Manuscript I explore the CARM mechanisms in more detail, I summarize their key elements here. The first mechanism, *cost-capability transformation*, refers to actions directed at either improving the cost/capability ratio of green hydrogen or deteriorating the cost/capability ratio of gray hydrogen and fossil fuels. The cost-capability ratio reflects firms' attempts to optimize their costs in relation to their capabilities. Ideally, investments in new capabilities should reduce production costs, providing a (temporary) competitive advantage (Coe and Yeung 2015).

Moreover, the GPN literature highlights that firms seek access to regional assets to improve their capabilities or lower costs. For example, some regions offer skilled labor or specialized firms (MacKinnon, Dawley, Steen, et al. 2019). The GPN literature and adjacent strands of research increasingly assume a dynamic understanding of assets, highlighting the agency of different actors in re-using, creating or destroying assets (McGregor and Coe 2021; Trippl et al. 2020). The concept of regional assets is crucial for understanding how geographical disparities influence the adoption of green hydrogen.

In regard to the second mechanism, *market development*, strands of research, which conceptualize market creation from an actor-centered perspective (Beise and Rennings 2005; Mazzucato 2016), have increasingly received attention in economic geography (e.g., Losacker and Liefner 2020; Dewald and Truffer 2011). For example, states use mandates to create markets. These mandates require "a certain fraction of consumption to be accounted for by renewable energy" or green hydrogen (Clancy and Moschini 2018, 199). By integrating these strands of research into the GPN framework I aimed at providing an understanding of how actors can purposefully create markets, e.g., for green hydrogen.

The third mechanism concerns, the *financing* of green hydrogen investments, which is challenging given capital intensive nature of green hydrogen projects. High capital costs often constitute a significant barrier to competitiveness, yet they remain underexplored in existing studies (Lee and Saygin 2023). Governments can play a pivotal role in shaping financing conditions. The climate finance literature highlights that states are not only direct sources of funding but also regulate financial markets to incentivize investments in climate-friendly projects (Bracking and Leffel 2021; Hildingsson, Kronsell, and Khan 2019).

Mechanism	Function	Key Actors	Instruments
Cost-Capability Transformation	Improve cost-capability ratio of firms using green hydrogen	Governments, Infrastructure Providers, Firms, Public Research Institutes	Production subsidies, asset creation & re-use, R&D
	Deteriorate cost-capability ratio of firms using gray hydrogen or fossil fuels	Governments	Asset destruction (of assets related to fossil fuel use), Carbon pricing
(Lead) Market Creation	Create green hydrogen markets to provide revenues for green hydrogen producers	Governments	Demand creation through public procurement, mandates
		Buyers	Willingness to pay for and adopt green hydrogen
Climate Financing	Provide preferential financing terms to climate friendly investments	Governments,	Public funding for climate friendly investments; Regulation of financial markets
		Private financiers	Climate financing instruments (e.g., climate bonds)
Risk Mitigation/ De-Risking	Decrease investment risks to decrease financing costs	Governments,	Subsidies & Regulation; Increase Political Reliability of Climate Policies
		Public Research Institutes, Firms	Improve Technological Reliability
		Buyers/Offtakers	Commit to binding offtake agreements to secure business case of producers

Table 2: Overview of the CARM mechanisms, their main function, central actors and the instruments they can use for triggering the mechanisms (the author)

The fourth mechanism relates to *risk mitigation*, recognizing that financing costs depend on the risks that financiers associated with investments. Risks are subjective (Völlers et al. 2023) and investment decisions are often based on an entity's past performance. In this regard, reputation plays an important role. A strong heritage – symbolizing a history of successful investments – can enhance investor confidence, leading them to anticipate future success (Billing and Bryson 2019). Similarly, a reputation for innovativeness can attract financing (Höflinger, Nagel, and Sandner 2018). To understand how different actors mitigate risks associated with investments in green hydrogen projects, I build on a typology of different state roles by Horner

(2017). I differentiate facilitative, regulatory, and entrepreneurial approaches to de-risking. Entrepreneurial de-risking entails direct government engagement in GPNs through SOEs. Facilitative de-risking involves the provision of investment incentives to lower financial barriers. In contrast regulatory de-risking operates through disincentives, such as penalties for non-compliance with mandates or pricing mechanisms designed to deter undesired investments.

2.2.2. Actors, Interests, and Influence on German Hydrogen Policy

When I began this dissertation in late 2020, limited research existed on the actors deploying the CARM mechanisms to enhance the competitiveness of green hydrogen. Early on, Brauers et al. (2021) highlighted the German natural gas industry's vested interest in green hydrogen, supported by other German industrial sectors, including the automotive industry. To develop an analytical heuristic for examining actors, their interests, and their coordination strategies, I employed the governance concept. Governance can be defined as "the process of steering society and the economy through collective action and in accordance with common goals" (Ansell and Torfing 2016, 3). Therein, I differentiated between different governance scales and researched their influence on the green hydrogen sector (Bache, Bartle, and Flinders 2022).

Analyzing actors and their interests is essential for understanding how they influence policies. This approach follows the strategic-relational perspective of the state, which views state action as shaped by underlying and often competing social forces (Dawley, MacKinnon, and Pollock 2019; Smith 2015). Consequently, actors exert influence and express their interests through different state institutions, leading to incoherent state actions (Jessop 2016).

To assess the extent to which key actors – particularly states – can use the CARM mechanisms, I identify legitimacy as an important enabling condition (Binz, Truffer, and Coenen 2016; Heiberg, Binz, and Truffer 2020; MacKinnon, Afewerki, and Karlsen 2022). Legitimacy, as defined by Suchman (1995, 574) refers to "a generalized perception or assumption that the actions of an entity are desirable, proper, or appropriate within some socially constructed system of norms, values, beliefs, and definitions". Following MacKinnon et al. (2022), I focus specifically on "pragmatic" legitimacy, which "rests on the self-interested calculations of an organization's most immediate audiences" (Suchman 1995, 578). Building on these insights, I argue that the perceived appropriateness and desirability of using CARM mechanisms for the green hydrogen sector depends on the extent to which the involved actors can reconcile the use of green hydrogen with economic development (see 2.3.; cf. Tödtling, Trippl, and Desch 2022).

2.2.3. Hydrogen Policies: Post-Neoliberalization?

Beyond the necessity for legitimation, whether and how the German state intervenes into the hydrogen sector is also shaped by the ideological orientation of social forces and state institutions towards neoliberal ideas. To develop an understanding of hydrogen policy design, I draw on literature discussing the extent to which neoliberal ideas shape contemporary policies. This debate reflects that economic and other policies are being renegotiated in recent years due to crises, geopolitical conflicts, and geo-economic competition (H. W. Yeung 2023). As a result, state interventions are increasing, prompting discussions about whether policies remain neoliberal in orientation or not (Gabor 2021; Gerstle 2022).

As state transformation is contested and takes place in diverse, historically inherited institutional environments, it takes on variegated forms across different countries, state institutions, and scales (MacKinnon 2012b; Peck, Brenner, and Theodore 2018; Peck and Theodore 2007). Therefore, some researchers prefer to speak of neoliberalization as an ongoing, uneven process instead of neoliberalism. Neoliberalization can be conceptualized "as one among several tendencies of regulatory change that have been unleashed across the global capitalist system since the 1970s: it prioritizes market-based, market-oriented, or market-disciplinary responses to regulatory problems; it strives to intensify commodification in all realms of social life; and it often mobilizes speculative financial instruments to open up new arenas for capitalist profit-making" (Brenner, Peck, and Theodore 2010, 329–30).

By extension, "post-neoliberalization" is also likely to be variegated (Brenner, Peck, and Theodore 2010, 210). Since state interventions are necessary for the adoption of green hydrogen, hydrogen policies constitute an interesting research object to reflect on (post-)neoliberalization. Moreover, because hydrogen policies intersect with multiple policy fields, they provide an opportunity to analyze how post-neoliberalization manifests across different fields. The following section contrasts neoliberal and post-neoliberal policy ideas across key policy fields to develop an understanding of the extent to which hydrogen policies continue to reflect neoliberal ideas (Table 3).

State Ownership Policies

A rapidly growing body of literature examines the drivers (Alami and Dixon 2022), geography (Alami and Dixon 2020), and effects of increased state intervention in the economy through state-owned enterprises (SOEs), conceptualized as state capitalism (Alami and Dixon 2023; Babic 2023). The growing prominence of SOEs challenges neoliberal assumptions, which consider SOEs to be inefficient and advocate for their privatization (Alami and Dixon 2022; 2020). However, given the German state's limited direct influence over the energy sector via SOEs (Bieling 2008; Vogelsang 1988), it is unlikely that German hydrogen policy represents a typical case of state capitalism, even though the precise definition and distinction of state capitalism from other forms of state intervention remains contentious. State capitalism is often understood institutionally as policy through SOEs, development banks, and sovereign wealth funds

(Alami and Dixon 2023), raising the question of whether other forms of policy could also be classified as state capitalist.

Policy Field	Neoliberal Policy Approach	Post-Neoliberal Policy Approach
State ownership policies	Privatization	Explicit use of and founding of new state-owned enterprises
Industrial policies	Horizontal Industrial Policy	Mission-Oriented Industrial Policy
Regional policy	Strengthening most competitive regions in global competition	Increasing territorial cohesion between leading and lagging regions
Fiscal policy	Fiscal rules (debt brakes) to prevent inflation	Public debt to finance mission-oriented policies
Climate policy	Carbon pricing to maximize cost-efficiency of defossilization across sectors	Mandates to incentivize defossilization in specific sectors
Trade policy	Free trade to maximize international market efficiency	Carbon border tariffs to protect low-emission lead markets

Table 3: Contrast between neoliberal and post-neoliberal ideas in different policy fields

Industrial Policy

State influence on economic development extends beyond SOEs, encompassing industrial and innovation policy. A targeted industrial policy for hydrogen development would diverge from neoliberal industrial strategies, which emphasize horizontal support across industries rather than targeted sectoral interventions. In contrast, vertical industrial policies prioritize specific sectors or technologies (Pianta, Lucchese, and Nascia 2020). According to neoliberal theory, vertical industrial policies distort market coordination, lead to inefficiencies and higher costs by artificially sustaining non-competitive industries (Wigger 2019). This raises the question of whether and how states should direct industrial development (Bergek, Hellsmark, and Karltorp 2023; Mazzucato 2018a).

In the literature on innovation and industrial policy, there is growing consensus that states should influence the direction of economic development, referred to as "directionality" (Parks 2022; Weber and Rohracher 2012). States should align economic development with addressing so-called missions or challenges, such as socio-ecological crises (Coenen, Hansen, and Rekers 2015; Mazzucato 2021). Consequently, mission-oriented innovation or industrial policy are neither horizontal nor vertical but support all actors addressing specific challenges, such as climate-neutral heat provision (Mazzucato 2018a; 2016). The German government and the EU aim for technological leadership in hydrogen and other emerging technologies through large-scale industrial policy programs (Gabor 2023; Kleimann et al. 2023). However, whether these programs follow a neoliberal, horizontal industrial policy approach or a post-neoliberal, mission-oriented approach has not been researched.

Regional Policy

From a geographical perspective, the spatial dimension of directionality and its spatial politics remain insufficiently conceptualized. It can be assumed that state subsidies are allocated to specific locations (Coenen, Hansen, and Rekers 2015) and that the dissemination of new energy carriers, such as hydrogen, requires the establishment of supporting infrastructure (van de Graaf et al. 2020), which connects places in an uneven manner. This raises the question whether states use (mission-oriented) industrial policies to balance regional development (Cappellano, Molica, and Makkonen 2024).

According to MacKinnon et al. (2024, 2) "the crisis of neoliberal capitalism is evident in the realm of spatial policy, particularly in terms of how post-industrial and rural areas have been marginalised by the adoption of competitiveness strategies focused on the most economically dynamic city regions as 'engines of growth' or the withdrawal of the state from spatial planning processes". However, recent research suggests that states are increasingly re-engaging in regional policy to enhance territorial cohesion, often through public investment and infrastructure development (Olesen 2023; Schindler and Kanai 2021). Consequently, hydrogen policies may also serve regional policy objectives.

Fiscal Policy

Given the financing requirements of industrial and regional policies, authors such as Bofinger et al. (2023) increasingly advocate for financing public policies and investments with public debt, suggesting the abandonment or weakening of fiscal rules. On the contrary, industrial policy is supposed to be fiscally constrained according to neoliberal theory (Spies-Butcher and Bryant 2024; Whiteside 2016). These constraints should reduce public spending and maintain macroeconomic stability, i.e., prevent state spending from stimulating consumption, which may meet limited supply and lead to inflation (Campbell 2020; Saad Filho 2018). Germany and the EU are subject to such fiscal rules, constraining their ability to finance industrial policies (Gabor 2023). Therefore, I examined the influence of persisting fiscal rules on (industrial) hydrogen policies.

Climate Policy

Neoliberal theory conceptualizes environmental problems, such as greenhouse gas emissions, as environmental externalities, which should be internalized through pricing, to not distort the governance function of markets (K. Bakker 2010; Castree 2008; Lockie 2013). From this perspective, carbon pricing is expected to drive cost-efficient defossilization, incentivizing firms with lower abatement costs to defossilize first. These early adopters contribute to technological innovation, reducing costs for later adopters and facilitating broader diffusion.

Despite the theoretical efficiency of neoliberal climate policies, empirical evidence indicates that many countries have increasingly relied on non-market-based climate policy instruments, such as renewable energy mandates and feed-in tariffs, over the past decades (Meckling, Sterner, and Wagner 2017). These policy tools incentivize the deployment of low-emission technologies rather than penalizing emissions, effectively functioning as vertical industrial policies. Moreover, such policies help mitigate competitive disadvantages arising from national-level carbon pricing in a globalized economy (Clark 1995). Against this background, I investigated the role of carbon pricing and less market-based climate policies for the development of the hydrogen sector.

Trade Policy

To counteract the competitive disadvantages associated with unilateral carbon pricing, the EU has historically allocated free carbon certificates to energy-intensive industries, which were expected to be at risk of carbon leakage – the relocation of emissions-intensive production to countries without carbon pricing (Åhman, Nilsson, and Johansson 2017; Bataille et al. 2016). However, this approach has weakened the effectiveness of the European Emissions Trading System (EU ETS). Consequently, starting in 2026, the EU will gradually phase out free certificates while introducing tariffs on emission-intensive imports from non-EU countries (so-called Carbon Border Adjustment Mechanism, CBAM; Dröge 2021; Graichen and Healy 2022).

As a protectionist instrument, the CBAM challenges the neoliberal free trade principles of the World Trade Organization (WTO) (Le Blanc 2023). In the context of growing geopolitical and geo-economic competition, Poitiers and Sekut (2024) warn that states may increasingly create trade barriers to restrict knowledge and technology transfers for industrial policy purposes. Such restrictions could slow the global diffusion of climate technologies. Hence, hydrogen policies potentially face a trade-off between industrial and climate policy goals.

2.2.4. State Agency in Global Production Networks

Given that the hydrogen sector is organized in global production networks, state intervention may be challenging. While a growing body of literature explores state agency in GPNs, it has largely focused on typologies of state roles and the extraterritorial influence of states through SOEs (Glassman 2011; Horner 2017; Lim 2018; McGregor and Coe 2021). A more comprehensive understanding is needed to capture extraterritorial state action beyond SOEs and to account for the diverse ways in which states shape GPNs. To address this gap, I have developed the concept of "extraterritorial state agency", which highlights that states can influence economic development beyond their borders through the CARM mechanisms. Nevertheless, whereas states can regulate industries within their territories, they find it difficult to do so outside their territories (Krisch 2022). Hence, the territorial reach of some instruments able to influence firms through the CARM mechanisms is limited. This raises the question of how the territorially uneven agency of states in deploying CARM mechanisms shapes economic developments in the green hydrogen sector.

2.3. Uneven Development

In this last sub-section of the theoretical part, I introduce the concepts that I use to explore the last research question, i.e. to what extent the hydrogen sector propels economic developments that align with or differ from historically uneven economic developments. This question is debated controversially. Some scholars argue that the hydrogen sector fits within existing politico-economic structures of wealth, knowledge, infrastructure, markets, financing, and political power, and thus represents a continuation of these structures (Fladvad 2023; Kalt et al. 2023; Müller 2024; Tunn et al. 2024). They argue that the plans of the German government and other Global North countries to export hydrogen technologies to the Global South while importing green hydrogen (derivatives) will exacerbate unequal ecological trade relations (Gabor and Sylla 2023).

Conversely, other authors argue that the materiality of green hydrogen challenges a simple reproduction of historically uneven developments. Firstly, the renewables pull effect speaks against the reproduction of historically unequal development between renewable energy-poor regions in the Global North and renewable energy-rich regions in the Global South (Samadi, Fischer, and Lechtenböhmer 2023). Secondly, the use of green hydrogen is far from cost-competitive with fossil fuels, requiring substantial subsidies or regulatory incentives (EWI 2024; Liebreich 2023; Odenweller and Ueckerdt 2025). As a result, governments or buyers need to pay for the additional costs of green hydrogen (derivatives), the so-called "green premium" (Caldeira, Duan, and Moreno-Cruz 2023), which governments in the Global South will unlikely be able to cover, given their fiscal constraints (Scholvin, Black, and Robbins 2025). Consequently, governments in the Global North will need to subsidize export-oriented green hydrogen projects in the Global South.

In light of these debates, I understand development as resulting from the interplay between human-made historical structures (i.e. uneven developments), the materiality of green hydrogen and its derivatives (articulated in the renewables pull), and the uneven agency of the involved actors. Based on this understanding, I investigated the development and geographies of green hydrogen markets as indicators of the importance of green hydrogen in the energy transition and its potential to foster economic development. Moreover, I employed the strategic coupling concept to examine the interface between local firms and regions, both in Germany and abroad, and their integration into the global economy.

2.3.1. *Market Development*

A nuanced analysis of the hydrogen sector requires differentiation within it, as research has demonstrated that renewable energy encounters distinct dynamics and challenges across various market segments and geographies (Dewald and Truffer 2012; 2011). More specifically, energy carriers constitute more or less important production cost factors in different industries, being particularly important as a location factor in energy-intensive industries (Michielsen 2013). Furthermore, different industries use different energy carriers at different costs, meaning that green hydrogen competes with energy carriers at different prices. Since hydrogen is currently traded both in its pure form and as component of various hydrogen derivatives, and is expected to gain market share in new markets in the future, such as steel production, the defossilization of these various market segments will exhibit different dynamics.

To analyze where green hydrogen markets emerge and where companies create value and jobs, I build on the lead markets and geography of markets literatures. Lead markets refer to the "most competitive market in which the nature of impending global changes is mirrored" (Barlett and Ghoshal 1990, 242). Hence, the creation of lead markets can create incentives for innovative firms to invest in these markets and, hence, foster economic development (Beise 2001). To better understand the geography of these markets, I follow Jones (2013), who identifies four spatial forms of markets: First, market folds describe intersections among two markets, such as electricity and hydrogen. Since green hydrogen production depends on access to renewable electricity, the form of renewable electricity markets will likely shape the form of green hydrogen markets. Second, markets are territorially differentiated, shaped by state regulation. For instance, the creation of a 'German' lead market for green hydrogen would provide specific investment incentives in Germany. Third, markets represent actor networks, especially connecting sellers and buyers, as well as, fourth, commodity flows. For example, green hydrogen markets and transport infrastructures connect actors in different places.

2.3.2. *Strategic Coupling*

The renewables pull and the carbon leakage concept highlight that climate action can incentivize firms to relocate. To analyze such relocation processes, this dissertation builds on the strategic coupling concept (H. W. Yeung 2016). Strategic coupling refers to "the dynamic processes through which actors in regions coordinate, mediate, and arbitrage strategic interests between local actors and their counterparts in the global economy" (H. W. Yeung 2009, 332). Local actors include firms and regional institutions, which are "not only regionally specific institutions, but also local arms of national/supranational bodies (e.g., a trade union's 'local' chapters), and extra-local institutions that affect activities within the region without necessarily having a presence (e.g., a national tax authority)" (Coe et al. 2004, 474). Strategic coupling processes involve negotiations between global lead firms and local actors regarding access to and use of regional assets, whereby regions are integrated into global production networks (Coe et al. 2004; H. W. Yeung 2015). I used the concept to analyze the negotiation processes between multinational firms and regions in the green hydrogen sector regarding location decisions.

From a temporal perspective, strategic coupling can take three distinct forms: initial strategic coupling, recoupling, or decoupling (MacKinnon 2012a). Initial strategic coupling occurs when global lead firms access regional assets in previously untapped markets through foreign direct investment, acquisitions, trading, or contractual agreements with local firms (Coe and Yeung 2015, 180). Over time, initial strategic couplings may evolve into recoupling – characterized by reinvestments in industrial assets and/or the restructuring of trade and contractual relationships with local firms – or decoupling, which entails divestment from regional assets and/or the termination of trade and contracts with local firms (Horner 2014; MacKinnon, Dawley, Pike, et al. 2019). Based on these thoughts, I argue that that new investments as part of new strategic coupling or recoupling dynamics improve the legitimacy of using the CARM mechanisms as long as firms do not increase prices to finance these investments. On the contrary, price increases and divestment, as a result of decoupling, undermine the legitimacy of using the CARM mechanisms (Manuscript I).

2.4. Summary of Theoretical Framework

Summarizing the theoretical framework, I explain uneven development as resulting from the interplay of structures and agency. Structures refer to the inherited infrastructures and sunk costs of the fossil-fuel based economy, which do not necessarily align geographically with the regional availability of sufficient, globally competitive renewable energy resources. Therefore, the adoption of green hydrogen could result in industrial relocations due to the renewables pull effect. To what extent industrial relocations materialize and green hydrogen is being adopted depends on the use of the CARM mechanisms by different actors. Therein, state institutions play an important role, even though their agency can be constrained in global production networks. Moreover, how states design policies depends on their adherence to neoliberal ideas. The (uneven) economic developments that result from the interplay of structures and agency can resemble historical forms of uneven development more or less (Figure 5).

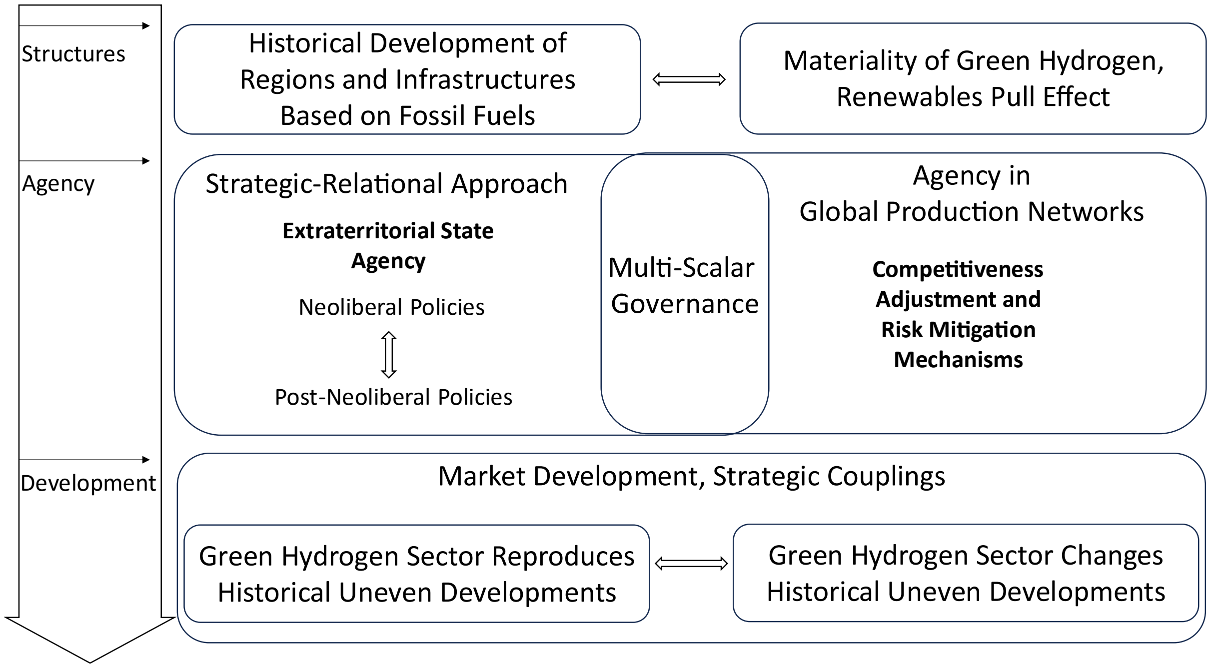

Figure 5: Visual Summary of the Theoretical Framework (bold indicates original conceptual contributions)

3. Research Design and Methods

The theoretical framework was developed and refined over four years of research (October 2020 – December 2024), and applied to analyze empirical data gathered between October 2021 and September 2023. Given the international scope of Germany's hydrogen sector and the diverse applications of hydrogen and its derivatives, further refinement of the research focus was necessary. This was achieved by narrowing the analysis to specific countries, industries, and market segments within the hydrogen sector.

The geographical focus of this study is Germany, an especially relevant case due to its anticipated dependence on green hydrogen imports (van de Graaf et al. 2020). This dependence makes Germany a particularly suitable starting point for analyzing the emergence of international trade flows for green hydrogen. The international dimensions of the German hydrogen sector were examined through selected countries where the German government and other actors are involved in developing export-oriented green hydrogen projects.

Since Germany's hydrogen strategy is focused on non-European countries (Quitzow, Nunez, and Marian 2024), this dissertation investigates Namibia and South Africa. These two countries present distinct contexts, allowing for a comparative analysis of how green hydrogen project development varies across different settings (Seawright and Gerring 2008). In Namibia, hydrogen projects are under heightened public scrutiny due to its colonial history (Shilongo 2024). In addition, the country offers few infrastructures and industrial assets on which green hydrogen projects could build. In comparison, South Africa, as an industrialized BRICS member and a technology leader in synthetic fuels, offers a more established industrial basis for green hydrogen projects (Chireshe et al. 2025).

In addition to selecting specific countries, this research also focused on particular market segments within the hydrogen sector. Specifically, it examined the use of green hydrogen for the production of synthetic aviation fuels. In Germany, several cement companies plan to use their CO_2 emissions to produce synthetic aviation fuels, offering insights into the defossilization of both the cement and aviation industries. Furthermore, the focus on synthetic aviation fuels allowed me to analyze the international competitive dynamics between Germany and South Africa. In South Africa, plans exist to convert synthetic fuel production facilities from fossil feedstocks to green hydrogen. These plants would compete with the German cement producers' synthetic fuel plants for buyers in the aviation industry.

The empirical research was based on qualitative methods. Various data collection methods were combined, and the data were analyzed using Kuckartz's structuring content analysis[8] (Kuckartz 2014; Kuckartz and Rädiker 2022). A central challenge regarding the quality[9] of the empirical data was their validation, as few hydrogen projects exist on an industrial scale to date. Many data therefore reflected expectations and forecasts rather than reliable statements on costs and benefits. To validate the data, I actively sought to incorporate critical perspectives on the plans of the German government and the hydrogen sector in general (Liebreich 2023; Liebreich and Schmid 2024; Paul Martin et al. 2024; Shafiee and Schrag 2024). I then conducted triangulation (Flick 2017) to validate the data and derive my own conclusions following a critical realist interpretation (Cruickshank 2017).

The data collection included (1) participant observation of expert presentations, discussion panels, and conferences (Angrosino 2007; Archibald et al. 2019); (2) analysis of websites and documents (Noetzel 2018), particularly national hydrogen strategies (see Appendix); and (3) site visits to various production facilities to gain firsthand insights into the hydrogen sector. Sites visited included electrolyzers and other hydrogen production facilities, research institutes and pilot plants, technology developers' manufacturing facilities, and cement plants. Central to the study were (4) semi-structured expert interviews (see Appendix; Bogner, Littig, and Menz 2009; Helfferich 2022; Kaiser 2014; Niebert and Gropengießer 2014). These were conducted primarily online during the COVID-19 pandemic, with most being recorded and transcribed, with a few exceptions. The interviews, averaging one hour, were guided by the

[8] In Udo Kuckartz's structuring content analysis, deductive elements of category formation are combined with inductive elements of coding. This methodology allowed for a blend of theory-driven and subject-oriented analysis.

[9] See the quality criteria for qualitative research defined in (Steinke 2017).

respective research questions and conceptual perspectives. Actor-specific questions were also posed to assess the roles and influences of various stakeholders.

The empirical data collection was conducted in five work packages, which overlapped temporally. The research began with a first, exploratory work package between September 2021 and March 2022. Its aim was to capture the perspectives of a diverse[10] range of actors, providing an overview of the stakeholders in the German hydrogen sector, their positions, and their influence. Subsequently, three work packages collected data on specific topics, more or less in parallel between March 2022 and September 2023, with most interviews taking place until January 2023. Representatives from companies, ministries, labor organizations, academia, and civil society were interviewed. The second work package focused on hydrogen production sites in Germany and the regulation of the German and European hydrogen markets, primarily at the EU level. As part of this, a database of all known green hydrogen production projects in Germany was compiled. The third work package centered on innovation policy and technology development in Germany, detailing the largest government funding programs by financial volume and the hydrogen projects they supported. The fourth work package consisted of interviews were conducted with stakeholders from the cement, synthetic fuel, and aviation industries. A total of 112 interviews were carried out in Germany (see Appendix). In addition to the interviews I personally conducted, I had access to nine interviews conducted by my co-author, Frederick Coulomb, for two articles.

The fifth work package consisted of data collection in Namibia and South Africa and took place in February and March 2023. Together with Britta Klagge, Clemens Greiner, and Linus Kalvelage, I conducted 26 interviews in South Africa and Namibia (see Appendix). An additional 23 interviews were conducted in Namibia by Britta Klagge and Linus Kalvelage without my involvement but were used for joint publications. These efforts focused on analyzing and comparing export-oriented hydrogen projects in both countries and examining the influence of the German government.

4. Empirical Findings

Following the structure of the theoretical framework, this section presents the empirical findings. First, I contrast the physical-geographical conditions of green hydrogen production with the historical development of energy-intensive industries (4.1.). Highlighting the economic challenges associated with the adoption of green hydrogen, particularly in renewable-energy-poor regions of Germany, I then explain which actors, with what interests, exert influence on

[10] A diverse range of actor types from academia, government, trade unions, research, businesses, and politics from various federal states, as well as in relation to different application areas of hydrogen technologies, were interviewed.

German hydrogen policies and the German hydrogen sector (4.2.). Finally, the last sub-section explains the uneven developments that result from these dynamics (4.3.).

4.1. Structures: The Materiality of the Hydrogen Sector in Germany, Namibia, and South Africa

This section summarizes my findings regarding the first research question, namely how the uneven geographical distribution of renewable energy, the material properties of hydrogen, and the sunk costs of the fossil-fuel-based economy influence the development of the German hydrogen sector.

4.1.1. Natural Material Dependencies in Germany, Namibia, and South Africa

The uneven spatial distribution of renewable energy sources creates material dependencies that shape the energy transition. At the regional scale, wind and solar energy potentials vary significantly within Germany, Namibia, and South Africa, with onshore wind full-load hours differing by up to 100% within each country and photovoltaic capacity differing by approximately 30%. Moreover, cross-national disparities are even greater, as the best locations for onshore wind and solar energy generation in Namibia and South Africa exhibit full-load hours up to 100% higher than those in Germany (author's calculation based on: Fraunhofer ISE 2024; Hauser 2020; IEA 2019; Wirth 2020). These differences explain why specific actors prioritize certain regions for investment and why the German government is particularly interested in securing access to Namibia's and South Africa's renewable energy resources.

In Germany, offshore wind offers the highest full-load hours, making access to offshore wind capacity a critical regional asset for the green hydrogen sector. Similarly, in Namibia and South Africa, the most favorable renewable energy resources are concentrated in southwestern Namibia and northwestern South Africa, influencing the spatial distribution of green hydrogen projects.

Beyond renewable energy, biogenic carbon sources are also unevenly distributed. Countries such as South Africa possess greater biomass resources, making them more favorable for renewable carbon production compared to Germany. Given Germany's relatively large industrial carbon demand – driven by its extensive (petro)chemical industry – alongside its limited domestic renewable carbon supply, the country faces not only a renewable energy shortage but also a renewable carbon deficit (Manuscripts I, II).

4.1.2. Human-Made Material Dependencies in Germany and South Africa

The spatial mismatch between industrial energy demand and renewable energy potential constitutes a human-made material dependency that complicates the energy transition. In southwestern Germany, for example, the region's high population density and concentration of energy-intensive industries are poorly aligned with local renewable energy availability. Similarly, in South Africa, industrial energy demand historically followed coal reserves rather than renewable energy potential, creating a regional disconnect between energy-intensive industries and accessible renewable energy sources. To defossilize existing industrial assets, renewable electricity and green hydrogen must be transported across large distances – whether from within the country or from abroad. In this regard, South Africa's industrial heartland around Johannesburg faces similar infrastructural challenges as southern Germany (Manuscript II).

Already today, bottlenecks in electricity transmission grids constrain the transport of renewable electricity in Germany, Namibia, and South Africa. As a result, most planned green hydrogen production facilities are co-located with renewable energy sources in all three countries (Articles II, IV, Manuscript II). These findings underscore the multi-scalar nature of the renewables pull effect: while international green hydrogen transport is costly and infrastructurally complex, even national transmission grid constraints hinder the redistribution of renewable electricity. Consequently, the renewables pull effect is evident not only at the global but also the national scale.

While the location of some industrial assets presents challenges for defossilization, certain fossil-fuel-based infrastructures and industrial assets are perceived by their owners as opportunities. In South Africa, e.g., Sasol's existing synthetic fuel production facilities are being positioned for conversion from fossil fuels to green hydrogen and renewable carbon. In the short term, repurposing these existing facilities is more cost-effective than developing new synthetic fuel plants, given the high technology costs. However, as technology costs decline, purpose-built plants optimized for local renewable energy sources are expected to gain a competitive edge (Manuscript II). These findings indicate that the green hydrogen sector will initially reproduce historical patterns of uneven development but, over time, will create new opportunities for historically peripheral yet renewable energy-rich regions (Article II, Manuscript II).

Similarly, in Germany, the existing natural gas grid is often seen as an asset for overcoming electricity transmission bottlenecks by transporting green hydrogen instead of renewable electricity (Article II). However, reconverting hydrogen into electricity is highly inefficient and, at best, economically viable as a backup power source during dark doldrums ('Dunkelflauten'). Beyond this, green hydrogen can only serve as an alternative to electricity transport if end users require hydrogen directly, rather than as a medium for electricity storage. Consequently, significant portions of the natural gas grid are likely to become stranded assets (Article I).

4.1.3. Materially-Induced Challenges to the Economic Competitiveness of Green Hydrogen

To analyze the challenges that the competitiveness of green hydrogen faces, I applied the GPN 2.0 approach and its analytical categories cost/capability ratio, market development, financing, and risks. In terms of capability development, I found that R&D efforts in Germany have historically prioritized hydrogen applications in automobiles and decentralized heating – technological fields in which hydrogen competes with more mature and energy-efficient alternatives (Article III). Regarding industrial hydrogen use, German firms have comparatively limited capabilities in industrial applications where green hydrogen does not directly compete with electrification, such as cement production and synthetic fuels – two key industries analyzed in this dissertation. As a result, German firms in these industries rely on technology transfers from other countries or, where possible, seek alternatives such as biomethane to avoid using green hydrogen (Manuscripts I, II). Regarding green hydrogen production, some leading multinationals specialized in electrolyzer manufacturing and green hydrogen project development are headquartered in Germany and are well positioned to create and capture value in green hydrogen markets (Article IV).

The different cost components of producing green hydrogen (derivatives) create uneven geographical conditions for its production and use. Renewable electricity represents the dominant cost factor, reinforcing the renewables pull (Article II). The second largest cost component – capital investment costs in electrolysis and related infrastructure – is currently geographically undifferentiated, due to free trade rules and the relatively low transport costs of technologies. However, industries already using gray hydrogen require less capital investments to switch to green hydrogen, creating sector-specific cost advantages (Manuscript II). Geographically uneven financing costs suggest that hydrogen projects will initially be developed in the Global North, where financing costs are lower compared to the Global South (Manuscript II). Last, infrastructure and transport costs favor the use of hydrogen in geographical proximity to its production (Article II, Manuscript I).

In regard to the cost/capability ratio of green hydrogen use, forecasts about the future costs of green hydrogen became increasingly pessimistic – or realistic – over the course of this dissertation (cf. Baker 2024; Bindman 2024; Snieckus 2021; IEA 2019). Several studies (e.g., Dahal et al. 2021; Shafiee and Schrag 2024) indicate that even as capability development reduces costs over time, green hydrogen and its derivatives will struggle to achieve cost parity with gray hydrogen and fossil fuels. Consequently, the adoption of green hydrogen in the sectors analyzed – cement and synthetic aviation fuel production – would result in higher production and service costs, affecting downstream industries such as aviation (Manuscripts I, II).

Due to its persistent cost disadvantage and the technological capability challenges outlined above, the development of markets for green hydrogen and its derivatives is entirely dependent on state intervention. In the absence of well-defined markets, securing private financing for green hydrogen projects remains difficult, as investors perceive substantial risks linked to demand uncertainty. Additionally, investors associate high political risks with green hydrogen investments, given that their economic viability is contingent on state support – such as subsidies, mandates, or carbon pricing – which remains subject to shifting political priorities, particularly in the context of climate policies (Article IV, Manuscripts I, II).

4.2. Agency of the German State and Other Actors

In view of the missing competitiveness of green hydrogen, its uptake depends on interventions by various actors, particularly the state. The following sub-section answers the second research question of which actors try to make green hydrogen (derivatives) competitive with fossil fuels and which CARM mechanisms they use for this purpose (4.2.1.). Moreover, I outline the key actors and conflicts of interests shaping German hydrogen policy (4.2.2.) and answer the third research question, namely to what extent hydrogen policies reflect neoliberal ideas (4.2.3.). Finally, I assess the agency of the EU and the German state in global production networks (4.2.4.).

4.2.1. Competitiveness Adjustment and Risk Mitigation Mechanisms (CARM)

I scrutinized how different actors, especially the EU and the German national government, have employed the four CARM mechanisms to support the green hydrogen sector. First, the EU's emission trading system increases the costs of emission-intensive production. However, current carbon prices remain insufficient to incentivize large-scale adoption of green hydrogen alone (Manuscript I). In response, the EU and the German state have provided billions of euros in subsidies to reduce investments costs and support capability development, mostly in Europe and Germany but – to a lesser extent – also South Africa (Article III, Manuscript II).

Second, the EU and the German government support the creation of green hydrogen (derivatives) markets by subsidizing the development of green hydrogen infrastructures (Article III). In addition, mandates require specific industries to use green hydrogen derivatives. For instance, beginning in 2026, the aviation industry must use at least 0.5% synthetic aviation fuels at all German airports, with the mandated share increasing to 35% by 2050. Non-compliance results in financial penalties, ensuring demand for green hydrogen derivatives (Manuscript II).

Third, public subsidies play a critical role in financing hydrogen projects by offsetting investment risks and improving access to capital. Moreover, green hydrogen projects increasingly leverage climate finance instruments, such as green bonds, to secure private financing under more favorable terms in Europe (Manuscript I). Thus, the hydrogen sector – as least within the EU – benefits from preferential financing conditions.

Fourth, risk mitigation remains crucial. Both the EU and the German government subsidize institutions that sign binding offtake agreements, reducing demand risks (Article IV). Furthermore, both governments fund demonstration projects, enabling firms to build heritage and showcase the reliability of their technologies. Despite these efforts, private buyers remain unwilling to sign long-term offtake agreements, which are crucial for producers to secure project financing (Manuscript II). Consequently, financial commitments for large-scale green hydrogen projects are lacking, limiting the pace of market development.

4.2.2. Actors, Interests, and Influence on the State

Following the strategic-relational approach, I researched which actors try to make green hydrogen competitive and to what extent they can mobilize state institutions to serve their interests. This analysis was conducted across different governance levels (Article I), policy fields (Article IV), and the history of hydrogen policy (Article III). I also examined the inconsistencies in policies across government levels (Manuscript II) and intra-governmental coordination aimed at mitigating these inconsistencies (Article IV).

Support for green hydrogen in Germany is high since fossil fuel prices in Europe are uncompetitive in international comparison following the end of pipeline-based fossil fuel trade between the EU and Russia in the wake of the Russia-Ukraine war. In this context, green hydrogen offers a “desperate offensive” (“eine Flucht nach vorn”) for German (energy-intensive) industries (BCG and IW 2024, 6). Therefore, broad-based support for green hydrogen (policies) exists among industrial associations, labor unions, and climate action advocates. Moreover, there is widespread consensus that hydrogen imports will be necessary, given Germany’s limited renewable energy resources relative to the expected future energy demand (Article IV).

Conflicts of interest exist regarding the sustainability of the hydrogen sector. Environmental and international organizations call for stricter sustainability standards than those proposed by industry representatives (Article I). Standards should prevent the externalization of unresolved domestic conflicts surrounding the expansion of renewable energy and the environmental damage, land, and water usage associated with green hydrogen production. Additionally, there is disagreement over whether the state should support alternative forms of hydrogen production beyond green hydrogen. While industry representatives – except the German Renewable Energy Association – support the inclusion of blue hydrogen, environmental organizations oppose it (Article I).

Regarding hydrogen use, actors such as the Federation of German Industries (BDI), the gas industry, municipal utilities, and parts of the German automotive industry advocate for widespread hydrogen deployment, arguing that imported hydrogen will be abundant and cost-competitive. However, critics – including segments of the academic community and environmental organizations – challenge these assumptions, emphasizing hydrogen’s inherent energy inefficiencies and forecasting that it will remain scarce and costly. These critics argue that direct electrification should be prioritized wherever feasible (Articles I, III). Furthermore, industries mandated to adopt green hydrogen derivatives, such as aviation, express concerns over the cost implications (Manuscripts I, II).

The renewables pull effect is relevant to understand conflicts of interest across scales. At the regional scale, various German federated states seek to leverage the green hydrogen sector for economic development. However, states in Southern Germany face a structural disadvantage due to their limited renewable energy resources for green hydrogen production. They have lobbied the EU to relax regulations regarding the renewable electricity sourcing criteria for green hydrogen production (Article II). At the international scale, German industry representatives and labor unions advocate for hydrogen imports as a means to sustain energy-intensive industries domestically, resisting pressures to relocate production to regions with superior renewable energy resources (Manuscript II). Conversely, some end-users, particularly in the aviation sector, argue that green hydrogen derivatives – such as synthetic jet fuels – will be more cost-effectively produced abroad and, therefore, demand that the state prioritizes the facilitation of imports (Manuscript II).

The conflicts lead to regulatory delays, create uncertainty for investors and slow market development. The legitimacy of hydrogen policies depends on two key factors: first, the extent to which they result in cost increases for end-users, and second, the distribution of (re-)investments within Germany and internationally. The German national government's policies reflect the underlying, competing interests. Despite the renewables pull effect, its financial support focuses on domestic green hydrogen production. Green hydrogen is framed as an opportunity to defossilize Germany's energy-intensive industries while simultaneously creating and securing access to green lead markets (Manuscript I). However, in the long term, the German government anticipates that the majority of green hydrogen and its derivatives will be imported (Articles III, IV). To this end, the German government has already begun subsidizing R&D, industrial demonstration projects, and large-scale commercial ventures abroad, which should not only produce green hydrogen and its derivatives but also energy-intensive (pre)products such as iron, thereby fostering competition between domestic and international producers (Article IV, Manuscript II).

4.2.3. Hydrogen Policies: Variegated Post-Neoliberalization

How the German state pursues the interests of competing social forces reflects variegated post-neoliberalization processes. The findings suggest that in some policy fields, German hydrogen policy adheres to neoliberal ideas, whereas in others, it follows post-neoliberal ideas.

Regarding SOEs, German hydrogen policies follow the neoliberal emphasis on private entrepreneurship and do not reflect typical examples of state capitalism. Attempts to establish an SOE to develop Germany's hydrogen pipeline infrastructure failed to receive the necessary political backing (Manuscript II). Only at the local level are municipal utilities (Stadtwerke) employed for investments in hydrogen projects (Articles II, III). However, the German state uses private companies to pursue strategic goals and exerts considerable influence on them.

Therefore, I have argued that German hydrogen policies reflect elements of neoliberalism and state capitalism (Article IV).

Besides the lack of large-scale SOEs, German and European policymaking is further constrained by the persistence of fiscal rules, the so-called 'debt brakes'. Unlike the US and China, the EU and Germany cannot finance green hydrogen subsidies through public debt. These fiscal rules limit the scale at which the state can make subsidies available and, hence, limit opportunities for policy capture. They also shape how subsidies are allocated. Subsidy programs of the German government and the EU must have a predefined budget to ensure compliance with debt rules. In contrast, subsidy schemes in the US do not require pre-defined budgets. Hence, subsidies can be granted to a theoretically unlimited number of firms. Consequently, German and European funding policies focus more on R&D as opposed to broad-scale deployment in the US. Moreover, competition for funding is more intense in Europe, and delays and uncertainty often accompany subsidy disbursement (Manuscript II).

Given the economic importance attributed to hydrogen, one might expect the EU and German government to adopt measures aimed at preventing technology transfers abroad. However, in practice, the German government supports international R&D projects, facilitating international technology transfers in the process. One reason for this is Germany's dependence on foreign technology leaders in industries such as the production of synthetic fuels and cement (Manuscripts I, II). This adherence to the neoliberal ideal of open (technology) markets promotes the international diffusion of climate technologies but stands in tension with more protectionist industrial policy goals (Manuscript II).

While the previous paragraphs point towards the continuity of neoliberal ideas, a range of results indicates a variegated post-neoliberalization process. First, German and European industrial policies deviate from neoliberal, horizontal approaches but are not entirely mission-oriented. Instead, they follow a vertical industrial policy, promoting hydrogen technologies through facilitative and regulatory means, even in sectors where cheaper alternatives exist, such as heating and automobiles (Article III).

Second, the mandates for using green hydrogen (derivatives) also diverge from neoliberal ideas. The mandates force certain industries to use green hydrogen while other industries that also depend on green hydrogen (derivatives) for defossilization, such as shipping or long duration energy storage, are not subject to similar regulations (Manuscript II). This form of vertical policy incentivizes transformation in some industries but not in others, deviating from the neoliberal emphasis on market-based, cost-efficient defossilization.

Third, the EU strengthens its carbon pricing policy – according to neoliberal theory the ideal tool to price externalities – by the introduction of the carbon border tariff CBAM (Manuscript

I). This protectionist measure marks a significant shift away from the neoliberal commitment to open, globally integrated markets.

Fourth, the German federal government also spatially steers the development of the hydrogen sector within the country by allocating subsidies to specific places (Article III). Allocation criteria include, in particular, the goal to support regions undergoing structural economic change. In this sense, the state follows a dedicated regional policy approach that diverges from the neoliberal policy idea of concentrating funding on 'engines of growth'. Likewise, the German government subsidizes projects abroad for political rather than purely cost-efficiency reasons.

4.2.4. State Agency in Global Production Networks Producing and Using Green Hydrogen

Given the international orientation of the German and European hydrogen strategy, the EU and the German government promote the development of international hydrogen markets. By selecting appropriate third countries, the EU and the German federal government steer the spatial development of the hydrogen sector. As a result, the scales and places where actors bear the costs of hydrogen projects and where actors accrue profits can diverge (Articles II, Manuscript II).

Subsidies for green hydrogen projects abroad are financed through the EU or federal budget. For example, the German government finances R&D projects in Namibia and South Africa (Article IV, Manuscript II). Moreover, the EU and Germany provide loans to third countries, enabling them to invest in hydrogen projects. However, the specific use of these loans for subsidies, equity acquisitions, or credit provision remains uncertain (Article IV). In any case, financing by third countries implies that these states assume project-related risks and may become financially liable to the EU in the event of project failure (Manuscript II). As of yet, neither the Namibian nor South African government has offered subsidies to export-oriented green hydrogen projects, so the EU or the German government will need to offset the green premium. Regulations, like the mandates, force buyers in Europe to cover the green premium, while enabling value capture abroad. For example, German airlines plan to buy synthetic fuels from South Africa to fulfill their mandates. Hence, synthetic fuel plants abroad will compete with synthetic fuel plants and refineries in Germany for supply contracts (Manuscript II).

Despite the introduction of the CBAM to enable higher carbon prices in Europe, the organization of some industries, such as the aviation industry, in global production networks, still constrains state agency. For example, airlines and passengers may re-route flights to avoid European airports and the synthetic fuel mandates, undermining the intended regulatory impact (Manuscript II). Hence, regulations that increase prices create competitive disadvantages and can lead to divestments by global lead firms. In contrast, subsidies provide incentives for global lead firms to (re-)invest (Manuscript I). The EU's and German government's willingness to pursue regulatory measures – despite potential competitive disadvantages, increased prices, and market contraction – underscores the influence of climate action proponents at both governance levels (Article IV, Manuscript I).

4.3. Impact of the German Hydrogen Sector on Uneven Development

This section examines the developmental implications of the German hydrogen sector, addressing the final research question: To what extent does the hydrogen sector reinforce or diverge from historically uneven economic development patterns? Development is understood as the outcome of interactions between pre-existing forms of uneven development, the material characteristics of green hydrogen, and the agency of actors shaping its deployment.

4.3.1. Development of Markets for Green Hydrogen, Derivatives, and Technologies

While the carbon price set by the EU ETS is insufficient to incentivize the use of green hydrogen (derivatives), it already makes other emission mitigation technologies, such as carbon capture and storage, economically viable today. Therefore, the markets of other emission mitigation technologies develop more dynamically (Manuscript I). In addition, regulatory instruments such as the EU ETS and mandates increase production and service costs in industries like aviation. Once firms pass these costs on to consumers, the market share of green hydrogen and its derivatives will increase within regulated segments (e.g., jet fuel markets), but the absolute size of these markets will contract due to price-induced demand reductions (Manuscripts I, II).

Due to the missing competitiveness of green hydrogen, the geography of green hydrogen (derivative) markets reflects the geography of state incentives. In the absence of (inter-)national hydrogen pipelines capable of transporting hydrogen at large scale, the development of green hydrogen markets in Germany takes place at the local and regional scale. These markets connect producers, transporters, and buyers who frequently collaborate in close proximity. Production and use often takes place where hydrogen is already used today or where regional surpluses of renewable electricity exist. Thereby, new intersections between different markets – or market folds – emerge. In the future, the national government and natural gas pipeline operators plan to integrate the local and regional markets through international pipelines (Article III).

Beyond defossilizing existing gray hydrogen markets, Germany hosts numerous projects exploring green hydrogen use in new market segments, including mobility, heating, and industry (Articles II, III). The diversity of these initiatives reflects strong political support for hydrogen technologies. However, in applications where green hydrogen competes with direct-electric alternatives, its ability to capture significant market shares remains uncertain – if not unlikely – posing challenges to its broader role in the energy transition (Article III).

Projects abroad often focus on ammonia production, as ammonia is relatively inexpensive to transport and does not require renewable carbon feedstocks. Additionally, individual projects – e.g. in South Africa – plan to produce synthetic fuels. However, the realization of most large-scale projects abroad before 2030 remains uncertain due to the economic and political risks associated with international projects, the early planning stage of many initiatives, and limited available subsidies. Some smaller projects funded by the German government are under construction or already operational, but source (some of) their technologies – such as electrolyzers – from countries other than Germany, particularly China. As a result, if export markets for hydrogen derivatives and technologies emerge in the coming decade, they are likely to remain small. The role of German technology firms in these markets is uncertain. At present, German firms are primarily engaged in service markets related to project planning, feasibility studies, and consulting. Their strong participation in international projects suggests a competitive edge in these high-value service segments rather than in technology segments (Article IV).

4.3.2. New Strategic Couplings and Recouplings but no Decouplings (yet)

The use of the CARM mechanisms improves the competitiveness of green hydrogen (derivatives) in geographically uneven ways, exemplified by the allocation of subsidies to certain places (Article III). As a result, the CARM mechanisms create geographical uneven incentives for global lead firms to invest in green hydrogen.

In Germany, Namibia, and South Africa, I observed instances of new strategic couplings as global lead firms started to develop green hydrogen projects in regions where they have not been active before, although they have not made major investments yet. Examples include companies planning to produce ammonia, iron (Article IV), and synthetic fuels (Manuscripts I, II). These new production sites abroad are expected to compete with both planned and existing production facilities in Germany, potentially leading to the closure of domestic plants due to cost disadvantages (Manuscript II). However, German companies are involved in developing production capacities abroad. This generates new jobs in Germany related to the planning, development, and potentially the operation of these facilities abroad (Article IV). At the same time, jobs in energy-intensive production and associated value creation in Germany is at risk (Manuscript I).

I also investigated recoupling processes between cement companies in Germany, a synthetic fuel producer in South Africa, and their industrial assets. These recoupling processes reflect that multinational companies with operations across multiple countries prioritize defossilization efforts based on location-specific factors. In industries that depend on green hydrogen for defossilization, access to large volumes of cost-competitive green hydrogen is a prerequisite. However, additional factors – such as infrastructures, skilled labor, the technological capabilities of local suppliers and partners, and political frameworks – also influence investment decisions. As a result, companies may pursue hydrogen projects in locations that are not globally competitive for hydrogen production, such as Germany, but offer strong political incentives and technological expertise. Nevertheless, within Germany, firms tend to establish hydrogen projects in regions with superior renewable energy resources, leading to new uneven regional developments (Manuscript I). Furthermore, as hydrogen technologies become more competitive, energy availability will increasingly outweigh other location factors, strengthening the renewables pull (Manuscript II).

When recoupling is successful and companies invest in emission mitigation, two outcomes can be observed. First, plants prioritized by global lead firms in regard to defossilization develop new capabilities (Manuscript I). If multinational companies then aim to diffuse these capabilities across their global operations, plants with such expertise gain importance within the company's internal hierarchy. These locations evolve into hubs for training, research, and development, creating opportunities for value creation and capture. Second, companies are only willing to bear the costs of emission reductions if they can pass these costs on to buyers through higher product prices or if state interventions offset the financial burden. However, higher prices reduce demand as customers purchase fewer goods or trigger substitution effects if customers switch to cheaper alternatives (Manuscripts I, II).

Despite the risks of shrinking markets and intensified international competition, I have not yet observed instances of multinational companies actively decoupling from specific locations. This is largely because mandates for green hydrogen use in Germany will only take effect in 2026 and, initially, will apply to a limited share of total production. As a result, the full impact of these policies on market dynamics and location decisions remains uncertain. For now, multinational firms continue production in regions without access to – or plans for – affordable green hydrogen supplies, relying instead on fossil fuels (Manuscript I).

5. Discussion

The materiality of renewable energy sources and green hydrogen plays an ambiguous role in economic geography and political practice. Whereas economic geography often takes materiality for granted (Njøs et al. 2024), in political practice, actors mobilize materiality-related arguments in their interests. For example, gas grid operators mobilize the properties of hydrogen to advocate for repurposing natural gas infrastructure for renewable energy transport via green hydrogen.

The renewables pull concept is central to understanding how the materiality of renewable energy and green hydrogen influences the development of the green hydrogen sector (Samadi, Fischer, and Lechtenböhmer 2023). While previous research has primarily examined the renewables pull at the global scale, I adopt a multi-scalar perspective. My findings highlight significant regional disparities in renewable energy supply and demand within Germany, which existing infrastructure struggles to overcome.

The renewables pull concept provides a critical lens for evaluating the feasibility of plans imagining green hydrogen imports as a substitute for fossil fuel imports. For example, the German government assumes that infrastructure and transport costs will play a minor role in the development of the hydrogen sector (Quitzow, Nunez, and Marian 2024). However, since energy transport costs will in reality become an increasingly important cost factor in an economy based on renewable energy sources, it seems unlikely that the German government and German buyers will be willing to permanently bear high energy transport costs to enable the production of energy-intensive products in Germany instead of buying cheaper energy-intensive products from abroad. As a result, climate-neutral energy-intensive industries in Germany will face growing competition from climate-neutral production abroad and may eventually relocate (similarly Verpoort et al. 2024; Eicke, Kramer, and Quitzow 2024). Consequently, I argue that the spatial restructuring of production driven by green hydrogen-based production will be more profound than suggested by studies that frame the hydrogen sector primarily as a continuation of colonial or other historical development patterns (e.g., Gabor and Sylla 2023; Kalt et al. 2023; Tunn et al. 2024).

To conceptualize the agency of different actors in making green hydrogen competitive with fossil fuels, I developed the CARM mechanisms based on the GPN 2.0 approach (Coe and Yeung 2015). As in regard to the GPN 2.0 approach, these mechanisms are not exhaustive and could be further expanded (G. Yeung 2016).

The capability concept allowed me to engage with research and innovation trying to make green hydrogen more (cost-)competitive. Based on the assumption that green hydrogen prices would fall rapidly as a result of capability development and against the background of uncompetitive fossil fuel prices in Europe, green hydrogen has been imagined as a win-win situation for industrial development and emission mitigation in Germany. This narrative has contributed to the high legitimacy of the hydrogen sector since 2020, leading the EU and the German government to intensively deploy the CARM mechanisms. Similar findings regarding the strong political legitimacy of green hydrogen support in Germany have been reported by other scholars (Belova et al. 2023; Flath, Kemmerzell, and Knodt 2023; Kern, Schmelzle, and Hummel 2023; Löhr, Markard, and Ohlendorf 2024; Ohlendorf, Löhr, and Markard 2023).

Given that cost forecasts are an essential, performative indicator driving the development of the green hydrogen industry, this dissertation encountered a key methodological challenge in the absence of a robust strategy for validating these forecasts. To address this issue, I argue that economic geography should go beyond constructivist, future-oriented concepts, such as expectations, visions, and imaginaries (Benner 2024; H. Gong 2024; Steen 2016). They seem ill-equipped to conceptualize the material constraints on capability development and, hence, cost developments. Instead, I suggest to integrate methods of future analysis, such as reference class forecasting (Servranckx, Vanhoucke, and Aouam 2021) or learning curves (Samadi 2018). These methodologies clarify that cost declines are neither random nor universally transferable across technological fields. Thus, the historical collapse in renewable electricity generation costs does not necessarily imply a parallel trajectory for green hydrogen production (Rambøll 2023).

While state intervention in the hydrogen sector has enjoyed strong public support in recent years, the precise mode and extent of this intervention remain contested. Hydrogen policies reflect a variegated post-neoliberalization process across different policy fields (Brenner, Peck, and Theodore 2010; Peck, Brenner, and Theodore 2018). A critical avenue for future research is to investigate why some policy fields continue to reflect neoliberal orientations, whereas others have shifted towards post-neoliberal approaches.

In regard to industrial policies, green, mission-oriented, and other sustainability-oriented approaches have gained prominence (Mazzucato 2018b; Rodrik 2014). However, as industrial policies gain acceptance and the financial volume of subsidies increases, so too does the risk of policy capture. A diverse array of actors advocates for hydrogen deployment in areas where more cost-effective direct electrification alternatives exist. This advocacy is often motivated by either a strategic intent to delay electrification or a perception of competitive advantage in hydrogen-based technologies (similarly Belova et al. 2023; Szabo 2021; Wright, Nyberg, and Bowden 2024).

At the same time, the persistence of (neoliberal) fiscal rules constrains the state's ability to further expand subsidies for hydrogen technologies that are unlikely to contribute cost-effectively to the energy transition. Although the abolition of these fiscal rules is increasingly debated, they remain in place (Schneider 2023; Seelkopf and Haffert 2024). Hence, the persistence of neoliberal ideas in some policy fields, such as fiscal policy, undermines post-neoliberal policy approaches in others, i.e. industrial policy. However, post-neoliberalization within one policy field can as well reinforce neoliberal approaches in another policy field, as could be observed in regard to the CBAM, which strengthens the neoliberal carbon pricing approach to climate policies. These dynamics underscore the inherently variegated nature of post-neoliberalization (Peck, Brenner, and Theodore 2018; Brenner, Peck, and Theodore 2010).

My research also shows that the EU and the German government have increased their agency in driving emission mitigation in global production networks by adopting post-neoliberal policies (Åhman, Nilsson, and Johansson 2017; Bataille et al. 2018; Coe and Gibson 2023). Trade policies, like the CBAM, are less oriented towards the neoliberal policy ideal of free trade and more oriented towards climate policy goals, such as preventing carbon leakage (Weinhardt and Ville 2024). However, while protectionist trade policies may help maintain the competitiveness of European industries in domestic markets despite the adoption of higher-cost climate-neutral production processes, they do not shield European producers from competitiveness losses in export markets, where rising production costs due to carbon pricing pose a structural disadvantage (Bellora and Fontagné 2023).

A post-neoliberalization process is also emerging in technology trade policies. Although technology markets between the EU and other countries remain largely open, parts of the European hydrogen sector have long lobbied for local content rules to ensure that publicly funded hydrogen projects use European technologies (Hydrogen Europe 2024). Consequently, as of late 2024, new EU funding programs will impose restrictions on the share of Chinese electrolyzers used in hydrogen projects. If Chinese electrolyzers eventually surpass their European counterparts in terms of cost-efficiency, import tariffs could inflate project costs in Europe, thereby hindering the energy transition (Currie 2024). Therefore, future research should assess the trade-offs between industrial policy objectives and the international diffusion of climate technologies (Manuscript II, Poitiers and Sekut 2024).

Despite significant incentives from the German state, the EU, and other actors, a growing implementation gap has emerged between announced green hydrogen projects and those currently in realization (Odenweller and Ueckerdt 2025). Various actors now express doubts regarding the feasibility of green hydrogen (and its derivatives) becoming cost-competitive with gray hydrogen and fossil fuels by 2050 (Baker 2024; Bindman 2024; Collins 2024; Polly Martin 2024), whereas the opposite was true a few years ago (Snieckus 2021; IRENA 2020b; IEA 2019). The Energy Economics Institute at the University of Cologne recently estimated that achieving the goals of the German hydrogen strategy faces a funding gap of up to 10 billion euros annually by 2030 and up to 200 billion euros annually by 2045 (EWI 2024). In view of these financial challenges, the federal government has shifted its focus away from green hydrogen towards blue hydrogen and lobbied the EU to relax its regulatory requirements regarding the use of renewable electricity in green hydrogen production (Habeck 2024). These shifts underscore the deep entanglement of hydrogen in German industrial, energy, and climate politics. Rather than considering alternative pathways to defossilization, there has been a tendency to lower environmental standards, a development that increases the risks of lock-ins (cf. Brauers, Braunger, and Jewell 2021; Wright, Nyberg, and Bowden 2024).

As the realization grows that green hydrogen may not provide the anticipated win-win scenario for industrial growth and defossilization, a series of conflicts of interest have surfaced. These tensions were not prominent in my early research or in the existing literature on

German hydrogen governance (Belova et al. 2023; Flath, Kemmerzell, and Knodt 2023; Kern, Schmelzle, and Hummel 2023; Löhr, Markard, and Ohlendorf 2024; Ohlendorf, Löhr, and Markard 2023). Nevertheless, the conflicts are intrinsic to German hydrogen politics, as my later research showed (Article II, Manuscript I, II).

Two conflicts of interest are integral to the geographical political economy of the German hydrogen sector. The first arises from the lack of cost-competitiveness of green hydrogen. Given the absence of cost-competitiveness, either the state or private buyers must absorb the green premium associated with green hydrogen. However, constrained by fiscal policies, the state can only mitigate the premium through subsidies to a limited extent and mandates that buyers opt for green hydrogen (and its derivatives) instead of gray hydrogen (and its derivatives). This creates a conflict between firms and labor unions advocating for green hydrogen, those supporting fiscal rules, and buyers primarily concerned with cost minimization. The second conflict stems from the renewables pull effect, which challenges the future viability of Germany's energy-intensive industries. This introduces a tension between producers, labor unions, and other stakeholders invested in maintaining industrial activity in Germany, and climate activists and buyers who prioritize a rapid and cost-efficient transition to renewable energy.

Looking ahead, the question arises as to how Germany will handle the competitive disadvantage resulting from the renewables pull once it becomes more publicly recognized. Already, the Alternative for Germany (AfD) warns about the implications of energy transition and hydrogen policies for the future of German industry (Deutscher Bundestag 2024a) and the cost of living in Germany (Deutscher Bundestag 2024b). In contrast, Meier (2024) advocates for the relocation of energy-intensive production from Germany to countries in the Global South, viewing relocations as means to counteract historically unequal development and part of a degrowth strategy. Given these two opposing political opinions, it seems necessary to think about industrial policy strategies that take the renewables pull into account and aim to create win-win scenarios between Germany and countries in the Global South (Samadi, Fischer, and Lechtenböhmer 2023). Developing such strategies is a task for future applied economic geography.

Outlines of a hydrogen strategy based on the import of energy-intensive intermediate products are already emerging. For example, Verpoort et al. (2024) argue that the most energy-intensive parts of production in Germany are associated with relatively low value-added and few jobs. Building on this observation, I suggest the development of governance mechanisms that facilitate the relocation of the most energy-intensive parts of production from Germany to the Global South. In return, Germany could benefit from more sustainable relationships with resource-producing countries, while German firms could participate in value creation abroad. To this end, Germany's hydrogen and raw material partnerships could be integrated and expanded. From an industrial policy perspective, companies that divest from energy-intensive production steps in Germany should be supported in internationalizing and establishing and operating corresponding plants abroad to participate in value creation. Within Germany, an industrial modernization strategy should be pursued, focusing on energy efficiency and higher-value forms of production, where energy is a smaller cost factor (cf. Wesseling et al. 2017). Such a strategy would also focus more on technologies that may be less developed than green hydrogen technologies but promise economic benefits besides reducing emissions, such as energy cost savings (Justnes 2012; Rippy, Bell, and Leick 2024). Ultimately, climate policies that create economic co-benefits would hopefully be more resilient against political opposition to climate action. Given the resistance to relocations from labor unions, new instruments must be developed to allow workers to participate in the internationalization and ecological modernization process, such as training programs.

In terms of price increases for buyers, my research showed that the political economy in Europe and Germany enables the EU and the German state to use regulatory measures, in contrast to Gabor's findings (2023). In this regard, the key challenge for ambitious climate policies does not seem to be the state's missing agency to regulate industries, but rather its apparent inability to compensate the resulting price increases for buyers through social policies that mitigate rising living costs of low-income households, who are particularly affected by climate-policy-driven cost increases (Edenhofer, Kalkuhl, and Roolfs 2021; Ohlendorf et al. 2021). This inability to integrate climate and social policies is exemplified by the failed attempt of the 20th German government, the so-called traffic light coalition ('Ampelkoalition'), to compensate households for rising CO_2 prices (Wille 2025). Against the background of uncertain majorities for climate policies, the costs of CO_2 abatement, induced by regulations, matter more than some social scientists, such as Gabor (2023) and Christophers (2022; 2024) acknowledge.

Although price increases have yet to materialize – since the mandates will only take effect in 2026 – such increases are likely to undermine the legitimacy of climate policies (Drews and van den Bergh 2016). Industries affected by regulation do not only include the aviation industry – the empirical focus of my research – but also industries delivering arguably more essential goods, such as the fertilizer industry, where production costs are directly correlated with food prices (Alexander et al. 2023). As regulations increase prices, they increase inflation (Hubertus and Schaefer 2023), while demand decreases (Manuscripts I, II).

My conceptual approach for researching development, based on the concepts of market development and strategic coupling, allowed me to examine positive and negative effects of climate policies on economic development on a case-by-case basis. While the EU and Germany accept higher production costs and thus a competitive disadvantage in export markets, they simultaneously create demand for more climate-friendly products within Europe, thereby establishing what are known as green lead markets (Manuscript I). Green lead markets can incentivize multinational companies to invest in the development of new climate-neutral production processes and technologies in certain countries, as long as those states can ensure demand for more expensive products. However, from an economic perspective, it is questionable to what extent the growth of green lead markets can offset the contraction of existing fossil markets (Manuscript I).

My theoretical framework and methodological approach did not enable me to research the macro-economic effects that subsidies and price increases have on economic development, especially in terms of inflation. In general, I think that contemporary economic geography, with its focus on regional development (Peck, Werner, and Jones 2023), is not well positioned for researching such macro-economic developments and would require major innovation to address them (see for a review of somewhat dated attempts to develop a macro-economic geography: Warntz 1957).

My thesis was also constrained because I did not include other countries with similarly ambitious hydrogen strategies in terms of technology development into the research design. However, differences between the German and European, the US American and Chinese policy approaches became apparent on the sidelines of my research. The US, at least under the Biden administration, pursued fiscally unconstrained industrial policy focusing on subsidies instead of regulations and CO_2 pricing (Gabor 2023). Moreover, the US concentrated funding on industrial hubs more than the EU (Eicke 2024). By contrast, the Chinese green hydrogen strategy – at the first glance – appears as an ideal-typical example of state capitalism (Alami and Dixon 2024). China uses SOEs to develop hydrogen technologies and build green hydrogen projects. It builds hydrogen projects much more quickly than Europe or the US (X. Gong, Quitzow, and Boute 2023; Nakano 2022). The country now accounts for 40% of the globally planned electrolyzer capacity, with investment decisions already made (IEA 2024). To better understand and compare these national green hydrogen strategies, research could draw from frameworks such as the varieties of capitalism literature (Bailey 2024; Nölke 2019; Bruff 2021).

In addition to distinguishing and comparing green hydrogen strategies internationally, contextualizing them within the broader scope of industrial and climate policy approaches would provide deeper insights into how geo-political and geo-economic competition shapes hydrogen policies. For example, China focuses more on (industrial) electrification than the US and Europe, and electrification is progressing faster in China than in the EU and USA (Barnard 2024). In comparison, the development of a US petro-state seems likely under the Trump administration, whereas Europe pursues ambitious climate policies, yet focuses less (effectively) on electrification than China (Liebreich and Worthington 2025).

6. Conclusion and Outlook

The emergence of green hydrogen markets promises new opportunities for the energy transition, particularly in energy-intensive industrial and mobility sectors that have made little progress so far (Markard 2018). However, considerable materially-induced economic challenges must be overcome before green hydrogen can be used at scale. To develop an understanding of these challenges, I analyzed, as my first research question, how the uneven geographical distribution of renewable energy, the material properties of hydrogen, and the sunk costs of the fossil fuel-based economy influence the development of the green hydrogen sector.

First, green hydrogen production and use are significantly less energy-efficient than the direct use of electricity and, hence, do not offer economic co-benefits such as energy cost savings. As a result, green hydrogen remains uncompetitive with gray hydrogen and fossil fuels, with cost reductions only expected in the long term (Baker 2024; Bindman 2024). In some cases – such as synthetic aviation fuels – cost-parity may never be achieved (Dahal et al. 2021).Therefore, the hydrogen sector is likely to contribute to the energy transition more slowly and in fewer applications than some stakeholders hope.

Second, the uneven geographical distribution of renewable energy sources and their materially-conditioned higher transport costs compared to fossil energy carriers are reshaping opportunities for value creation and appropriation. The high transport costs of green hydrogen impose material constraints to the agency of actors in integrating green hydrogen into inherited industrial structures, which developed under the assumption of low-cost fossil fuel transportation. As a result, energy is becoming a more critical location factor as the economy transitions to renewable energy sources (Samadi, Fischer, and Lechtenböhmer 2023; Verpoort et al. 2024). This shift creates latent conflicts of interest between regions rich in renewable energy but lacking energy-intensive industries and those with established industrial bases but limited renewable energy resources. These tensions raise fundamental questions about the future spatial organization of energy-intensive industries.

To examine the second research question, i.e. which actors seek to make green hydrogen competitive with fossil fuels and how they attempt to do so, I conceptualized the agency of different actors in adjusting the competitiveness of and mitigating risks associated with certain products in global production networks. My key conceptual contribution lies in developing the notion of extraterritorial state agency and competitiveness adjustment and risk mitigation (CARM) mechanisms, building on the GPN 2.0 approach (Coe and Yeung 2015). While firms, public research institutions, and financiers can employ the CARM mechanisms, state institutions play the central role in defossilizing global production networks. Therefore, I developed the concept of extraterritorial state agency to highlight the opportunities and constraints that states face in using the CARM mechanisms beyond their territorial boundaries.

Grounded in the strategic-relational perspective on the state (Jessop 2016), I understand the actions of state institutions as shaped by struggles for political influence among competing social forces. In Germany, state support for the hydrogen sector enjoys widespread legitimacy (Löhr, Markard, and Ohlendorf 2024). However, significant disagreements exist over the desirable policy instruments for supporting green hydrogen. These conflicts reflect processes of variegated post-neoliberalization (Brenner, Peck, and Theodore 2010; Peck, Brenner, and Theodore 2018).

To address the third research question of the extent to which hydrogen policies reflect neoliberal ideas, I used various conceptual perspectives, including state capitalism (Alami and Dixon 2024), mission-oriented innovation and industrial policy (Mazzucato 2021), and de-risking (Gabor 2023). My contributions in this regard are threefold. First, I problematized the definitional boundaries of state capitalism by examining the mobilization of private companies for strategic state objectives (Article IV). Second, I analyzed the influence of fiscal rules on contemporary industrial policy, differentiating between vertical, horizontal, and mission-oriented industrial policies while emphasizing their spatial dimensions (Article III). Third, I underscored the central role of regulatory instruments in the EU's and Germany's hydrogen policies and evaluated their potential price effects (Manuscript II).

The findings indicate that while hydrogen policies continue to be shaped by neoliberal ideas in policy fields such as state ownership policy and fiscal policy, other policy fields reflect post-neoliberal ideas. For example, the German government and the EU are promoting the hydrogen sector with tariffs, local content rules, vertical industrial and climate policies. However, the reliance on carbon pricing and regulatory mandates as key policy instruments means that the costs of green hydrogen adoption will largely be passed on to consumers, leading to higher living expenses that remain unmitigated by compensatory social policies. As a result, I expect that hydrogen policy will jeopardize the legitimacy of the energy transition (Drews and van den Bergh 2016). This concern is already evident among corporate buyers – such as those in the aviation industry – who perceive regulatory obligations as threats to both industrial competitiveness and market development.

The costs associated with Germany's hydrogen strategy are further increased because the German state, in the (short-term) interest of German firms and workers, seeks to defossilize the German industry within Germany rather than fostering the import of climate-neutral, energy-intensive (pre-)products from abroad. While there are instances of state support for hydrogen-based, energy-intensive production in the Global South, the dominant strategic focus remains on transporting green hydrogen (or its derivatives) to existing energy demand centers rather than establishing energy-intensive production sites in regions with globally competitive renewable energy resources. However, the renewables pull concept suggests that the latter approach would yield greater cost efficiencies and competitiveness in the long term (Samadi, Fischer, and Lechtenböhmer 2023; Verpoort et al. 2024).

The last research question addresses the extent to which the hydrogen sector propels economic development that is aligned with or differs from historically uneven economic developments. Understanding development as resulting from the interplay of structures and agency, I examined the economic implications of the hydrogen sector through the lens of strategic coupling (H. W. Yeung 2016) and the market developments observed in Germany, Namibia, and South Africa.

My research revealed that initial local and regional green hydrogen markets are emerging across Germany. According to the plans of gas transmission grid operators and the German government, these markets will eventually be integrated through a hydrogen pipeline network. However, long-term market dynamics remain uncertain, particularly in segments where green hydrogen competes with direct electrification. As a result, the ultimate scale and scope of the green hydrogen market require ongoing examination. Nevertheless, the nascent German green hydrogen market functions as a lead market, attracting the interest of global lead firms.

Applying the strategic coupling concept, I researched to what extent the use of the CARM mechanisms has incentivized global lead firms to either newly couple in Germany, Namibia, and South Africa, recouple with existing assets, or decouple (Manuscripts I, II). New strategic couplings could be observed in all three countries, as global lead firms have started to develop green hydrogen projects. However, the firms have often not made major investments as part of these new couplings yet, limiting their influence on economic development. I could observe recoupling dynamics in both Germany and South Africa, though, similar to new strategic couplings, recouplings have not resulted in large-scale investments in green hydrogen yet. Instead, significant investments are being made in carbon capture in the German cement industry, underscoring the persistent (cost-)competitiveness gap between green hydrogen and other emission mitigation technologies. Finally, I did not observe decoupling from either country but I expect that the green hydrogen mandates will lead to increasing prices and shrinking markets. Moreover, energy-intensive producers in Germany will increasingly compete with producers in renewable energy-rich regions in the Global South and elsewhere. Hence, I expect decouplings to materialize in the future, which present an important research object given the political conflicts they will involve.

Whereas the strategic coupling concept enabled me to research economic development implications on a case-by-case basis, it is less well suited to research the economy-wide effects of scaling green hydrogen use, particularly regarding price increases and inflation. Therefore, future research should integrate macro-economic approaches to assess the inflationary impacts of climate policies.

Methodologically, this work has demonstrated that research on transformation processes like the energy transition is inherently future-oriented. This should be reflected in corresponding methodological approaches, which, however, remain underexplored in economic geography (Steen 2016). Future research should also account for the geopolitical and geo-economic dimensions of emerging green industrial sectors and employ comparative frameworks to analyze international climate and industrial policy strategies.

In conclusion, the hydrogen sector has experienced a hype in recent years, fueling an investment surge that is expected to drive innovation. Even if only a fraction of the announced projects will materialize, these projects nonetheless represent the first attempt to defossilize entire energy systems. However, exaggerated hopes are often accompanied by disappointments (S. Bakker and Budde 2012; Konrad et al. 2012). A consolidation of both the hydrogen sector and political goals is therefore foreseeable. Given the escalating climate catastrophe, however, any revision of political goals should not result in diminished ambitions. Instead, it should serve as an opportunity to integrate lessons from the past years and strategically recalibrate Germany's hydrogen strategy to ensure long-term effectiveness (Walker et al. 2024).

7. Literature

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Summary of the Articles

While page II clarifies the contributions I made to each co-authored article, this section offers a brief summary of the articles and unpublished manuscripts (Table 4). I point out the relationships between each article and the research questions presented in the introduction, the theoretical approach of the dissertation, and the scholarly debates addressed. Each paper formulates detailed research questions that specify the overarching research questions presented in the introduction, which I repeat:

Question 1: How do the uneven geographical distribution of renewable energy, the material properties of hydrogen, and the sunk costs of the fossil-fuel-based economy influence the development of the German hydrogen sector?

Question 2: Which actors try to make green hydrogen competitive with fossil fuels and how do they attempt to do so?

Question 3: To what extent do hydrogen policies reflect neoliberal ideas?

Question 4: To what extent do the economic developments, the hydrogen sectors propels, align with or differ from historically uneven economic developments?

Article I: Walker, B., 2022. Governance der deutschen Wasserstoffwirtschaft. Standort 46, 265–270. https://doi.org/10.1007/s00548-022-00789-z

This article provides an overview of actors and conflicts of interest governing the German hydrogen sector. The article uses the governance concept as a heuristic and distinguishes between different segments of the green hydrogen value chain, namely production, transport, and use, to distinguish particular actors and conflicts of interest in regard to these segments. The article addresses the research questions one, particularly in regard to hydrogen transport, two, in regard to actors and their interests, and four, in regard to regional development in Germany.

Article II: Walker, B., Klagge, B., 2024. Infrastructure Bottlenecks as Opportunity for Local Development: The Case of Decentralized Green-Hydrogen Projects. Tijdschrift voor Economische en Sociale Geografie. https://doi.org/10.1111/tesg.12633

The article dives into the uneven geographical distribution of renewable energy sources and energy demand in Germany, focusing on how capacity constraints of the electricity grid in Germany constrain electricity trade and, thereby, opportunities to produce green hydrogen away from renewable energy sources. Hence, the article speaks to research on the materiality of energy and the research question one. In addition, the article is also concerned with the question of regional development and to what extent the green hydrogen sector offers new opportunities for development in rural and peripheral areas, thereby addressing research question four.

Article III: Walker, B., 2024. Place-based allocation of R&D funding: Directing the German innovation system for hydrogen technologies in space. Environmental Innovation and Societal Transitions 52, 100878. https://doi.org/10.1016/j.eist.2024.100878

This article reflects on subsidies for research and development on green hydrogen. It addresses the research questions two and three. Specifically, the paper speaks to research on mission-oriented policy – as one post-neoliberal industrial policy approach – and discusses to what extent German hydrogen policies follow this approach. Through an analysis of the criteria by which funding is allocated to different places in Germany, the paper also comes to the conclusion that regional policy goals play an important role in German hydrogen policymaking, thereby addressing the research question concerning uneven development.

Article IV: Kalvelage, L., **Walker, B.**, 2024. Strategic coupling beyond borders: Germany's extraterritorial agency in Namibia's green hydrogen industry. Journal of Economic Geography lbae036. https://doi.org/10.1093/jeg/lbae036

In this article, Linus Kalvelage and I develop the concept of extraterritorial agency to provide an understanding of how states can influence the development of global production networks abroad. We distinguish three mechanisms of extraterritorial agency, through which states can provide incentives to firm, namely asset creation, market development, and de-risking, i.e. making risk/return profiles more attractive. This approach is particularly helpful to understand the agency of German state institutions in supporting green-hydrogen projects abroad. It is also important to consider the agency of the German state from the perspective of international uneven development to reflect on whether the German state can and does pursue its interest against the interest of local stakeholders and the Namibian state. Hence, the article especially addresses questions two and four.

Manuscript I: **Walker, B.**, Coulomb, F. Climate action driving competitive dynamics and recoupling? Why cement lead firms plan to produce jet fuels in Germany. Unpublished manuscript, under peer review at Progress in Economic Geography.

In this unpublished manuscript, my co-author Frederick Coulomb and I further develop the mechanism-based approach of Article IV and adapt it to analyzing how different actors, particularly states, can make certain products, such as green hydrogen (derivatives), more competitive. Thereby, we address research question two. The paper develops a more comprehensive understanding of competitiveness adjustment and risk mitigation mechanisms (CARM). Moreover, it provides specific insights into how the uneven geographical distribution of renewable energy and renewable carbon sources influence defossilization efforts in the cement and aviation industries. Since these efforts result in uneven geographical development, the paper also adresses research question four.

Walker, B., Coulomb, F. The de-risking state in global production networks: Why and how the German state de-risks investments in synthetic aviation fuels. Unpublished manuscript, under peer review at Advances in Economic Geography (ZfW).

This last research paper focuses on risk mitigation or de-risking. The paper focuses on regulatory means of de-risking, i.e. regulations that increase the prices of unwanted products, in our case, fossil jet fuel. Against this background, the paper emphasizes that the EU and the German government use regulations to incentivize airlines to buy synthetic fuels. Thereby, we contribute to debates on (post-)neoliberalization in the de-risking literature (question two). Moreover, we discuss, based on the finding that renewable energy and renewable carbon sources are unevenly distributed between Germany and South Africa, the uneven developments that result from attempts to use synthetic fuels instead of fossil jet fuels. The paper highlights that the renewables pull offers new opportunities for development to energy rich regions in the Global South (question four).

A./ M. Nr.	Title	Research Questions	Conceptual approach	Central Results/Arguments
A. I	Governance der deutschen Wasserstoffwirtschaft	What governance functions are performed by different levels of government concerning the hydrogen sector? What conflicts of interest exist regarding the hydrogen sector in Germany?	Multilevel governance, value chains, uneven regional development	The division of labor between government levels corresponds to the governance of renewable energy installations; conflicts of interest concern the issue of direct vs. indirect electrification, as well as uneven regional development.
A. II	Infrastructure Bottlenecks as Opportunity for Local Development: The Case of Decentralized Green-Hydrogen Projects	How do infrastructure bottlenecks and the market design for green hydrogen influence the geography of green hydrogen markets in Germany, particularly the development of central and decentralized green hydrogen projects in different regions? What types of actors are involved in decentralized green hydrogen projects and why, i.e., what are their motivations? How do infrastructure bottlenecks support or hinder the development of decentralized and/or centralized production?	Geography of markets, spatial forms of markets, infrastructure bottlenecks, market regulation/design	The conflict between advocates of a decentralized/centralized energy transition also shapes the hydrogen sector. Electricity grid bottlenecks influence the locations of electrolyzers due to access to green electricity. EU regulation prevents electrolyzers from sourcing only virtual green power, resulting in a dual structure of green hydrogen production in Germany: large, centralized electrolyzers in northern Germany and small, decentralized electrolyzers across the country.
A. III	Place-based allocation of R&D funding: Directing the German innovation system for hydrogen technologies in space	To what extent is the allocation of R&D funding to locations in Germany mission-oriented, and how does it contribute to the formation of a green hydrogen market?	Place-based innovation policy, mission-oriented innovation policy, geography of markets	The allocation of funding is based on various place-based criteria (e.g., uneven regional development), industry and innovation policy is not mission-oriented but vertical.

A. IV	Strategic coupling beyond borders: Germany's extraterritorial agency in Namibia's green hydrogen industry	How can states influence strategic coupling processes beyond their territories? Why and how does the German state support the strategic coupling of the company Hyphen in Namibia? What impact have these efforts had on the Namibian state?	GPN-2.0, Strategic coupling, "mechanisms of extra-territorial agency" (= de-risking, market creation, asset creation), distancing, flanking	The support of private companies by the German government has advantages over the use of state-owned enterprises due to the perceived distance between the two in the eyes of other governments. The Namibian state agreed to the coupling of Hyphen due to the support of the company by the German government and the EU.
M. I	Climate action driving competitive dynamics and recoupling? Why cement lead firms plan to produce jet fuels in Germany	What economic challenges do climate-friendly cement and synthetic fuel production face? How do the EU, German state, and firms in three global production networks increase the competitiveness of these products in Germany? Why have the involved actors increased the competitiveness of the products the way they did?	GPN 2.0, strategic coupling, de-risking, climate finance, lead markets, renewables pull, CARM mechanisms	Government incentives, climate finance, and R&D are making climate-friendly cement production increasingly competitive in Germany. The renewables pull creates an incentive for companies to (re-)invest in regions with the most competitive renewable energy resources. Companies use organizational strategies to leverage or offset the competitive advantages and disadvantages of different locations.
M. II	The de-risking state in global production networks: Why and how the German state de-risks investments in synthetic aviation fuels	What role does regulatory de-risking play in the EU's de-risking strategy and why? Why and how do the German government and the EU attempt to reduce the risks of investments in the production of synthetic aviation fuels? What are the development policy implications of this?	De-risking, particularly regulatory de-risking, technology transfers, entrepreneurial reputation	Regulatory de-risking can be more effective than supportive (facilitative) measures. Regulatory de-risking leads to higher consumer prices and thus hinders economic growth. The German government actively promotes technology and reputation transfers between South Africa and Germany.

Table 4: Summary of the Articles, A. = Published Article; M. = Manuscript

Article I

Walker, B., 2022. Governance der deutschen Wasserstoffwirtschaft. Standort 46, 265–270. https://doi.org/10.1007/s00548-022-00789-z.

Governance der deutschen Wasserstoffwirtschaft

Zusammenfassung

Der Artikel analysiert die Governance der deutschen Wasserstoffwirtschaft mit Fokus auf die noch unerforschten geographischen Aspekte aktueller Konflikte, für die der Beitrag Verfahrensvorschläge formuliert. Es wird konstatiert, dass staatliche Förderprogramme die Verbreitung von Wasserstofftechnologien trotz teilweise hinderlicher Marktbedingungen finanzieren. Die Programme sind als Wettbewerbe ausgestaltet, richten sich an alle Industriebranchen und berücksichtigen keine strukturpolitischen Kriterien. Da Wasserstofftechnologien jedoch fossile Technologien in verschiedenen Industriebranchen ersetzen sollen, setzen sie in diesen Branchen einen Strukturwandel voraus und besitzen damit strukturpolitische Relevanz. Deshalb impliziert der Wettbewerb um Fördergelder latente Verteilungskonflikte im politischen Mehrebenensystem und zwischen den beteiligten Industriebranchen.

Der Artikel erörtert exemplarisch einige dieser Konflikte entlang der Wertschöpfungskette von Wasserstoff. Es wird angeregt, die Marktbedingungen zu verbessern, um den Finanzierungsaufwand der Förderprogramme zu reduzieren. Die Programme sollten zudem strukturpolitische Kriterien berücksichtigen und Strukturhilfemaßnahmen branchenübergreifend ausgehandelt werden. Dadurch könnten Synergien zwischen dem Wachstum der Wasserstoffwirtschaft und dem dafür notwendigen Strukturwandel realisiert sowie das Konfliktpotential aufgrund von Verteilungsfragen reduziert werden. Zukünftig ist davon auszugehen, dass mit zunehmender Anzahl und Größe von Wasserstoffprojekten lokale Konflikte um deren Standorte sowie zwischen Regionen um die wirtschaftlichen Auswirkungen der Projekte zunehmen werden.

Abstract

The article analyzes the governance of the German hydrogen economy. The focus lies on still unexplored geographical aspects of current conflicts, for which the article formulates procedural proposals. The article argues that state subsidy programs finance the diffusion of hydrogen technologies despite partially obstructive market conditions. The programs are designed as competitions, are aimed at all branches of industry and do not take structural policy criteria into account. However, hydrogen technologies should replace fossil technologies in various industrial sectors, so they presuppose a structural change in these sectors and are of structural policy relevance. Therefore, the competition for funding implies latent distribution conflicts in the political multi-level system and between the industrial sectors involved.

The article discusses some of these conflicts along the value chain of hydrogen. It is suggested to improve the market conditions to reduce the financing costs of the funding programs. The programs should also take structural policy criteria into account and structural aid measures should be negotiated across sectors. This way, synergies between the growth of the hydrogen economy and the necessary structural change could be realized, and the potential for conflict due to distribution issues could be reduced. In the future, it can be assumed that the increasing number and size of hydrogen projects, local conflicts over their sites and between regions over their economic effects will increase.

Keywords: Wasserstoffstrategie, Markthochlauf, Strukturpolitik, Förderprogramme, Verteilungskonflikte

1. Einleitung

Mit Wasserstoff soll die vollständige Defossilisierung des deutschen Energiesystems gelingen. Wasserstoff kann erneuerbare Energie langfristig speichern, ist interkontinental transportierbar und kann in den vier Verbrauchssektoren des Energiesystems, dem Strom-, Mobilitäts-, Industrie- und Wärmesektor, genutzt werden (BMWi 2020).

Jedoch setzt der Markthochlauf der Wasserstoffwirtschaft (die Verbreitung von Wasserstofftechnologien) eine Transformation der vier Verbrauchssektoren und der dazugehörigen Industriebranchen voraus. Während die bislang auf den Stromsektor fokussierte Energiewende die Geschäftsmodelle weniger Industriebranchen – wie der Kohleindustrie – gefährdete (Walker et al. 2021), stellt der Hochlauf der Wasserstoffwirtschaft die auf fossiler Energie beruhenden Geschäftsmodelle weiter Teile der deutschen Industrie in Frage. Damit geht insbesondere in denjenigen Regionen Deutschlands ein Strukturwandel einher, in denen die betroffenen Industriebranchen konzentriert sind. Zugleich verspricht die Wasserstoffwirtschaft diesen Industriebranchen aber auch neue Wertschöpfung und Arbeitsplätze (Abb. 6).

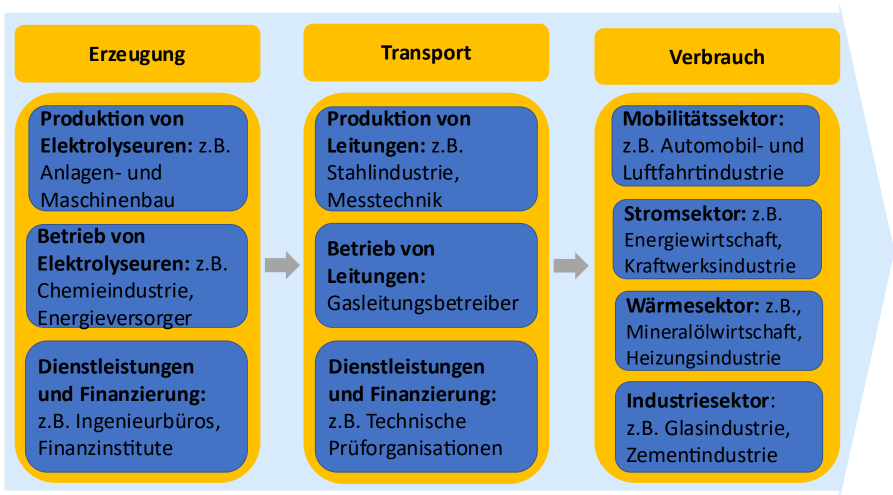

Abbildung 6: Segmente der Wasserstoffwertschöpfungskette und wichtige, beteiligte Branchen (eigene Darstellung)

Noch ist klimaneutraler (mit erneuerbarer Energie erzeugter) Wasserstoff jedoch gegenüber fossiler Energie nicht wettbewerbsfähig (Agora Energiewende und Guidehouse 2021). Der Markthochlauf ist also von Fördermitteln abhängig, deren Ausgestaltung im politischen Mehrebenensystem aufgrund der strukturpolitischen Auswirkungen umstritten ist und geeigneter Koordinationsstrukturen bedarf. Darum sollte sich die angewandte Geographie mit den Hintergründen der Konflikte beschäftigen und an der Formulierung von Verfahrensvorschlägen mitwirken. Sie kann dabei an Beiträge zur Governance der Energiewende (Klagge 2013) und der Wasserstoffwirtschaft (Hisschemöller et al. 2006) anknüpfen.

Die Literatur bietet bislang aber nur partielle Einblicke in die Governance der Wasserstoffwirtschaft. In Deutschland fokussierte die Governance-Forschung zur Wasserstoffwirtschaft auf die Automobilbranche (Budde und Konrad 2019), die zuerst ein kommerzielles Interesse an Wasserstofftechnologien entwickelte (Hekkert et al. 2005). Die ebenfalls an Wasserstoff interessierte Forschung zur Governance der Energiewende konzentrierte sich auf den Stromsektor (Walker et al. 2021). Die Koordination der gesamten Wasserstoffwertschöpfungskette fand hingegen bisher keine Aufmerksamkeit.

Dieser Forschungslücke widmet sich der folgende Artikel. Hierzu wird zuerst die Verteilung von Steuerungsfunktionen auf unterschiedliche Governance-Ebenen untersucht. Sodann werden entlang der drei Segmente Erzeugung, Transport und Nutzung Interessenskonflikte analysiert. Abschließend formuliert das Fazit Verfahrensvorschläge und erklärt weiteren Forschungsbedarf. Die Analyse basiert auf der Auswertung von Positionspapieren und Studien, der Teilnahme an 28 Fachveranstaltungen sowie 34 leitfadengestützten Interviews mit Vertreter*innen aus Wirtschaft, Zivilgesellschaft, Forschung und Politik, die zwischen Juli 2021 und März 2022 geführt wurden.

2. Mehrebenen-Governance des Markthochlaufs

Die Governance des Markthochlaufs kann anhand der Verteilung von Steuerungsfunktionen auf unterschiedliche Ebenen betrachtet werden. Auf europäischer, nationaler, regionaler und lokaler Ebene sind Beteiligte aus Wirtschaft, Wissenschaft, Zivilgesellschaft, Verwaltung und Politik in Netzwerken organisiert, in denen sie Einzelmaßnahmen erarbeiten. Die einzelnen Maßnahmen werden auf den verschiedenen Ebenen in den Wasserstoffstrategien der Regierungen zusammengefasst. In deren Entwicklung und Monitoring sind wiederum Stakeholder-Gremien wie der Nationale Wasserstoffrat einbezogen (vgl. z.B. BMWi 2020).

Neben der horizontalen Koordination unter den Beteiligten einer Ebene dienen die Wasserstoffstrategien auch der vertikalen Koordination zwischen den Ebenen, indem sie den Beteiligten gegenseitig Orientierung bieten (Abb. 7). Die vertikale Koordination ist jedoch kaum formalisiert. So können zwar z.B. die Länder an Treffen des Nationalen Wasserstoffrats teilnehmen (BMWi 2020), die Koordination unter den Ländern und Kommunen ist jedoch nicht explizites Ziel der Nationalen Wasserstoffstrategie.

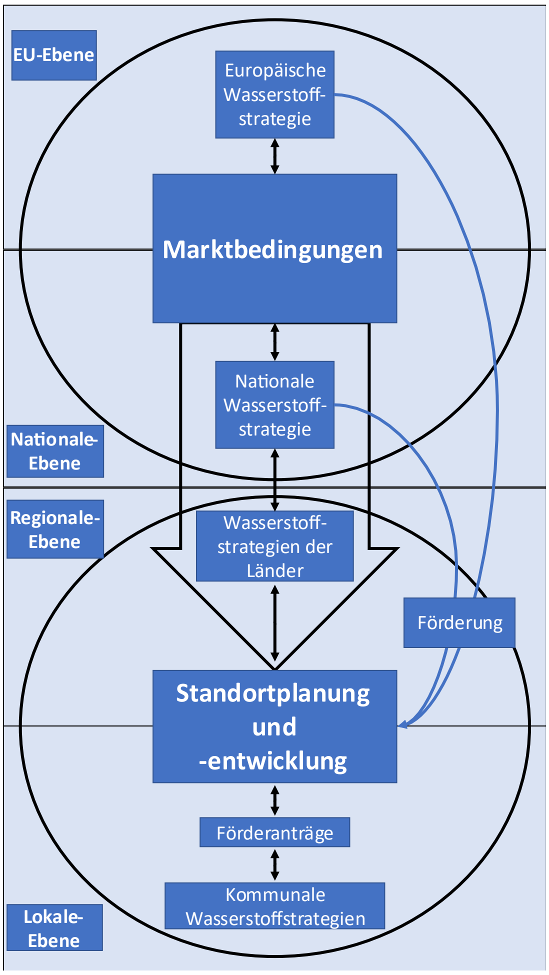

Abbildung 7: Mehrebenen-Governance des Markthochlaufs der deutschen Wasserstoffwirtschaft (eigene Darstellung)

Die schwache vertikale Koordination verstärkt die Arbeitsteilung zwischen den Ebenen, die in Anlehnung an die Governance-Forschung zum Ausbau Erneuerbarer-Energien-Anlagen (Klagge 2013) wie folgt beschrieben werden kann. Auf europäischer und nationaler Ebene werden mit regulatorischen, steuer-, infrastruktur- und wirtschaftspolitischen Maßnahmen die Marktbedingungen gestaltet. Außerdem werden auf diesen Ebenen die finanzstärksten Förderprogramme ausgehandelt. Dagegen werden auf regionaler und lokaler Ebene Wasserstoffprojekte an spezifischen Standorten entwickelt und dafür Förderanträge erarbeitet (Abb. 7).

Bislang wird der Markthochlauf von Förderprogrammen bestimmt, weil die Marktbedingungen keine ausreichenden Anreize für Investitionen leisten (Agora Energiewende und Guidehouse 2021). Teilweise behindern die Marktbedingungen (z.B. Fortbestand fossiler Subventionen) sogar die Wettbewerbsfähigkeit von Wasserstoff und erhöhen damit den Finanzierungsaufwand der Förderprogramme.

Innerhalb der Förderprogramme stehen die Fördermittelanträge im Wettbewerb zueinander und es besteht kein Anspruch auf Förderung (Seier and Streitz 2021). Die horizontale Koordination des Markthochlaufs in den Bundesländern und Kommunen findet somit im Rahmen des Wettbewerbs einzelner Förderprogramme statt. Im Ergebnis reproduziert der Wettbewerb räumlich ungleiche Ausgangsbedingungen der Wasserstoffwirtschaft, denn für die meisten Förderprogramme stellen Strukturaspekte kein Auswahlkriterium dar. Deshalb fließen Gelder überwiegend an innovative, strukturstarke Standorte von Großunternehmen (Interview mit Arbeitsgemeinschaft industrieller Forschungsvereinigungen am 22.03.2022).

Während die Förderstrategie einerseits ungleiche Entwicklungen fördert, werden andererseits Fördergelder für Strukturwandelregionen branchenspezifisch (z.B. für die Kohleindustrie) zwischen Bund, Ländern und Kommunen ausgehandelt. Eine branchenübergreifende Koordination der Strukturhilfemaßnahmen und der Förderprogramme für die Wasserstoffwirtschaft findet hingegen nicht statt. Deshalb ist fraglich, inwiefern mögliche Synergien zwischen Markthochlauf und Strukturwandel realisiert werden. Denn Fördermittel für den Strukturwandel oder die Strukturstärkung sind nicht spezifisch auf die Förderung von Wasserstoffprojekten zugeschnitten. Ihre Nutzung zur Finanzierung von Wasserstoffprojekten erfordert deshalb besonderes Engagement durch lokale und regionale Aktive, weshalb Erfolgsbeispiele noch rar sind (Interview H2-Netzwerk-Ruhr am 09.11.2021). Ein solches Beispiel ist die Stadt Herten, der es schon seit Anfang der 2000er Jahre gelang, Strukturfördergelder zur Entwicklung eines Anwenderzentrums für Wasserstoffunternehmen auf einem ehemaligen Zechengelände zu mobilisieren (Abb. 8).

Abbildung 8: Anwenderzentrum der Stadt Herten auf einem ehemaligen Zechengelände (eigene Aufnahme, 5.11.2021)

Zusammenfassend kann die Governance des Markthochlaufs als Zusammenspiel aus vertikaler Aufgabenteilung und horizontalem Wettbewerb beschrieben werden. Die in diesem Wettbewerb angelegten Verteilungskämpfe äußern sich entlang der Wasserstoffwertschöpfungskette in Konflikten um den Markthochlauf, die im Folgenden exemplarisch erläutert werden.

2.1. Wasserstofferzeugung

Die Förderung von Erzeugungsstandorten ist umstritten, weil sie die Maßstabsebene beeinflusst, auf der Wasserstoff zukünftig gehandelt wird, und sich daraus regional ungleiche Entwicklungsmöglichkeiten ergeben. Prinzipiell kann Wasserstoff mit Schiffen interkontinental transportiert werden. Da die Bundesregierung davon ausgeht, dass innerhalb Deutschlands nicht genug Flächen für Erneuerbare-Energien-Anlagen zur Wasserstofferzeugung mobilisiert werden können und die Gestehungskosten im globalen Wettbewerb nur bedingt konkurrenzfähig sein werden, fördert sie außereuropäische Wasserstoffprojekte und die globale Handelsplattform H2-Global (Interview mit H2 Global Advisory GmbH am 20.10.2021).

Nichtsdestotrotz ist auch wissenschaftlich umstritten, ob Fördermittel nicht stärker inländischen und europäischen Erzeugungsstandorten zukommen sollten (Wietschel et al. 2021). Auf lokaler und regionaler Ebene setzen sich die Befürworter*innen der dezentralen Energiewende für die Erzeugung und Nutzung von Wasserstoff auf lokaler Ebene ein (Interview mit GP Joule am 4.11.2021). Dafür müssten Länder und Kommunen jedoch die notwendigen Flächen für Erneuerbare-Energien-Anlagen bereitstellen. In Anbetracht des damit einhergehenden Konfliktpotentials vertritt der Wirtschaftsminister Brandenburgs, Jörg Steinbach, die Forderung, dass ein neuer Länderfinanzausgleich als horizontaler Koordinationsmechanismus entstehen muss, damit Länder und Kommunen ausreichend von der Bereitstellung von Flächen profitieren (Teilnehmende Beobachtung am 1. Wasserstoff-Netzwerktreffen Brandenburg und Sachsen am 09.03.2022). Ebenso ist umstritten, welche Bedeutung europäischen Erzeugungsstandorten für die Versorgung Deutschlands zukommen soll. So bestehen z.B. in Bayern Projekte für Wasserstoffimporte aus Osteuropa mithilfe von Pipelines und Binnenschiffen (Interview mit bayernets am 25.03.2022), u.a. um unabhängig von Norddeutschland zu werden, wo global gehandelter Wasserstoff über die Seehäfen angelandet werden soll.

2.2. Wasserstofftransport

Die Förderung der Wasserstofferzeugung ist auch umstritten, weil sie den notwendigen Gas- und Stromnetzausbau beeinflusst, der sich ebenfalls regional ungleich auf den Markthochlauf der Wasserstoffwirtschaft auswirken könnte. So hatte die Bundesregierung angekündigt, Anreize zum netzdienlichen Betrieb von Elektrolyseuren in Regionen mit einem Überangebot erneuerbaren Stroms (v.a. in Norddeutschland) zu schaffen, um den Strom für die Energiewende nutzbar zu machen und den notwendigen Netzausbau zu reduzieren (BMWi 2020). Da Wasserstoff aufgrund fehlender Transportinfrastrukturen jedoch bislang nicht überregional gehandelt werden kann, würden solche Anreize die Verfügbarkeit von Wasserstoff in Süddeutschland minimieren (Interview mit Stiftung Arbeit und Umwelt der IGBCE am 26.11.2021). Im Interesse der Verfügbarkeit von Wasserstoff in ganz Deutschland fördert die Bundesregierung deshalb auch Elektrolyseure in Regionen ohne Überangebot erneuerbaren Stroms.

Für den überregionalen Wasserstofftransport kann perspektivisch das Erdgasnetz umgerüstet werden. Da erneuerbare Energie aber nicht nur in Form von Wasserstoff, sondern auch Strom transportiert werden kann und die räumliche Verteilung von Angebot und Nachfrage unsicher ist, ist die Entwicklung der Gas- und Stromnetze kontrovers (Bundesnetzagentur 2021). Bislang fehlt jedoch eine integrierte Planung des Gas- und Stromnetzausbaus auf nationaler Ebene, weshalb auf regionaler Ebene einzelne Projekte zur integrierten Netzplanung vorangetrieben werden.

Neben dem Netzausbau ist auch der mögliche Netzrückbau umstritten. So ist vor allem die Zukunft der lokalen Gasverteilnetze unsicher, da die Wasserstoffnutzung stärker an einzelnen Standorten konzentriert erfolgen könnte als die Erdgasnutzung (s.u.). Die Kosten der damit einhergehenden Entwertung würden die oft kommunalen Betreiber der Verteilnetze tragen (Interview mit Verband kommunaler Unternehmen am 14.10.2021), woran die ungleiche geographische Verteilung der Kosten des Markthochlaufs deutlich wird.

2.3. Wasserstoffnutzung

Um Entwertungen zu vermeiden, argumentieren Vertreter*innen betroffener Unternehmen oft für eine weitgehende Nutzung von Wasserstoff in allen Verbrauchssektoren. Dadurch könnte einerseits die Gasinfrastruktur ihren Wert erhalten. Andererseits ähneln die Wertschöpfungsketten von Wasserstofftechnologien stärker fossilen Technologien als direktelektrischen Alternativen, die Strom ohne Umwandlung in die Verbrauchssektoren lenken (Abb. 9). Deshalb versprechen Wasserstofftechnologien bestehende Industriestandorte zu stärken.

Ob die weitgehende Wasserstoffnutzung zukunftsfähig ist, ist jedoch umstritten, da unklar ist, inwiefern sich Wasserstofftechnologien am Markt gegenüber direktelektrischen Alternativen behaupten können, welche aufgrund ihrer besseren Energieeffizienz Betriebskostenvorteile aufweisen. Besonders umkämpft ist die Nutzung von Wasserstoff in PKWs sowie zur dezentralen Wärmeerzeugung, wo Brennstoffzellen mit batterieelektrischen Antrieben respektive Wärmepumpen konkurrieren (Abb. 9).

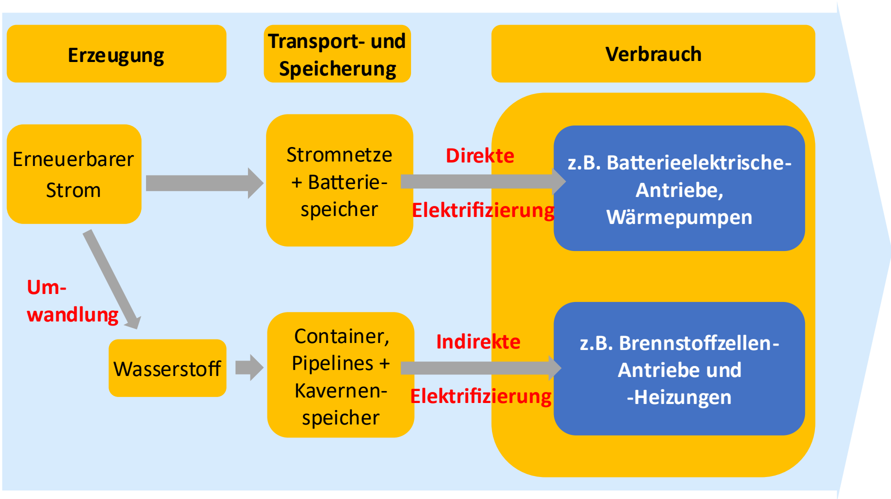

Abbildung 9: Alternative Defossilisierungspfade und -technologien (eigene Darstellung)

Deshalb ist auch fraglich, inwiefern Wasserstofftechnologien und die dafür notwendigen Infrastrukturen (Abb. 10) in Bereichen, in denen sie mit direktelektrischen Alternativen konkurrieren, Fördermittel erhalten sollten (Interview mit Klima-Allianz Deutschland am 15.10.2021). Bislang verzichten die Förderprogramme auf eine Priorisierung der direkten oder indirekten Elektrifizierung. Damit umging die Bundesregierung bislang, dass Standorte mit größerem Know-How im Bereich der direkten oder indirekten Elektrifizierung favorisiert werden. Die neue Bundesregierung will zukünftig aber die Förderung direktelektrischer Alternativen priorisieren (Teilnehmende Beobachtung an der Vollversammlung des Forschungsnetzwerk Wasserstoff am 31.03.2022), woraus entsprechende Verteilungswirkungen resultieren würden.

Abbildung 10: Von der Bundesregierung geförderte Wasserstofftankstelle in Herten (eigene Aufnahme, 6.12.2021)

2.4. Fazit

Zusammenfassend entstehen durch den Markthochlauf neue Koordinationsbedarfe auf und zwischen den Governance-Ebenen. Die Koordination erfolgt derzeit vertikal durch die Aufteilung von Steuerungsfunktionen auf unterschiedliche politische Ebenen sowie horizontal durch den Wettbewerb um Fördergelder. Sie stößt an verschiedenen Stellen an ihre Grenzen, wie die analysierten (Verteilungs-)Konflikte zeigen, die zugleich den Finanzierungsaufwand erhöhen.

Zunächst erhöht ein Teil der Marktbedingungen den Finanzierungsaufwand der Förderprogramme. Die Förderprogramme verstärken wiederum ungleiche geographische Ausgangsbedingungen des Markthochlaufs, da sie überwiegend an innovative Standorte von Großunternehmen fließen, wodurch der Finanzierungsaufwand für Strukturhilfemaßnahmen an weniger innovativen Standorten steigt. Letztendlich ist fraglich, inwiefern dieser gesteigerte Finanzierungsaufwand mittelfristig aufgebracht werden kann, ohne dass eine Priorisierung einzelner Verbrauchssektoren, der dazugehörigen Industriebranchen und damit ihrer Standorte erfolgt.

In Anbetracht dessen sollten zuerst die Marktbedingungen so überarbeitet werden, dass sie den Markthochlauf nicht behindern. Um Unterstützung für die Anpassung der Marktbedingungen zu finden, könnte die Bereitstellung von Fördergeldern für einzelne Branchen und Regionen von deren politischer Unterstützung der Reformen abhängig gemacht werden. Sodann sollten strukturpolitische Kriterien Teil der Auswahlkriterien von Förderprogrammen werden, um Synergien zwischen Markthochlauf und Strukturwandel zu stärken und damit den Finanzierungsaufwand, insbesondere in strukturschwachen Regionen, zu reduzieren. Zuletzt kann die Priorisierung einzelner Verbrauchssektoren, wie von der Bundesregierung geplant, den Finanzierungsaufwand des Markthochlaufs reduzieren.

Die beschriebenen Interessenskonflikte konzentrieren sich bislang noch auf die Förderprogramme. Mit zunehmender Anzahl und Größe von Wasserstoffprojekten ist jedoch davon auszugehen, dass lokale Konflikte um ihre Standorte sowie zwischen Regionen um die mit den Projekten einhergehenden strukturpolitischen Auswirkungen zunehmen werden. Zugleich wird die europäische Ebene für die Gestaltung der Marktbedingungen sowie die globale Ebene für den Handel von Wasserstoff an Bedeutung gewinnen. Die dadurch entstehenden Koordinationsformen stellen interessante Gegenstände für weitere Forschungsarbeiten dar.

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Article II

Walker, B., Klagge, B., 2024. Infrastructure Bottlenecks as Opportunity for Local Development: The Case of Decentralized Green-Hydrogen Projects. Tijdschrift voor Economische en Sociale Geografie. https://doi.org/10.1111/tesg.12633.

Infrastructure bottlenecks as opportunity for local development: The case of decentralized green-hydrogen projects

Abstract

Energy geography has not scrutinized the role of energy infrastructures and market design for decentralized energy production and local development. The paper addresses this research gap by looking at the emerging green-hydrogen market in Germany. We argue, first, that the capacity and geography of infrastructures and associated bottlenecks determine how supply and demand can be matched at different scales. Second, market design and associated controversies over infrastructure bottlenecks are important for understanding the green-hydrogen market and its geography and financing. Conceptually, we draw on the geography-of-markets literature. Empirically, we show how infrastructure bottlenecks and market design link the green-hydrogen to the renewable-electricity market. As long as the market design requires green-hydrogen production in geographical and temporal correlation with renewable-electricity generation, the geography of green-hydrogen production follows the geography of renewable-electricity generation. Moreover, bottlenecks in transportation infrastructures offer a window of opportunity for decentralized production and local development.

Keywords

Energy geography, energy market, hydrogen, transportation infrastructure, market design, Germany

1. Introduction

Energy geographers have controversially discussed the advantages and disadvantages of centralized and decentralized renewable energy production, i.e. large-scale and concentrated versus small-scale and distributed renewable-electricity generation (Naumann and Rudolph 2020). Some authors have argued that decentralized energy generation offers opportunities for local actors to contribute to economic development by substituting imported fossil fuels and using local resources (Heinbach et al. 2014). In addition, local energy generation offers opportunities to participate politically in the energy system and can reduce the need for grid expansion for transporting electricity from elsewhere (E. Schmid, Knopf, and Pechan 2016). However, decentralized renewable-energy generation only developed in countries with early market builders (Dewald and Truffer 2011), public funding and other favorable support mechanisms (Bauwens et al., 2016), and/or financing by local banks (Hall 2016). The phasing-out of these support mechanisms has resulted in a shift towards more centralized, large-scale renewable-energy facilities (Beermann and Tews, 2017), which allow for economies of scale in financing, production and trade, and are favored by industrial buyers as well as institutional investors (Christophers, 2022).

In practice, so-called renewable-energy regions have explicitly – and often successfully – taken-up decentralized renewable energy production as a development model (Späth and Rohracher, 2010). However, especially renewable-electricity regions use pre-existing grid infrastructures and remain embedded in national markets. They often do not engage with electricity-grid development and energy-market regulation and, consequently, miss out on opportunities to work on (more) suitable framework conditions for decentralized energy production (Beermann and Tews, 2017). Similarly, energy geography has neither conceptually nor empirically scrutinized the role of grid and pipeline infrastructures, and energy-market designs for investments in decentralized energy production and subsequent local development. Addressing this research gap is particularly important in the current situation of energy transitions in many countries worldwide. Firstly, electricity grids in countries like Germany, the United States, Chile and South Africa face increasing difficulties in integrating renewable electricity and transport it from the places of generation to demand centers due to infrastructure bottlenecks (IEA, 2023). Secondly, the share of renewables in the electricity sector has grown in many countries but other sectors, such as industry, heating and mobility are left behind (Markard, 2018). Thirdly, to support the defossilization[11] of those sectors, governments globally have started to promote the production of green hydrogen (van de Graaf et al., 2020). Since green hydrogen can be transported in pipelines, by ships and trucks, it has the potential to circumvent bottlenecks in electricity grids.

In this paper, we focus on the role of infrastructure bottlenecks and market design for the geography of energy markets by looking at the emerging green-hydrogen market in Germany. We argue that the capacity and geography of infrastructures and associated bottlenecks determine how supply and demand can be matched at different scales. Accordingly, we contend that the size and geography of markets evolve as the underlying infrastructure changes and that we need to analyze green-hydrogen market formation and structures from a geographical perspective. We therefore distinguish between large, centralized and small, decentralized projects as two market segments (cp. Dewald and Truffer 2011 on the German photovoltaic market), and are particularly interested in the infrastructural and regulatory conditions enabling local actors, like municipal utilities, to invest in green-hydrogen projects. We conceive

[11] We speak of defossilization instead of decarbonization, because in a climate-neutral economy carbon from renewable resources will still be required by various industries. Hence, not the use of carbon per se but the use of carbon of fossil origin should be abandoned (Falcone, Hiete, and Sapio 2021).

energy markets as structures that enable the coordination of supply and demand according to their political regulation (Muellerleile, 2018) or what, in energy policy, is called market design (Lindberg 2022). Furthermore, drawing on the geography-of-markets literature (e.g. Berndt and Boeckler, 2009), we use four spatial forms of markets (Jones, 2013) to conceptualize energy markets and better understand infrastructure bottlenecks. This approach leads to our research questions: How do existing infrastructure bottlenecks and the green-hydrogen market design shape the emerging geography of green-hydrogen markets in Germany, specifically the development of centralized and decentralized green-hydrogen projects in different regions? What types of actors engage in decentralized green-hydrogen projects and why, i.e. what are their motivations? And, more generally, how do infrastructure bottlenecks support or constrain the development of decentralized and/or centralized production?

The paper is structured as follows: In the next section, we develop our conceptual perspective, which focuses on how infrastructure bottlenecks and market design have an impact on the geographies of markets. Then, we explain our methodology, specifically the creation of a database on green-hydrogen projects and expert interviews. Afterwards three analytical sections follow, in which we first analyze the emerging market design, then the geography of centralized green-hydrogen projects, and finally the geography of decentralized projects. In our conclusion, we discuss our conceptual approach and empirical findings, and point out future research opportunities.

2. Geographies of energy markets, infrastructure bottlenecks and local development

The role of infrastructures for energy markets and their development seems self-evident, as infrastructure bottlenecks can hamper market development (Kuzemko et al., 2018). Similarly, based on a study of financial markets, Muellerleile (2018) highlights that removing infrastructure bottlenecks can improve the conditions for accumulation and market participation. However, neither article explores the implications of bottlenecks and how they might also enable accumulation, especially in an emerging market like the one for green hydrogen. In this article, we show that when infrastructure bottlenecks constrain energy transportation and trade over long(er) distances, market development can still occur at local scale. Thereby, infrastructure bottlenecks might not lead to less accumulation but to a (more) decentralized geography of production with opportunities for local development.

There is a lack of understanding of infrastructure systems, such as power grids, and their importance for energy transitions in energy geography (Baker and Phillips, 2019; Bolton and Foxon, 2015). Likewise, the socio-political development of energy-market designs is under-researched (Lindberg 2022). In particular, energy geographers have not considered bottlenecks and spatial forms of energy infrastructures nor the importance of market design as conditions for the successful development of decentralized energy projects by local shareholders. Instead, the economic viability of decentralized energy projects is often perceived narrowly as a function of financial support (Beermann and Tews, 2017, Dewald and Truffer 2012) and/or the cost-competitiveness of renewables versus fossil fuels (Christophers, 2022).

In this sense, as in other fields of geographic research, “the market remains a black-box and is simply taken as given” (Berndt and Boeckler, 2009, pp. 538–9). However, as Jones (2013, p. 40) rightfully contends, “markets themselves need to be more explicitly analyzed as the spaces from which key economic outcomes emerge”. For example, research has shown that the degree of centralization of national financial markets and the (non-)existence of local banks can support or constrain the development of decentralized energy projects and local ownership (Hall et al., 2016). In the following, we draw from the geography-of-markets literature to conceptualize how market design and energy infrastructures support or constrain decentralized energy production.

The functioning of markets depends on various infrastructures, especially to facilitate the interaction between market participants and to transport goods from one place to another (Muellerleile 2018). The transportation of electricity or gas (including hydrogen) requires specific infrastructures such as power grids, gas pipelines, and specific vehicles (trucks, ships). The absence or missing capacity of these facilities can constitute infrastructure bottlenecks that prevent or limit transportation between certain places (Bridge and Bradshaw, 2017). We argue that these bottlenecks, and how they are integrated into market design, have an impact on the development of energy markets. To conceptualize these impacts and their role for the development of centralized and/or decentralized energy production, we follow Jones (2013) and distinguish between four spatial forms of markets.

Firstly, the space of markets can be conceived as contiguous territory and is equated with, e.g., regulatory territories like national states or the EU. Regarding energy markets, power grids and their territories are another example, which exist at different levels – the most important distinction being between local or regional (lower-voltage) distribution grids and supra-regional (high-voltage) transmission grids. At both levels, bottlenecks can occur and need to be taken into account. To function reliably, power grids necessitate a balance of electricity fed into and sourced out of the grid. Grid management, thus, requires monitoring grid-connected electricity generation and use, as well as various types of storages and/or power transformers to keep the grid in balance (the latter transferring electricity between higher- and lower-voltage grids) (Estermann et al., 2016). As green-hydrogen production requires renewable electricity, it is important to analyze at which grid level and in which grid territory renewable electricity can be sourced in sufficient quantities, and how bottlenecks in the power grid subsequently constrain green-hydrogen production in certain territories.

Secondly, we understand markets as actor and infrastructural networks, which connect suppliers and buyers (Jones 2013). For new markets to emerge, actor networks of suppliers and buyers must be motivated to engage in innovative activities, take over risks, and have the capabilities to assemble the necessary financial resources, which is facilitated by geographic proximity and locally shared expertise (Dewald and Truffer 2012; Schwabe 2024). In this context, local banks contribute to the development of decentralized renewable-electricity projects by making financing available to actors that are locally bound. However, neither local banks nor institutional investors are willing to take over major project risks (Christophers, 2021; Hall et al., 2016). At the same time, such networks may connect different scales by linking local actors with non-local actors like national or even international firms. Furthermore, transportation and trade can occur at different levels, depending on their infrastructure capacity and bottlenecks. For example, Bridge and Bradshaw (2017) show that natural-gas trade was limited to the continental reach of pipeline networks before the development of liquid natural gas (LNG) infrastructures (terminals, ships). In our case, decentralized and centralized green-hydrogen projects represent two segments of the emerging green-hydrogen market, which differ in their actor networks, linkages to power-grid levels and associated challenges regarding bottlenecks. Thus, they might complement or compete with each other.

Thirdly, and closely related, we conceptualize markets and the underlying infrastructures as enabling flows between market participants, such as electricity or gas flows. Infrastructure bottlenecks between places of production and use, for which Muellerleile (2018) mobilizes the metaphor of traffic congestions, can limit or even prevent such flows. Hence, they can constrain market exchange and lead to fragmented markets. Our analysis shows that, as long as infrastructure bottlenecks constrain green-hydrogen transportation over longer distances, local buyers and the possibility of short-distance hydrogen flows are an important condition and motivation for both centralized and decentralized projects.

Fourthly, market folds as fourth spatial form of markets deal with connections between markets, for example, because one market provides inputs for the other, as is the case with renewable electricity and green hydrogen. To produce green hydrogen, an electrolyzer, running on renewable electricity, splits purified water into oxygen and hydrogen. Thus, the production of green hydrogen depends on the creation of market folds with electricity and water markets as well as on their networked infrastructures. As we explain later, the market fold between green-hydrogen production and renewable-electricity generation is of utmost important to understand the role of infrastructure bottlenecks for the emerging green-hydrogen market and geography – and at the center of the green-hydrogen market design.

Muellerleile and Akers define market design as “a system of technical guidelines or norms […] concerned with economic exchange” (Muellerleile and Akers, 2015, p. 1782). Market designs deal with the legal rules under which markets can develop and often include rules for the use, provision and (re-)financing of transportation infrastructures. The construction of markets through rules makes their political dimension visible, because some actors have more power to shape the market design than others (Cooper, 2015). While the geography-of-markets literature has argued that “«market design» inevitably has distributional effects” (Cooper, 2015, p. 1788), energy geographers, to our knowledge, have not investigated this issue, particularly not regarding the discussion about decentralized versus centralized energy production. In an emerging market like the one for green hydrogen, we expect stakeholders to be very diligent in influencing the development of rules to their advantage. We therefore argue that the development of, and controversies around, market design are central for understanding the emerging green-hydrogen market and its geography.

3. Methodology

Our conceptual framework focuses on both market design and the spatial forms of markets. Conceptually, we argue that the four spatial forms of energy markets introduced above – grid and regulatory territories, actor and infrastructural networks, electricity and hydrogen flows, and market folds linking different markets related to green-hydrogen production – help to better understand the implications of infrastructure bottlenecks, their role in the emerging market design and its impact on the development of centralized and decentralized green-hydrogen projects. First, we investigate how market design and infrastructural conditions at different geographical scales, and partly contiguous with regulatory territories, have an impact on the development of the two market segments and the associated market folds, by supporting or constraining electricity and hydrogen flows that both types of projects necessitate. Therefore, our empirical analysis starts with a discussion of the emerging market design and is based on 14 interviews with experts at the regional, national, and EU levels.

We understand green-hydrogen projects as actor networks of suppliers and buyers and analyze how they create market folds, react to infrastructure bottlenecks, and what kind of motivations they pursue by developing decentralized projects. To get an overview of both centralized and decentralized green-hydrogen projects and their respective geographies in Germany, we created a comprehensive database of all green-hydrogen projects in Germany. The database compiles projects listed by two public databases (dena, 2022; Zukunft Gas, 2023) and additional projects we discovered online and during conference visits. In total, our database lists projects in almost 100 places across Germany, most of which are in development. Figure 11 shows all green-hydrogen projects with a size indication and illustrates how, over time, average project sizes are increasing. While all already operating projects have a production capacity of less than 15 megawatts (MW), the majority of projects that will start operation until 2030 are large-scale projects with more than 15 up to 1000 MW.

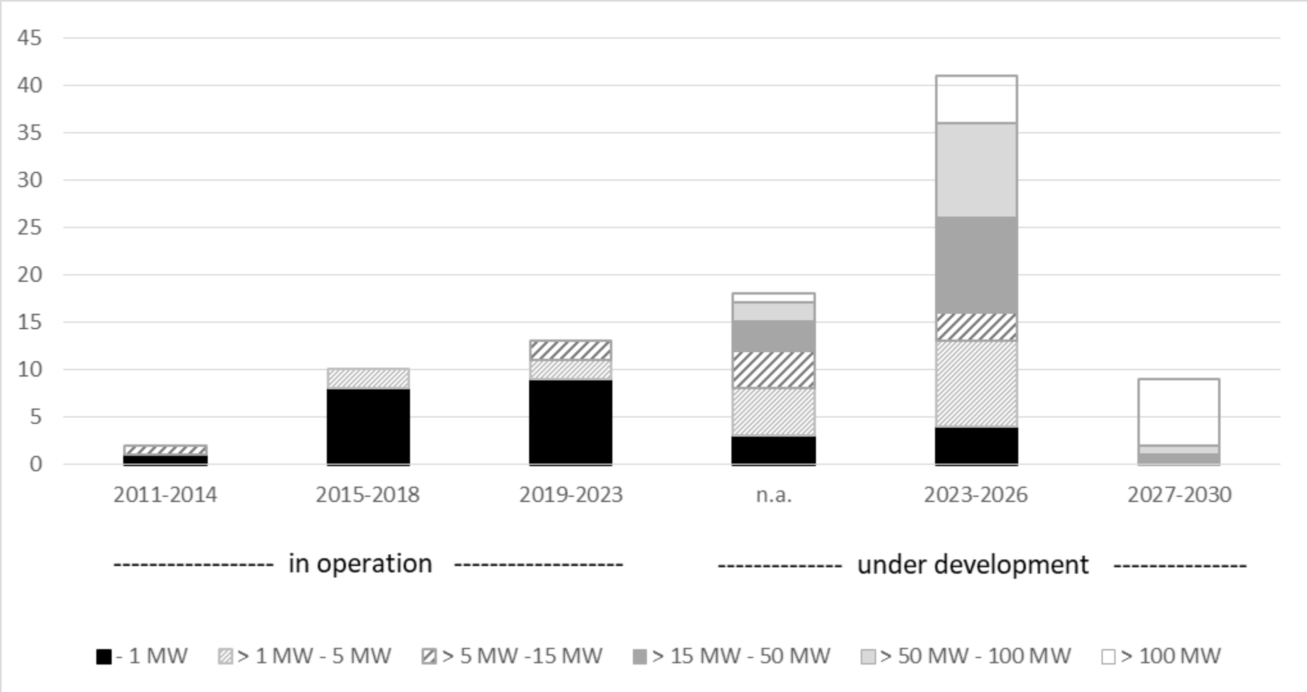

Figure 11: Green-hydrogen projects in operation or in development in Germany, by the start of operation and size in MW (Source: own database, last update April 2023)

To explain the geography of centralized green-hydrogen production in Germany, we draw from past research, including 34 expert interviews with project developers and other stakeholders (Walker, 2022). To learn more about decentralized green-hydrogen projects, their spatial forms and underlying motivations, we employed a case study approach. We concentrated on projects, which are already operational and have a capacity of more than 1 MW up to 15 MW. We decided to not consider very small projects as the associated opportunities for local development are limited. The upper threshold of 15 MW excludes projects which lead to additional costs for power-grid management and expansions and/or require electricity imports from other regions, thus contributing less to local value added (Schalling et al., 2022, p. 39). Based on our selection criteria, we identified seven projects that we studied in-depth. Our case-study data collection followed a mixed-methods approach, combining participatory observations of hydrogen conferences and webinars, field-site visits, website and document analyses, as well as expert interviews. We conducted interviews with 19 stakeholders who are directly involved in the seven selected projects or other projects as owners and financiers, buyers, and/or technology providers.

4. Regulating the market fold between green-hydrogen and electricity markets

The EU market design tries to make green hydrogen from wind and solar electricity an instrument to mitigate climate change by stipulating both geographical correlation and temporal correlation of renewable-electricity generation and green-hydrogen production (European Commission 2023b). By defining these two criteria, the EU market design regulates the market fold between electricity and green-hydrogen markets.[12] In particular, it restricts the production of one commodity (green hydrogen) based on the local non-availability of another commodity (renewable electricity) due to infrastructure bottlenecks. As a result, green-hydrogen production needs to take place in territories offering excess or additional renewable electricity.

4.1. EU market design for green hydrogen: Geographical correlation at which level?

The European Union's market design aims at preventing the direct or indirect use of fossil electricity for green-hydrogen production. To make sure that green-hydrogen producers do not use fossil electricity, the market design stipulates that operators of electrolyzers should either commission new renewable-electricity capacities or use renewable electricity that would otherwise be curtailed (European Commission, 2023b). This requirement has mixed geographical implications. Additional – purpose-built – new wind or solar parks are likely to be large to offer economies of scale and, thus, incentivize large-scale electrolyzer plants and a centralized geography of hydrogen production. By contrast, curtailed renewable electricity opens opportunities for smaller plants, contingent upon a combination of volatile renewable-electricity generation, distribution-grid bottlenecks and inflexible electricity demand. In Germany, such localized opportunities will persist for some time as grid expansion, which can reduce infrastructure bottlenecks, is slower than the addition of renewable-electricity capacities, resulting in an increasing amount of curtailed electricity (Ländner et al., 2019).

The EU market design tries to take power-grid bottlenecks into account by requiring the co-location of renewable-electricity sources and electrolyzers in the same bidding zone (so-called geographical-correlation criterion). It is assumed that within a bidding zone, there are no power-grid bottlenecks and electricity can flow freely between suppliers and buyers (Lindberg 2022). However, considerable grid constraints exist within the (one!) German bidding zone, which encompasses the contiguous territories of Germany and Luxembourg. Power-grid

[12] The EU market design, passed in February 2023, does not cover projects in operation. In addition, it grants projects that were to be developed before 2028 an exception from the additionality rule (See Article 11) and weakens the temporal correlation criteria until 2030 (See Article 6) (European Commission 2023a). However, hydrogen projects (especially large-scale) typically contract renewable-energy sources for 10-15 years and have even longer refinancing timelines, so the exceptions for early projects granted by the European Commission do not match the timelines of project development (Hydrogen Europe 2023). In addition, project developers expect to only receive the necessary subsidies if they adhere to the market design, even before it is binding. Hence, the market design is reflected in the planning of hydrogen projects, even though it is technically not binding yet.

bottlenecks in Germany affect the states of, and the industry in Southern Germany, especially Bavaria and Baden-Württemberg, most strongly, where renewable-electricity capacities are insufficient to serve large-scale electrolyzers. At the same time, bottlenecks in the transmission grid severely limit flows of renewable electricity from Northern Germany, where large off- and onshore wind capacities frequently surpass demand, to Bavaria and Baden-Württemberg. In both states, wind parks and transmission-grid expansion were met with resistance in the past, although a large (industrial) electricity demand exists (Deutsche Akademie et al., 2020).

Against this background, the two governments fear that industrial sites in Southern Germany, whose defossilization depends on green hydrogen, will face competitive disadvantages if green-hydrogen supply is uncertain. Therefore, both governments support the development of centralized electrolyzers on their territories, but have unsuccessfully lobbied the European Union to create a market design that would allow hydrogen producers to source renewable electricity across Europe, without considering grid constraints (see statements of the two governments submitted to the European Commission, 2022). Since bottlenecks prevent renewable-electricity flows, electrolyzers in the South would run on locally available electricity from fossil fuels, while the operators would virtually use "green" electricity from anywhere in Europe, thereby generating "green" hydrogen with a large carbon footprint (Interview energy provider; Pototschnig, 2021).

To address this problem, the EU has allowed national legislators to introduce stricter rules for geographical correlation. If the German government passes stricter rules, it would constrain the development of centralized green-hydrogen projects based on the virtual use of renewable electricity from Northern Germany in the South, and leave decentralized projects as the only development option. In its updated national hydrogen strategy, the national government supports stricter geographical correlation, despite the lobbying efforts of Bavaria and Baden-Württemberg (National Government 2023, 6–7). Against this background, investors have mostly shied away from developing large-scale green-hydrogen production in Southern Germany so far (see Figure 12 below), while it is still an open question whether and when the German government will introduce stricter rules on geographical correlation.

4.2. Temporal correlation and balancing markets

In addition to geographical correlation, the EU market design also requires a temporal correlation of renewable-electricity generation and hydrogen production (European Commission, 2023b). Temporal correlation means that electrolyzers, which are connected to the power grid, can only produce hydrogen at times when the contracted renewable-electricity source generates electricity. Especially in combination with a strict geographical correlation, the temporal correlation makes it difficult to achieve a large number of full-load hours for electrolyzers, particularly in areas where renewable-electricity generation is very volatile. Since in Germany offshore-wind turbines provide electricity more hours of the year than any other renewable technology, strict geographical and temporal correlation would favor centralized green-hydrogen production in the North.

The idea of temporal correlation is not new and is part of the German electricity-market design since 2001. In so-called balancing markets, market participants do not trade electricity but rather options to dispatch electricity supply or demand (Ländner et al., 2019). Green-hydrogen producers can participate in these markets because electrolyzers can flexibly produce hydrogen depending on the local availability of renewable electricity (Ruhnau, 2022). Thus, selling balancing options (dispatchable electricity demand) on balancing markets can provide an income stream for green-hydrogen producers and creates a market fold between electricity, hydrogen and balancing markets. While the transmission-grid level requires larger capacities, balancing markets also provide an incentive for small electrolyzers at the distribution-grid level. Various actors engaged in decentralized projects (e.g., Brunsbüttel, Haßfurt, Mainz, Wunsiedel) see this as an opportunity, and either take part in these balancing markets already or plan to do so in the future (Interview GPE; Interview municipal utility Mainz; Webinar municipal utility Haßfurt). Against this background, proponents of decentralized projects demand that the EU and the German government should subsidize decentralized green-hydrogen projects that contribute to distribution-grid balancing (GPE, 2022; Interview project developer). Before analyzing decentralized projects in greater detail, we take a closer look at centralized hydrogen production.

5. From gray- to green-hydrogen markets? Challenges and the geography of centralized green-hydrogen production

The development of a green-hydrogen market segment for centralized hydrogen production builds upon existing experiences, production facilities and – rather fragmented – infrastructures for so-called gray hydrogen. Gray hydrogen is produced from fossil fuels, usually at refineries and chemical plants, and its production emits carbon (dena, 2019). In Germany, oil- and chemical-industry multinationals such as Shell, Total, Linde or Air Liquide have been producing gray hydrogen for decades (Bundesnetzagentur, 2020). A few, mainly (petro-)chemical companies use most of the gray hydrogen at the respective production sites as part of local networks and with short-distance hydrogen flows. Accordingly, the gray-hydrogen market is highly centralized in few locations, and offers local-development opportunities only at production sites and places served by pipelines. By now, there are only three regional hydrogen pipelines in Germany, which connect hydrogen-production facilities with places of large demand. Hydrogen transportation by truck is expensive and only demanded by customers willing to pay a higher price. Therefore, hydrogen transportation over distances only takes place for sectors in which hydrogen constitutes a minor cost factor, like the food, glass, metallurgy and electronics industries (Linde Engineering, 2023). Hence, there currently does not exist a contiguous national hydrogen market, but rather multiple regional markets which are fragmented due to the limited reach of regional pipelines that enable large-scale flows between producers and buyers.

In the next two decades, as element of policies to mitigate climate change, green hydrogen and its derivatives (ammonia, methanol) are to replace not only gray hydrogen but fossil fuels as material feedstock and energy carrier in various industries, especially cement, steel and chemical (IEA 2019). Since green hydrogen is not yet cost-competitive with gray hydrogen or fossil fuels (IRENA, 2020), reducing the costs of green-hydrogen production is key to the formation of green hydrogen markets. The most important cost components of green-hydrogen production are the investment costs for electrolyzers and electricity costs (IRENA, 2020). To minimize the costs of electricity and electrolyzers by realizing economies of scale, the national government subsidizes large energy producers, such as RWE and Vattenfall, to develop large-scale renewable-energy parks and centralized electrolyzers, mainly in Northern Germany (Walker, 2022). Southern Germany, by contrast, lacks sufficient renewable-electricity capacities, and flows from Northern Germany are limited due to bottlenecks in the transmission grid (see above). As a result, the emerging geography of green-hydrogen production already reflects the transmission-grid bottlenecks between Northern and Southern Germany, and centralized green-hydrogen projects are concentrated in Northern Germany (Figure 12).

The long-term idea to address transmission-grid bottlenecks between North and South is to transport hydrogen instead of electricity to the South, since hydrogen pipelines can transport energy in larger volumes, and the existing natural-gas grid could be repurposed to this end (Interview GPE; Semeraro, 2021). Pipeline operators should gradually expand hydrogen pipelines to create one contiguous national market and enable large-scale flows of green hydrogen between centralized electrolyzers and the production sites of the steel, cement and chemical industries. Pipeline development started in 2022, and is moving from the northern sea ports to Southern Germany, but will only reach it around 2030. Against this background, the governments of Bavaria and Baden-Württemberg in Southern Germany plan to develop their own regional hydrogen pipelines to collect decentrally produced green hydrogen and channel it to demand centers (Figure 12). These plans would enable the development of regional green-hydrogen markets despite not being contiguous or networked with the North.

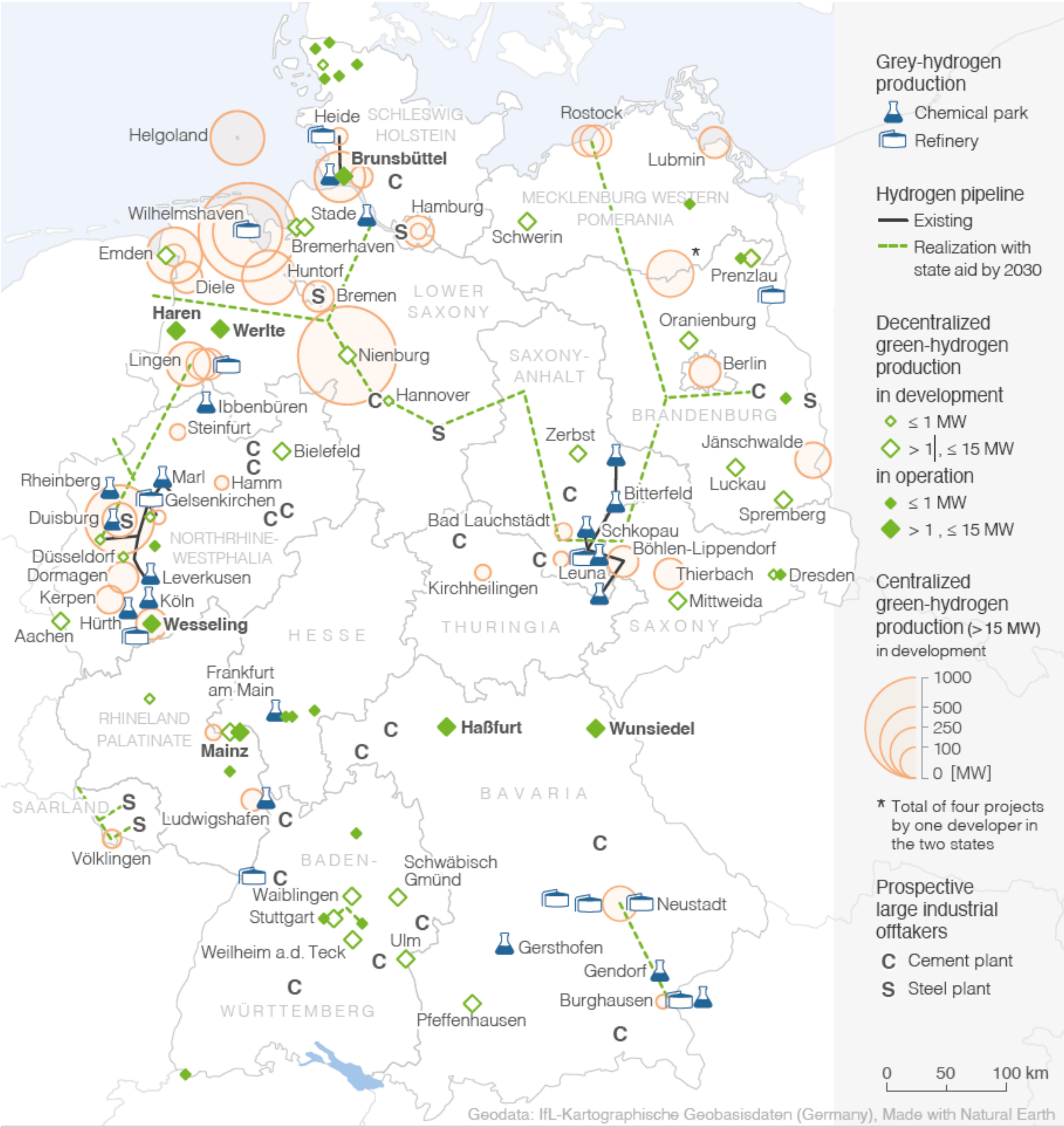

Figure 12: Emerging geography of hydrogen production and pipelines in Germany (Sources: own database, last update April 2023)

6. The geography of decentralized green-hydrogen projects

Whereas planning for centralized green-hydrogen projects concentrates on Northern Germany, small(er), decentralized projects exist and are being developed all over Germany (Figure 12). This leads to a dual geography of large centralized projects in the North and small(er) decentralized projects across the country. The following analysis highlights how local markets, actor networks and different types of motivations are important in understanding the economics and locations of decentralized green-hydrogen projects.

6.1. The economics and actor networks of decentralized green-hydrogen projects

Economies of scale and participating in balancing markets are not the only way to decrease green-hydrogen production costs. Both large- and small-scale operators can also reduce them by selling the byproducts of green-hydrogen production, i.e., heat and oxygen. Thereby, they maximize the efficiency of electricity use and create market folds with local heat and/or oxygen markets (Schalling et al. 2022). This strategy is pursued in several of our case studies, in which actor networks include buyers of oxygen and/or heat (Table 5), e.g., for district heating and use in wastewater treatment plants respectively (Interview municipal utility Mainz). Since municipal utilities often operate infrastructures like heating systems and wastewater treatment plants, and know about (other) local heat and oxygen demands, they are well-positioned to integrate electrolyzers into local heat and oxygen markets (Interview VKU). Consequently, we identified a range of municipal utilities that develop decentralized green-hydrogen projects.

While selling byproducts can improve the projects' economics, green-hydrogen production still requires favorable demand-side regulation and/or financial support to be economically viable. Especially important for decentralized projects are EU and national policies on clean vehicles and public transport. Such policies create demand for green hydrogen across municipal territories, which decentralized electrolyzers can supply, as for example in Brunsbüttel, Haren and Wunsiedel. Furthermore, all projects we selected as case studies received public funding by the respective regional state and/or the national government or even the EU (as in the case of Shell in Wesseling), even though the German national hydrogen strategy is strongly geared towards supporting centralized electrolyzers and large-scale imports (Schalling et al., 2022; Walker, 2022). Moreover, local governments supported some projects via investment by (and ownership of) their municipal utility (Haßfurt, Mainz, Wunsiedel).[13]

At this early stage of the industry, project development is contingent upon public funding and equity investments. Since specialized financial products (e.g., project financing) for hydrogen projects do not exist yet, project developers usually borrow from financiers with which they have already established relations, such as local banks or banks specialized in renewable energies (Interview Specialized Bank). However, according to our interviews, financial market actors are unwilling to act as shareholders and take over major green-hydrogen project risks (Interview Specialized Bank). They only provide debt capital up to 20 percent of the total financing volume (Craen 2023). Hence, we found that the market fold between the green-hydrogen and the financial market is less important for project development than other market

[13] While we acknowledge the importance of financial support for the development of the German green-hydrogen market, we do not explore the funding landscape in more detail (to this end, see Schwabe, 2024; Walker, 2022).

folds. Nevertheless, green-hydrogen projects provide opportunities for credit business to local banks and, thus, can contribute to local development (Interview Local Bank).

Municipality/ State	2023 capacity, start of operation (planned addition)	Owners		Hydrogen & byproduct uses* and buyers	Motivations of project development	Public (state) funding
		Local	Non-local*			
Brunsbüttel Schleswig-Holstein	2.4 MW, 2019	Project Developer	GPE	G–GPE M–H_2 filling station	Local supply, "green gas tariff" for consumer market	National
Haren Lower Saxony	2 MW, 2022	Project Developer, Wind park	--	M–H_2 filling station, Agriculture (G–planned)	Local supply, technology development (by tractor producer Fendt)	Regional
Haßfurt Bavaria	1.25 MW, 2016	Municipal utility	GPE	E/H–utility G–GPE I–malting plant BH–utility & malting plant	Local supply, "green gas tariff" for consumer market	Regional
Mainz Rhineland Palatinate	6 MW, 2015	Municipal utility	Technology firms Linde & Siemens Energy	G–utility I–chemical	Local supply, technology development	National
Werlte Lower Saxony	6 MW, 2013	(Initially regional energy provider)	(Initially Audi) Project Developer owned by former Audi managers	M–climate-friendly fuel production BH – regional energy provider	(Initially technology development), climate-friendly fuel market	National
Wesseling NRW	10 MW, 2021 (+100 MW 2026)	--	Energy multinational Shell	I–Shell BH/BO–Shell	Local demand	EU
Wunsiedel Bavaria	6 MW, 2022 (+2.5 MW 2023)	Municipal utility	Gas-trading and technology firms Rießner-Gase & Siemens Energy	I–auto, glass M–utility (planned) BH–utility	Local supply, local demand	National

*Table 5: Case studies of decentralized green-hydrogen projects (Sources: Websites of projects and shareholders) *Acronyms: GPE = Green Plant Energy; E = electricity generation, G = feed into natural-gas grid, H = heat generation from green hydrogen, I = industrial, M = mobility/transport, BH = by-product heat, BO = by-product oxygen*

In Germany, decentralized green-hydrogen production is, according to our project database, often managed by, or in cooperation with, local actors including utilities, project developers and operators. Six out of seven case-study projects were (co-)initiated by local investors; currently five still have local owners. Except for one project (Haren), all of these projects are joint investments with non-local actors (Table 5). There are currently only two projects without local co-owners. The first is in Werlte, which, however, was initiated in 2013 by the regional energy provider EWE together with Audi to produce synthetic gas from green hydrogen for automotive use. Meanwhile, the project produces green hydrogen as basis for climate-friendly kerosene and is owned by former Audi managers who had been in charge of the original project. The second project is integrated into Shell's refinery in Wesseling. It is the only project that started without local investors and is a special case also because it is conceived as the first step towards a large-scale centralized project with an additional capacity of 100 MW (European Commission, 2023a).

Future developments, especially the expansion of energy transportation infrastructures and a growing number of centralized green-hydrogen projects, might economically challenge decentralized green-hydrogen production. However, as transregional pipeline development moves forward rather slowly, proponents of decentralized green-hydrogen production argue that at least in the coming decade, decentralized and centralized hydrogen production will not compete in many regions, since infrastructure bottlenecks will constrain the emergence of transregional hydrogen markets (Interview plant manufacturer; Lundblad et al., 2023). Some interviewees even doubt that centralized green-hydrogen production, particularly in other countries, and its economies of scale will ever outweigh the additional costs of transportation (Interview GPE; Interview project developer). In remote areas with a small hydrogen demand, it could actually remain cheaper to produce green hydrogen locally than build a hydrogen pipeline or transport hydrogen by truck. Hence, even proponents of centralized hydrogen production sometimes argue that smaller scales of hydrogen demand should be met locally with decentralized production to avoid transportation costs (Forsberg, 2007).

6.2. Motivations for the development of decentralized hydrogen projects

During our empirical research, we developed a typology of four main motivations of decentralized green-hydrogen project developers. These motivations are not mutually exclusive and coincide in most projects, especially when local and non-local actors form networks to jointly realize green-hydrogen production. Both non-local and, to a lesser extent, local actors invest in green-hydrogen projects in reaction to local demand (1). Generally, however, local actors are mainly supply-driven, i.e., motivated by making use of existing, or generating more, renewable electricity in their region (2). Some non-local investors also aim at developing climate-friendly consumer products (3) or new technologies (4).

First, local demand for green hydrogen is one important motivation to develop decentralized projects. Actors with a demand for green-hydrogen see decentralized production as an opportunity to become (more) climate-friendly and save transportation costs compared to centralized gray- and green-hydrogen production. In our case studies, demand for green hydrogen exists from regional industries (Haßfurt, Mainz, Wesseling, Wunsiedel) and/or mobility, mostly public transport and (hydrogen) filling stations (Brunsbüttel, Haren, planned for

Wunsiedel), but also agricultural tractors (Haren). Furthermore, one project uses locally-produced green hydrogen to generate electricity and heat in a combined heat-and-power plant (Haßfurt). The case of Wunsiedel is particularly instructive regarding potential transportation-cost savings through decentralized production. Wunsiedel is located in North-East Bavaria, a region where small-scale industrial hydrogen demand has been met by truck transport from the three closest places of gray-hydrogen production in Leuna, Frankfurt am Main and Burghausen, which are more than 200 km away (Figure 12). Since the transportation costs of hydrogen by truck amount to around 1-2€ per kg of hydrogen per 100 km and gray hydrogen usually costs around 10€ per kg in Germany, transportation costs can easily become a relevant part of the total costs (Interview EnBW). Saving these transportation costs motivated an industrial-gas trading firm to commit to buying green hydrogen produced in Wunsiedel to supply regional industries with green instead of gray hydrogen (Interview gas trader).

Second, marketing an existing or prospective local supply of renewable electricity is another important motivation for developing decentralized green-hydrogen projects in regions characterized by distribution-grid bottlenecks. Unlike at transmission-grid level with its North/South divide, distribution-grid bottlenecks exist across Germany (Deutsche Akademie et al., 2020). Existing distribution-grid bottlenecks or concerns for future bottlenecks motivated actors such as local utilities, project developers, and/or even a wind-park company in Brunsbüttel, Haren, Haßfurt, Mainz and Wunsiedel to develop such projects (Table 5). For them, green hydrogen constitutes a way of integrating excess electricity, that would otherwise be curtailed, into non-electricity renewable-energy markets. For example, one project uses green hydrogen to generate electricity and heat in a combined heat-and-power plant (Haßfurt), while three projects feed hydrogen into the natural-gas grid (Brunsbüttel, Haßfurt, Mainz, also planned for Haren). Besides, decentralized green-hydrogen production presents an opportunity to expand renewable-electricity production in those distribution-grid territories across Germany where renewable-electricity generation already exceeds grid capacity, at least temporarily. Haßfurt and Wunsiedel have even endorsed renewable energies explicitly as a development model and strive to increase local generation capacities to supply electricity to decentralized green-hydrogen production. In all these supply-motivated cases, the investors see the creation of market folds between the electricity market and fuel markets for industry, mobility and heating as an opportunity to market more electricity.

The development of entirely new consumer products and markets is a third motivation for investing in decentralized green-hydrogen projects. In our case studies, such products include “green gas” by GPE (Brunsbüttel, Haßfurt) and climate-friendly fuels for aviation (Werlte). Both aim at buyers willing to pay a premium for climate-friendly products. In the case of GPE, the company created a special “green gas tariff”, which allows customers to support the development of decentralized green-hydrogen projects. In return, GPE feeds green hydrogen into the natural-gas grid to create the economic conditions for a green-hydrogen consumer market, thus acting as a "market builder" (Interview GPE). Similarly, the project in Werlte mainly produces green hydrogen for kerosene production and is financed by Atmosfair clients to compensate CO_2 emissions of their flights. Thereby, it contributes to developing the climate-friendly aviation fuels market.

Fourth, despite subsidies and supportive demand-side policies, decentralized green-hydrogen projects can often only exist because the involved actors do not expect immediate economic returns. Engineering companies such as Audi (Werlte), Fendt (Haren), Linde (Mainz) or Siemens (Mainz, Wunsiedel) primarily engage in decentralized green-hydrogen projects to participate in developing carbon-neutral technologies (Interview Municipal Utilities Mainz). Thus, technology development constitutes an additional motivation to invest in decentralized green-hydrogen projects, which helps actors to contribute to emission savings voluntarily, to prepare for future legal requirements of carbon neutrality and/or to diversify into a new business field. However, technology-motivated (non-local) investors are usually also involved in centralized projects and view decentralized production primarily as a means of testing and developing technologies for future upscaling.

7. Conclusion

Geographers and transition researchers have argued that infrastructures (Kuzemko et al., 2018, Bridge and Bradshaw, 2017) and market regulation (Lindberg, 2022) can support or constrain the development of energy markets. However, there is little geographical research on this topic. Therefore, we asked how existing infrastructure bottlenecks and the evolving green-hydrogen market design shape the emerging geography of green-hydrogen markets in Germany. We analyzed what types of actors engage and invest in decentralized green-hydrogen projects and their motivations. More generally, we are interested in how infrastructure bottlenecks support or constrain the development of decentralized and/or centralized green-hydrogen production. We argue that when infrastructure bottlenecks constrain transportation over long(er) distances – as is the case in Germany for both hydrogen and renewable electricity –, market development can still occur locally. Thus, infrastructure bottlenecks and a market design requiring geographical and temporal correlation might lead to a (more) decentralized production pattern, which offers opportunities for local development.

Empirically, a duality of large centralized projects in the North and small(er) decentralized projects across the country characterizes the emerging geography of green-hydrogen production in Germany. The concentration of centralized projects in Northern Germany is a result of the (local) availability of large volumes of excess or additional renewable electricity and transmission-grid bottlenecks, while the latter constrain the development of centralized projects in Southern Germany. At the same time, the non-existence of hydrogen pipelines shields decentralized projects from competition with centralized production, as transportation by truck or ship is very expensive. The current geography of decentralized green-hydrogen projects reflects four main motivations: (1) Local demand for green hydrogen, incentivized by various EU and national policies (e.g. on clean vehicles and public transport) and (financial) support mechanisms; (2) local (over)capacities of renewable electricity, which cannot be integrated into the larger energy market due to distribution-grid bottlenecks, and the strategy of (local) renewable-electricity suppliers to enter (non-electricity) energy markets; opportunities for (3) downstream market development, e.g. for consumer uses or climate-friendly fuels, and/or for (4) technology development.

Overall, the geography of green-hydrogen markets is not simply a result of infrastructure bottlenecks and political support, but also contingent on market folds with other, especially renewable-electricity markets, their geographies and market design. To understand the emerging dual geography of green-hydrogen production in Germany, the market cannot "remain a black-box" (Berndt and Boeckler, 2009, pp. 538–9). Our conceptual framework builds on the geography-of-markets literature to explain the matching of supply and demand at different levels (Muellerleile, 2018; Muellerleile and Akers, 2015). We suggest conceptualizing green-hydrogen markets by looking at four spatial forms of markets (Jones 2013).

First, green-hydrogen markets are characterized by various market folds, as they connect to other markets. Folds include, first and foremost, the connection with the market for renewable electricity as largest cost factor of green-hydrogen production and focus of the EU market design, as well as connections to local markets for heat and oxygen. In comparison, the market fold with the financial market is, so far, less important. Whereas previous studies pointed to the important role of local banks for developing decentralized renewable-energy projects (Hall, Foxon, and Bolton 2016) and institutional investors for developing large-scale projects (Christophers 2022), neither of them plays an active role in the development of green-hydrogen markets yet, because they are unwilling to underwrite (major) project risks.

Second, the availability of renewable electricity depends on the geographies of renewable-electricity generation and grid infrastructures, which include distribution- and transmission-grid territories as different contiguous spaces. Third, the bottlenecks in Germany's power grids so far constrain the flows of renewable electricity from generation sites to more distant demand centers, while hydrogen pipelines are almost entirely missing. Together with the uneven geography of renewable-electricity generation, these infrastructure bottlenecks limit the expansion of green-hydrogen markets and only allow production in territories with a sufficient local supply of renewable electricity. Fourth, in the absence of national markets, networks of local and non-local sellers and buyers develop decentralized green-hydrogen projects in locations where local conditions are favorable.

While infrastructure bottlenecks help to explain the geography of green-hydrogen production, the ways in which market design integrates or disregards these bottlenecks is equally important. Currently, the EU market design regulates that the geography of green-hydrogen production follows the geography of renewable-electricity generation. By stipulating rules for the use of renewable electricity (e.g. geographical and temporal correlation), market design has an impact on where and on which level production can take place. How market design defines this connection – or market fold – between green-hydrogen and renewable-electricity markets is decisive for the emerging geography of green-hydrogen projects, especially the geography of, and balance between, centralized and decentralized projects. A strict definition of both geographical and temporal correlation of renewable-electricity generation and green-hydrogen production facilitates decentralized projects across Germany and a concentration of centralized projects in the North, thus reinforcing the emerging dual geography of the two market segments.

Our findings show that market designs, in combination with infrastructure bottlenecks, are inherently political (Lindberg, 2022) because they shape the geography of markets and their distributional effects (Cooper, 2015), as illustrated by the scarcity of centralized projects in the states of Bavaria and Baden-Württemberg. We also show that infrastructure bottlenecks do not necessarily impede accumulation, as assumed by Muellerleile (2018). Instead, they can support more decentralized production, thereby providing opportunities for local development in more places than in the case of centralized production.

The debate on how to define green hydrogen and regulate its production is ongoing and politically contested, not only in Germany and the EU, but also the USA and other countries (Chu, 2023). It begs the more general question why not all forms of industrial electricity-use should follow the availability of renewable electricity. In other words, the question of how to regulate and govern the geographical and temporal relationship between industrial activities and their supply with renewable energy is an important future research question for economic geography and sustainability studies.

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Article III

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Place-based allocation of R&D funding: Directing the German innovation system for hydrogen technologies in space

Abstract:

The geographical understanding of directionality in the literature on mission-oriented innovation systems is still underdeveloped. Therefore, this article reflects on whether the allocation of funding for R&D activities to different places can direct innovation systems in space. A place-based approach to the allocation of funding and its effects on innovation systems is developed to analyze how the German national government allocates funding to the national innovation system for hydrogen technologies. The results show that the allocation of funding considers place-based characteristics and has a range of systemic outcomes, encompassing the clustering of research activities, the specialization of certain places in certain market segments, and the increase of the spatial reach of the national innovation system by integrating left behind places. However, the funding contributes insufficiently to market formation at the local and regional scale, and is contested due to existing alternative routes that the innovation system could take.

Keywords: mission-oriented innovation systems, market formation, directionality, geography of innovation, transformative innovation policy, place-based innovation policy

1. Introduction

Advocates of the mission-oriented approach to innovation argue that conventional innovation policies and systems cannot develop innovations for solving societal challenges like climate change (Mazzucato 2021). In comparison, missions should direct established innovation systems to tackle those challenges (Parks 2022). Accordingly, a mission-oriented innovation system (MOIS) can be defined as „the network of agents and set of institutions that contribute to the development and diffusion of innovative solutions with the aim to define, pursue and complete a societal mission" (Hekkert et al. 2020, 77). However, it is still unclear how MOIS must differ from conventional innovation systems to address societal challenges, particularly from a geographical perspective (Coenen and Morgan 2020).

This article focuses on one particular type of mission, the so-called "transformative mission", which aims to address societal challenges by enabling systemic change (Wittmann et al. 2021). Central to analyzing whether MOIS can pursue transformative missions is the concept of directionality. Directionality can generally be understood as "promoting innovations that 'contribute to a particular direction of transformative change'" (Weber and Rohracher, 2012 as cited by Parks, 2022, p. 1). The literature on mission-oriented innovation advocates that governments at different levels should provide directionality by formulating measurable, time-bound, ambitious goals and by using mission-oriented innovation policies (MOIP) to not only correct market failures but create new markets (Mazzucato 2016; 2018; 2021; Hekkert et al. 2020; Bugge, Andersen, and Steen 2022; Fastenrath et al. 2023). Thus, "market creation is moving to the centre of mission-oriented innovation policies" and the challenge of providing directionality (Robinson and Mazzucato 2019, 936).

Although directionality is a spatial metaphor, its geographical understanding remains underdeveloped. Geographers have emphasized that missions are highly context-dependent and materialize differently in different places (Wanzenböck and Frenken 2020). Others have stressed that MOIS build on pre-existing innovation systems and inherit their path dependencies (Wesseling and Meijerhof 2021; Bugge, Andersen, and Steen 2022), which are often place-specific insofar as they result from the characteristics of certain places (Boschma and Martin 2007). To address such place-specific path dependencies and provide directionality to innovation systems, geographers have suggested place-based policies, i.e. policies that address the characteristics of places, to anchor missions in local and regional contexts (McCann and Soete 2020; Fastenrath et al. 2023; Henderson, Morgan, and Delbridge 2024). These studies do not address the challenges of providing directionality to national innovation systems and market formation, though. To address this research gap, this paper offers a geographical understanding of directionality by focusing on the spatial allocation of R&D funding. I argue that funders can direct (national) innovation systems in space by allocating funding to specific places.

I use the German national innovation system for hydrogen technologies to demonstrate the analytical value of my conceptual approach regarding the question of "how transformative change promoted by MOIP relate[s] to existing systems of innovation" (Bugge, Andersen, and Steen 2022, 2313). More specifically, I analyze how and to what extent the allocation of R&D funding to places across Germany is mission-oriented and contributes to the formation of a green hydrogen market in Germany. Hydrogen technologies offer opportunities and challenges for innovation policies oriented at defossilization because while green hydrogen could potentially defossilize a wide range of energy end-uses, it also competes with other, more energy-efficient options in most cases (Vezzoni 2024). In addition, powerful incumbent actors try to leverage hydrogen to prolong fossil fuel production (Szabo 2021), which means that innovation policies could obstruct the energy transition if they support (green) hydrogen without taking other options into account.

In this context, the German innovation system for hydrogen technologies constitutes an interesting case for two reasons: Firstly, the innovation system developed early on, but also showed early signs of path dependencies (Hekkert et al. 2005) and has failed to establish a green hydrogen market (Odenweller et al. 2022). Secondly, the German national government has published a national hydrogen strategy in 2020, which formulates the mission that the national innovation system for hydrogen technologies should contribute to making Germany climate-neutral by 2045 (BMWi 2020). As part of the strategy, the government has funded the development of various research organizations and numerous research projects across Germany. Given the wide range of possible hydrogen end-uses and the advanced German innovation system, the German national government could allocate funding to regions across Germany with capabilities in different green-hydrogen market segments while fostering coordination and synergies among them. At the same time, the government did not need to distribute funding unevenly across regions at the first glance. However, a second glance reveals that the German government did allocate funding, and, hence, regional development incentives, unevenly, despite the apparent ubiquitous applicability of green hydrogen. Thus, the innovation system provides an interesting case to reflect on the allocation of R&D funding as a means of directing innovation systems in space and contributing to market development, while offering insights into the challenges and opportunities of transforming existing systems of innovation with MOIP.

The paper proceeds as follows: In the next section, I review the literature on MOIP and MOIS, focusing on geographical perspectives and related research gaps, and I develop the conceptual framework of the paper. The third section presents the methodology, followed by the analysis. The conclusion reviews the findings and points out future research opportunities.

2. Developing a geographical perspective on directionality

The literature on MOIP and MOIS encompasses prescriptions for building MOIS and providing directionality, including actor configurations, mission formulation, and technology selection (2.1.). According to critics, the literature lacks spatial sensitivity, which geographers address by proposing a place-based approach to MOIP (2.2.). However, geographers have not addressed the challenges of directing national innovation systems and forming markets yet. To address this research gap, I reflect on the systemic outcomes that the allocation of R&D funding to different places has on innovation and market formation, and, ultimately, the direction of national innovation systems (2.3.).

2.1. Building MOIS and providing directionality

According to the prominent work of Mariana Mazzucato (2021), the state and parastatal organizations should build MOIS and provide directionality. Usually, the focus lies on national governments (Mazzucato 2018; Henderson, Morgan, and Delbridge 2024), even though supra-national entities (McCann and Soete 2020) and regional governments might also pursue missions (Bugge, Andersen, and Steen 2022). However, due to the complexity of grand societal challenges, no nation, region, or sector alone will be able to solve them without cooperation (Mazzucato 2016; Robinson and Mazzucato 2019). Hence, MOIS require increased coordinative capacities across scales (Wanzenböck and Frenken 2020)

Since governments might be unwilling to solve societal challenges themselves, due to vested interests, they should define clear, measurable goals against which third-parties can evaluate and control the success of their policies and the MOIS (Wesseling and Meijerhof 2021; Kirchherr, Hartley, and Tukker 2023). Control of the MOIS and opportunities for experimentation within it should be decentralized by incorporating new stakeholders (Mazzucato 2018; Parks 2022). Some authors specifically propose to integrate civil society actors and local governments in innovation systems to increase the systems' reflexive capacities (Lindner et al. 2016; Wiarda et al. 2023). Other authors argue that MOIS require better coordination and transfer between actors that develop technologies and those that apply them (Tödtling, Trippl, and Frangenheim 2020; Wanzenböck and Frenken 2020; Parks 2022).

The integration of additional actors into innovation systems requires a shared vision of what constitutes the mission. While some authors argue that these visions should be developed in a participative, deliberative manner (Wanzenböck et al. 2020), others doubt whether a participative, deliberative process can really be established (Reale 2021). In any case, mission formulation is a contested process because formulated goals will privilege some solutions over others (Wanzenböck and Frenken 2020). Therefore, mission formulation can be understood as the first step towards providing directionality to innovation systems (Wesseling and Meijerhof 2021).

After mission formulation, MOIS should create positive expectations about the future growth of markets that are necessary to address societal challenges, like renewable energy markets. On the one hand, positive expectations should crowd-in private investments, which governments can incentivize through different policies like public procurement and long-term, high-risk funding. Such funding should not only focus on basic research but cover the entire innovation process until technology deployment (Mazzucato 2018). On the other hand, governments can disincentivize innovation in unwanted directions by reducing the technological variety pursued by the innovation system (Hekkert et al. 2020). While the mission-oriented approach is not about picking winners, i.e. identifying one dominant technology (Robinson and Mazzucato 2019), policymakers should take the power dynamics between incumbent innovation systems and new technological solutions as well as between competing, new technologies into account (Dreher, Kovač, and Schwäbe 2016). To address such power dynamics, the literature suggests an "outcome-oriented approach" (Fastenrath et al. 2023, 3), according to which governments should focus on integrating and supporting actors that are "willing" to solve missions and discontinue research that hinders the completion of the mission (Mazzucato 2018, 805). However, critics of technology selection by the state argue that states should only provide a level playing field among (established and new) technologies and leave technology selection to market dynamics, i.e. competition (Sanders, Stam, and Thurik 2024).

Reducing technological variety to the detriment of any one innovation system will likely be met with resistance from that innovation system and the places in which it contributes to economic development, which might undermine the legitimacy of missions (Dreher, Kovač, and Schwäbe 2016). As Cappellano et al. (2023) have argued, missions might increase regional economic disparities if they do not take the geographical dimension of transformations and their uneven implications for different regional economies into account. Therefore, among other reasons, different authors have proposed a place-based approach to missions, which the next section reviews.

2.2. Mission-oriented and place-based innovation policies

Building on the literature on place-based innovation policies (Tödtling and Trippl 2005; Grillitsch and Asheim 2018; Coenen and Morgan 2020; Hassink 2020), a place-based perspective on missions emphasizes that societal challenges require place-specific instead of one-size-fits-all solutions (Wanzenböck and Frenken 2020; Fastenrath et al. 2023). The reason for this is that some places are better equipped than others for completing missions but all places need to solve societal challenges like becoming climate-neutral. Hence, a place-sensitive approach is needed that considers the knowledge base, industrial, organizational, and socio-cultural characteristics and contexts of different places(Grillitsch and Asheim 2018; McCann and Soete 2020). In the literature on place-based innovation, the characteristics that distinguish places are usually observed at the regional scale (Hassink 2020), even though places can also be characterized at other scales, from the local to the (supra-)national (Hansen and Coenen 2015). Without attention to these characteristics, MOIP, like other "place-blind" policies, risk resulting "in the heroic but naïve effort to build high-tech cathedrals in the desert" (Coenen and Morgan 2020, 6).

Besides reflections on where innovations can happen, the literature on place-based innovations also considers the "systemic outcome" of innovation policies, that is, change in innovative and entrepreneurial activities at the regional scale (Grillitsch and Asheim 2018, 1656). The literature has identified a range of systemic outcomes, including improvements in the interconnectedness between actors, the establishment of cross-sectoral platforms, the creation of extra-territorial linkages, the support of clustering and specialization, and the enhancement of regional attractiveness through marketing and targeted investments (Grillitsch and Asheim 2018). Other authors, particularly in the context of cohesion policies, have emphasized the importance to increase the spatial reach of (supra-)national innovation systems to integrate left behind places (McCann and Soete 2020). Whereas clustering and specialization require investments in places that are already characterized by certain kinds of research activities, increasing the spatial reach of the innovation system will require investments in places that were not integrated in an innovation system yet.

The place-based innovation literature usually focuses on systemic outcomes of place-based policies on innovation dynamics at the regional scale (Grillitsch and Asheim 2018), while the implications for MOIS at the national scale have not received attention yet. Moreover, the literature on place-based MOIP has focused on the challenge of anchoring missions in different local and regional contexts so far (McCann and Soete 2020), such as regional innovation systems (Bugge, Andersen, and Steen 2022), innovation districts (Fastenrath et al. 2023), and universities (Henderson, Morgan, and Delbridge 2024). In comparison, the challenge of market formation has received little attention. Hence, in the next section, I reflect on one particular type of innovation policies, namely policies that allocate R&D funding to different places, and their potential contribution to market formation at different scales.

2.3. Conceptual framework for analyzing the spatial allocation of R&D funding

The challenge in regard to the spatial allocation of R&D funding from a national perspective is to reconcile the ambition of the mission-oriented approach to direct innovation systems from basic research to market development, while being aware of place-based challenges and limitations to address grand societal challenges. Since MOIP aim particularly at market formation and development, it is important to not only consider the capabilities of actors in different places in basic and applied research, but also their capabilities and willingness to deploy new technologies and infrastructures (Dewald and Truffer 2011; 2012). Against this background, national governments need to reflect on the places where certain innovations can and should be developed and allocate funding accordingly.

Building on these propositions and the literature on place-based innovation, I argue that policymakers should take two aspects into account when they allocate funding to different places. First, a place-based perspective is required that breaks down overarching missions into sub-missions and innovative activities, which can be allocated to different places according to their characteristics and capabilities (Bugge, Andersen, and Steen 2022). In this regard, a distinction between different kinds of innovative activities is helpful. Following Liu und White (2001), I suggest to distinguish between research (basic and applied), manufacturing (of technologies), end-use (deployment of technologies), linkage (organizational and infrastructural connections), and education (professional training). Second, the spatial allocation of funding to different places should not only have systemic outcomes at the regional scale, but also at the national scale. The allocation of funding to different regions according to place-based criteria can have such positive outcomes at the national scale as it can promote regional specialization, which the national innovation system can harness as regions ideally innovate according to their strengths in mutually beneficial ways. Moreover, the systemic outcomes at the regional scale, distinguished in the last section, should also foster market formation, first at the regional and then at the national scale.

Considering that the literature on missions does not offer a geographical perspective on market formation yet, I draw from studies on the geographical dimension of market formation in technological innovation systems (Dewald and Truffer 2011; 2012). They have highlighted two aspects of market formation: On the one hand, the formation of market segments "that serve specific user segments and that are characterized by specific product forms and related actors, networks and institutions" (Dewald and Truffer 2011, 286). Market segments enable specialization in certain technological areas, which can increase productivity, and decrease production costs while increasing profitability (Strupeit 2017). On the other hand, the formation of market transactions, enabled by the establishment of communication between prospective producers and buyers, as well as the rule-based exchange of commodities and enabled by infrastructures. In regard to both the formation of market segments and transactions, spatial proximity, i.e. the concentration of actors and activities in certain places, can help to facilitate the formation of local markets, which can expand to the regional, national, and international scale as the market matures (Dewald and Truffer 2012, 286). In the energy sector, for example, market development depends on infrastructures that enable energy trade at different scales (Bridge and Bradshaw 2017; Walker and Klagge 2024). Hence, systemic outcomes such as specialization and clustering, networking, and the development of infrastructural linkages can promote the formation of market segments and transactions, first at the local or regional, and then at the national scale as market expansion integrates more and more regional market segments.

Since markets are likely going to emerge in a segmented and spatially fragmented manner, further reflections are necessary regarding which specific (regional) market segments should be supported. To conceptualize such different options within the directionality of a MOIS, Mazzucato (2016, 142) speaks of "»routes« within directions" of change. I will use the term routes to distinguish alternative pathways of MOIS, i.e. different – potentially competing – ways of completing missions.

Summarizing the conceptual framework, I propose that providing directionality to national innovation systems is a two dimensional process. Firstly, national governments can provide directionality by formulating missions, integrating actors willing to contribute to missions, and coordinating actors across regions and sectors at the national scale (Figure 13). To achieve this, governments will need to establish the organizational capacities and control functions that enable continuous evaluation and eventually reduction of technological variety (2.1.). Second, governments can direct innovation systems in space by allocating funding for R&D activities to different places so research in one place ideally supports research in another place. The successful allocation of funding requires a place-based approach that considers the characteristics of different places, and promotes systemic outcomes (2.2.) and market formation, first of certain regional market segments and then of an integrated national market. Given that mission formulation and completion is a politically contested process, governments should continuously reflect on the spatial direction and routes that the innovation system takes (2.3.). Hence, providing directionality in space is a process that requires continuous reflection, monitoring, and evaluation of its place-specific conditions, outcomes, and aggregated effects.

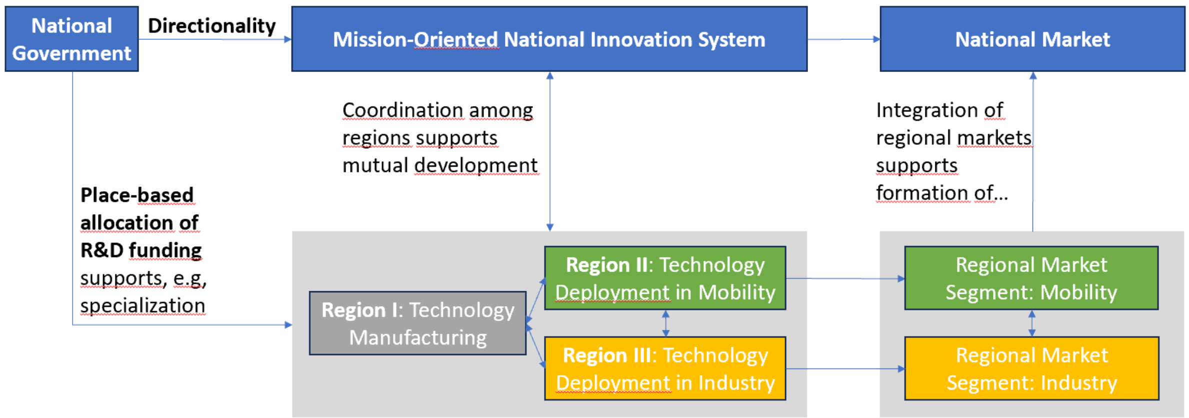

Figure 13: Visualization of conceptual framework (own illustration)

From an analytical perspective, the allocation of funding to different places will ideally support directionality but it might as well reflect the vested interests of governments or place-specific path dependencies (2.1.). Hence, a mixture of mission-oriented directionality, vested interests, and path dependencies will likely exist in innovation systems. This poses the empirical task of analyzing to what extent, in which places, and in regard to which market segments governments direct innovation systems towards the mission or rather vested interests, and which routes within a direction of change governments take.

3. Methodology

I developed and tested the analytical framework in an iterative process, alternating between theoretical work, data collection, and analysis. Data collection and analysis focused on the German national hydrogen strategy, as the mission-statement, and the national government, as the main director of the national innovation system for hydrogen technologies. Outside the scope of this study are the hydrogen strategies of the regional governments and challenges around multi-scalar coordination (see: Knodt et al. 2022; Walker 2022).

Based on a literature review, desk research, and primary data collected during the participatory observation of conferences (e.g., national hydrogen conference, regional industrial fairs and hydrogen network events), I first mapped the (historical) development of the German MOIS for hydrogen technologies (Figure 14). After this exploratory phase, I collected data on the newly established research organizations (see 4.3.) and the four largest funding schemes for hydrogen R&D projects by financial volume (see 4.4.). In total, I identified 14 newly established research organizations and 84 research projects with a focus on hydrogen technologies.

After clarifying the contours of my research object, I conducted 49 interviews between October 2020 and January 2023 with the directors of established (EST_#7) and newly funded research organizations (NEW_5#), project leaders of the 84 research projects (PL_#22), stakeholders involved in the development and execution of the national hydrogen strategy (NHS_#3) and other stakeholders (OS_#12) with an interest in the development of hydrogen technologies, such as industry representatives. I could not get access to the policymakers that developed the national hydrogen strategy. Therefore, reflections on the strategic intent of the national hydrogen strategy are based on the strategy (see: BMWi 2020), other publicly available data, and the interviews.

Most interviews were conducted by videocall, but six at conferences, and they all took around one hour. They were all semi-structured and addressed four topics, broadly reflecting the analytical framework presented above: The characteristics and history of the places in which the interviewee works; the possible contributions of the project/research organization in regard to the mission of a climate-neutral society and the competition that exists between the project/organization and other projects/organizations; coordination and cooperation with other actors in other places; the perceived challenges in regard to technology development, deployment, and market development. The four topics provided deductive coding categories which were then inductively specified using Kuckartz's semi-structured content analysis (2014). To increase the validity of my findings, I published preliminary results in a discussion forum of the hydrogen research network (see 4.2.) and asked the network for feedback, which I integrated into the paper.

4. Providing directionality to the German innovation system for hydrogen technologies

In this section, I first provide a historical overview over the development of the German national innovation system for hydrogen technologies, its path dependencies, and how the German state made it mission-oriented by formulating the national hydrogen strategy (4.1.) and building organizational capacities for providing directionality (4.2). The following sections then analyze to what extent the allocation of funding for research organizations (4.3.) and projects (4.4.) follows a place-based, mission-oriented approach that can contribute to the formation of different market segments. Here, I distinguish between different systemic outcomes that the spatial allocation of funding for research organizations and projects has at the regional scale. Last, I discuss the route that the national innovation system has embarked on as a result of the funding by the national government (4.5.).

4.1. Making an established innovation system mission-oriented

The German national innovation system for hydrogen technologies emerged in the 1970s, when the German automobile industry started to develop hydrogen technologies and the national government, shortly after, started funding these research efforts (Figure 14, BMWA 2005). Fuel cells developed for the automobile sector can also be used for combined heat and electricity production from hydrogen. To enable the use of fuel cells for the energy supply of buildings, the German state started funding the development of stationary fuel cells in the 1990s (Ruef and Markard 2010; Musiolik and Markard 2011; Musiolik, Markard, and Hekkert 2012). Even at this early stage, the innovation system showed signs of path dependencies by focusing on a narrow range of technologies (Hekkert et al. 2005).

Until the publication of the national hydrogen strategy, the innovation system was not oriented towards defossilization and did not contribute to the formation of a climate-neutral hydrogen market either. While initially the German state funded research on the production of hydrogen from renewable electricity,[14] research funding focused on fuel cells from the 1990s onwards. The national government thought that hydrogen produced from renewable energy could not compete with natural gas, which can also be used to power fuel cells. Since fuel cells are very efficient, the government funded fuel cell research to increase the efficiency of fossil fuel use rather than to develop a defossilization option (BMWA 2005).

Besides, the deployment of hydrogen-technology deployment and market formation were not sufficiently promoted by the innovation system (Interview EST_6, OS_2, Musiolik et al. 2020). The formation and development of a green hydrogen market hinges on cost reductions to make green hydrogen cost-competitive with fossil fuels. Cost reductions require, on the

[14] The HySolar project, for example, researched how renewable energy could be provided to houses all year by combining photovoltaic panels and hydrogen technologies

one hand, basic and applied research, e.g., to reduce material costs, increase technological efficiency, and develop new, disruptive technologies. On the other hand, cost reductions depend on the mass-deployment of hydrogen technologies, which should enable economies of scale in technology manufacturing and hydrogen production, as well as the development of transportation infrastructures, such as hydrogen pipelines (IRENA 2020).

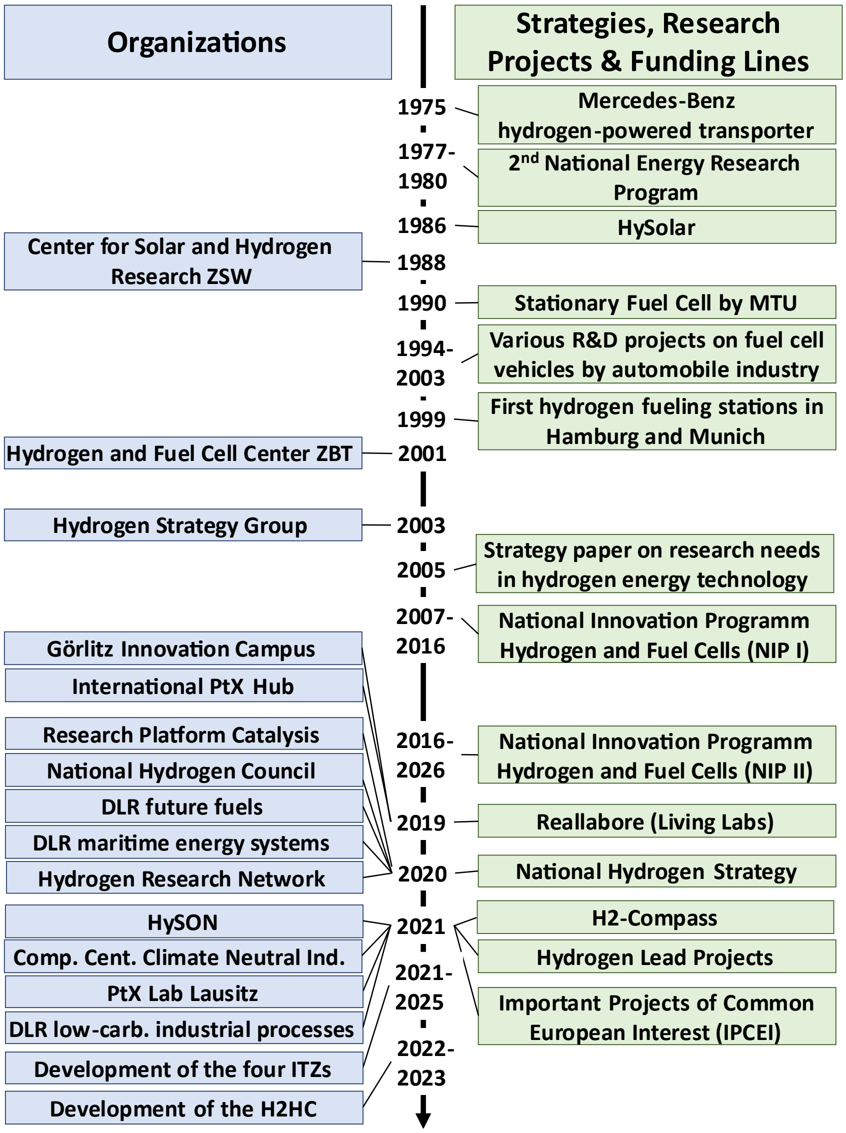

Figure 14: Timeline of the development of the German innovation system for hydrogen technologies (own illustration)

Against the background of path dependencies and the missing formation of climate-neutral markets, the national government formulated the national hydrogen strategy (BMWi 2020). The strategy formulates the goal to establish hydrogen technologies as a “decarbonization option” to make Germany climate-neutral by 2045 (BMWi 2020, 3). I understand the national hydrogen strategy as a mission statement,[15] which establishes a desirable timeline for innovation, e.g., the successful deployment of hydrogen technologies by 2030 (BMWi 2020, 17). Moreover, the strategy also encompasses an action plan with various measures and demands the evaluation of the strategy every three years (BMWi 2020, 9).

According to the strategy, innovation should be (re-)directed towards, firstly, electrolyzers, which are the central technologies to produce hydrogen with renewable electricity by splitting water. Secondly, modes of transport such as shipping and aviation should use green hydrogen(-based derivatives). Thirdly, green hydrogen should be used to curb industrial carbon emissions. Fourthly, the national government stated that to reach climate-neutrality, Germany would need to import renewable energy and that green hydrogen (and its derivatives) should serve as energy carriers enabling these imports. To this end, international projects should receive funding. Fifthly, infrastructure development (such as import terminals for hydrogen derivatives, pipelines, filling stations) should enable the formation of a green hydrogen market.

4.2. Building institutional capacities to provide directionality

The (re-)direction of the innovation system to integrate new sectors and technologies reflects a shared vision among the interviewed stakeholders and the literature because hydrogen technologies do not compete with other defossilization technologies in aviation, shipping, and some industrial sectors, such as chemicals or steel (Agora Energiewende and AFRY Management Consulting 2021). In comparison, hydrogen technologies do compete with other, more energy-efficient technologies in the market segments of automobiles and buildings (Wanitschke and Hoffmann 2020; Ueckerdt et al. 2021; Rosenow 2022; Walker 2022), which is why some interviewees argued that those fields of research should be abandoned (Interview NHS_1, EST_4). However, since the German national innovation system for hydrogen technologies has focused on using hydrogen in buildings and automobiles historically, it is characterized by considerable vested interests and a politically powerful narrative supporting "Technologieoffenheit" (literally: technological openness, more commonly called technology neutrality (Azar and Sandén 2011)) that has prevented the national government from reducing the variety of hydrogen technologies it supports (BMWi and BMV 2021).

To address the vested interests, decentralize control, and increase the organizational capacities to provide directionality, the national government has created three institutions as part of the national hydrogen strategy that could theoretically direct the innovation system. First,

[15] Although the German hydrogen strategy does not explicitly adopt a mission framing, its implications are transformative in so far as the energy transition is transformative (Wittmann et al. 2021). Therefore, I understand it as a mission statement.

the Federal Ministry of Economic Affairs and Climate Protection (BMWK) funds the German Hydrogen Research Network. It aims at integrating a representative share of researchers and actors from the public and private sphere, including civil society, and all German regions and sectors. The network is organized in four clusters, three of which represent the hydrogen value chain from production, over transport to use, while the fourth is concerned with the social acceptability and politics of technology deployment (Interview NHS_3). The clusters publish policy advice and engage in regular exchange with the BMWK and the Ministry of Mobility and Digitalization (BMVD).

Second, the BMWK and the Federal Ministry of Education and Research (BMBF) fund a research project called Hydrogen Compass. The project's research team engages in meta-analyses of studies regarding the development of hydrogen technologies. Moreover, the team asks stakeholders, including civil society actors, to comment on the results of its meta-analyses, to include non-public research results and investment decisions (Interview NHS_2). After the feedback process, the analyses are published and should serve the hydrogen innovation system in general, and the government specifically, as information regarding the direction that innovation in Germany currently takes.

Both the Hydrogen Research Network and the Hydrogen Compass struggle with providing policy advice on the desirable technological variety of the innovation system. The Network does not have the capacities to suggest the prioritization of certain market segments to the ministries because, due to disputes within the network, no shared vision exists about the future of hydrogen technologies in those market segments. Moreover, the integration of actors from different spheres of society and industrial sectors has made coordination more difficult, not least because of vested interests. In comparison, the Hydrogen Compass lacks the authority and capacities to develop scenarios for a climate-neutral Germany, which would be necessary to develop recommendations on mission-oriented technology selection and routes within the direction of change, e.g., concerning the question in which market segments green hydrogen should be used (Interview NHS_2). Therefore, representatives of the Hydrogen Compass and Network suggested that the National Hydrogen Council (German: Nationaler Wasserstoffrat, NWR) should advice the government (Interview NHS_3).

The national government created the NWR as part of the national hydrogen strategy. The NWR includes stakeholders from different fields of society (13x companies and industry associations, 2x civil society, 5x science, 1x labour union) and consults a committee of the state secretaries of the ministries concerned with hydrogen. The NWR and the committee evaluate and adapt the hydrogen strategy together (BMWi 2020). The NWR, whose composition was criticized for being dominated by industry stakeholders (Katzemich 2021), does not advise on reducing technological variety even though it has commissioned a study on using hydrogen for heating, which, like many other studies (Rosenow 2022), presents a compelling case against using hydrogen to heat buildings in most cases(Fraunhofer ISE and Fraunhofer IEE 2022).

The national government has not effectively reduced the technological variety pursued by the innovation system. While the green-party leadership of the BMWK has reduced funding for the deployment of hydrogen technologies in buildings (KfW 2023), the liberal-party-led BMBF still funds hydrogen research for hydrogen use in buildings. One such project even aims at developing a “blueprint for heating all over Germany” (translation by the author: ZfK 2023). Moreover, the BMDV, which is also under liberal leadership, has not reduced the technological variety regarding automobiles. In particular, it funds the development of fuel cell manufacturing sites, which should produce fuel cells at low costs for deployment in automobiles and buildings (BMWi 2021b).

4.3. Research & education: increasing spatial reach, regional specialization, and competition

Instead of reducing the technological variety pursued by the national innovation system, the national government has increased it in the national hydrogen strategy. To develop the necessary capacities in regard to basic and applied research as well as education in these new market segments, the national and some state governments, have funded the establishment of 14 research organizations (Table 6).

The allocation of funding for the establishment of these research organizations has taken two kinds of place-based characteristics into account. Firstly, most of the research organizations were co-located with existing research organizations (research institutes, universities, industry R&D departments), such as the Hydrogen and Fuel Cell Center (ZBT) in Duisburg (Figure 15). These places were chosen because they offer particularly suitable organizational and industrial contexts for technology development (Interview EST_4). In comparison, the allocation of funding to places that have no history in hydrogen research risks the establishment of ‘cathedrals in the desert’ and depends on the successful anchoring of the organizations within the local and regional context (Interview NEW_2).

By co-locating the new research organizations with existing research organizations, the national government and the leadership of the new organizations hope to achieve two systemic effects: On the one hand, clustering and spillover, and, on the other hand, specialization in new market segments (Interviews EST_3). However, not all specializations are mission-oriented. While some research organizations pursue mission-oriented directions, such as industrial defossilization, others focus on particular market segments, such as hydrogen use in heavy trucks, where hydrogen technologies compete with other defossilization options. Hence, the latter research organizations reflect a conventional technology-push approach.

Funding Organization	**Name of Research Organization (location)**	**Specialization**
Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMU)	PtX Lab Lausitz (Cottbus)	Synthetic, hydrogen-based fuels
Federal Ministry for Economic Cooperation and Development (BMZ)	International PtX Hub (Berlin)	International hydrogen economy
Federal Ministry of Economic Affairs and Climate Protection (BMWK)	Competence Center Climate-neutral Industry (kei) (Cottbus)	Climate-neutral industry
Federal Ministry for Digital and Transport (BMDV)	Hydrogen and Mobility Innovation Center (HIC) (Chemnitz)	Component manufacturing, cars, small and medium sized trucks, testing infrastructures
BMDV	Hydrogen Technology-User Center (WTAZ) (Pfeffenhausen)	Heavy trucks
BMDV	Northern Innovation- and Technology Center (ITZ North) (Bremen, Bremerhaven, Hamburg, Stade)	Hydrogen(-derivatives) in martime transport and aviation
BMDV	The Hydrogen Proving Area (TryHy) (Duisburg)	Standards, regulation, norms, security
Federal Ministry of Education and Research (BMBF), state of Northrhine Westphalia	Helmholtz cluster for sustainable and infrastructure-compatible hydrogen economy (HCH2) (Jülich)	Hydrogen transport in already existing infrastructures
BMBF	Catalysis Laboratory (CatLab), (Berlin)	Catalyzers for synthetic fuel production from hydrogen, knowledge transfer
National government, state of Saxony	Siemens Innovation Campus (including Fraunhofer Hydrogen Lab) (Görlitz)	Hydrogen gas turbines, hydrogen production and storage, fuel cells
National government, states of Saxony and Brandenburg	DLR Institute for low-carbon industrial processes (Cottbus)	CO_2 reduction in industrial processes
BMWK, state of Schleswig-Holstein	DLR Institute for maritime energy systems (Geesthacht)	Carbon neutral shipping; use of hydrogen(-derivatives) for low-carbon shipping
National government, state of Northrhine Westphalia	DLR Institute for future fuels (Jülich)	Production of climate-neutral, hydrogen-derived fuels
State of Thuringia	Institute for Applied Hydrogen Research (HySON) (Sonneberg)	a.o. hydrogen supply concepts

Table 6: Newly established research organizations with a focus on hydrogen technologies (compiled by the author)

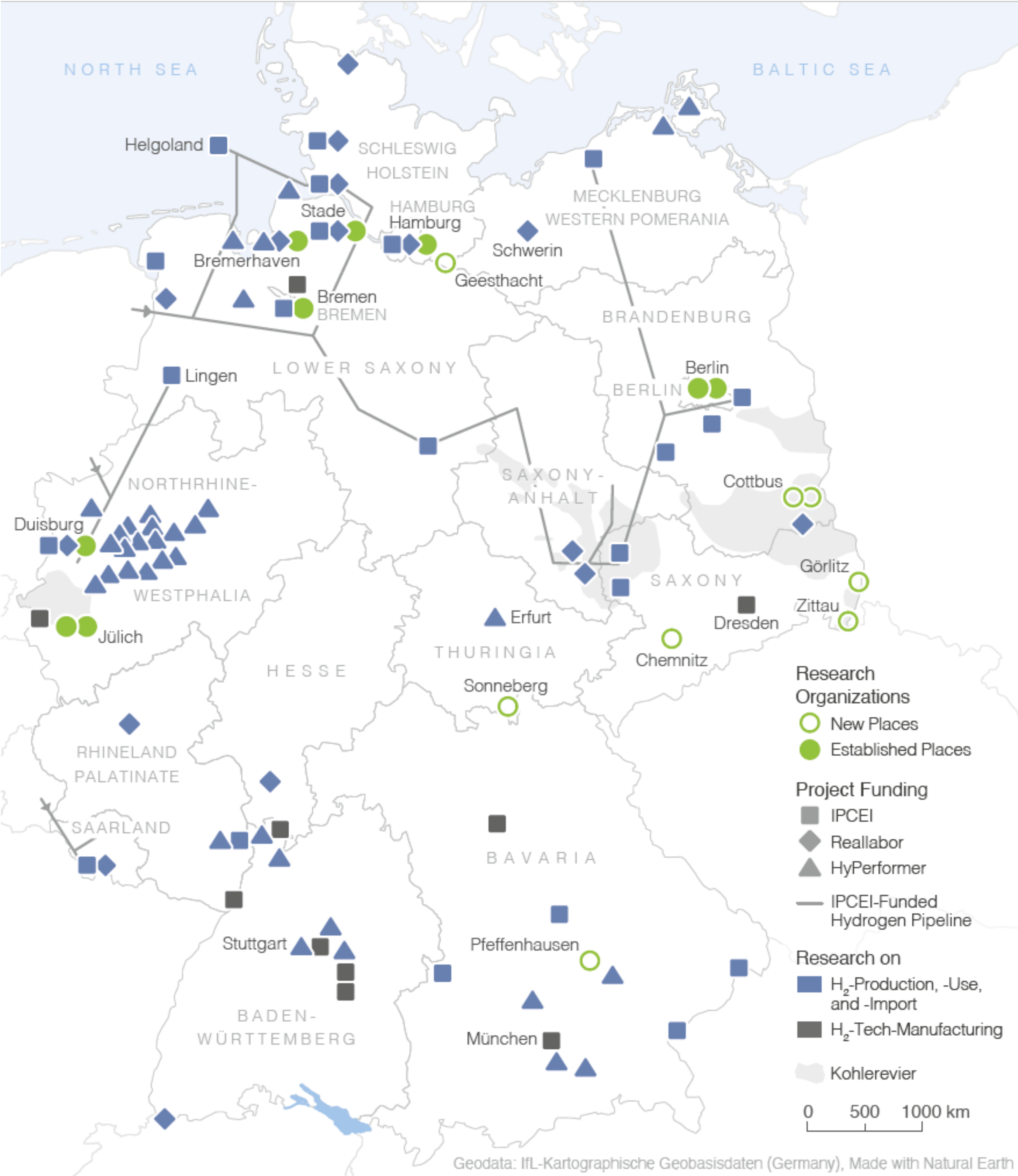

Figure 15: Map of new research organizations and large hydrogen R&D projects in Germany (Source: compilation of data based on websites, funding information, and interviews)

Secondly, the chosen locations for the new research organizations signal a move to East Germany, historically the economically less developed part of Germany, where the national innovation system for hydrogen was less present. Hence, there exists a twofold risk in East Germany to be left behind economically, and in regard to green hydrogen research, market formation, and technology deployment. Therefore, establishing research organizations in Eastern Germany aims at the systemic effect of increasing the spatial reach of the innovation system and counteracting uneven development. Similarly, six organizations were located in coal mining regions to contribute to their economic development and defossilization (Figure 15).

Besides specializing in new market segments, the research organizations should provide economic development impulses (BMWi 2020, 7). The national government increasingly expects that hydrogen research organizations actively engage in regional economic development, i.e. by attracting hydrogen firms and promoting the formation of regional hydrogen markets (Interview EST_2). As educational organizations, the research organizations contribute to developing a local knowledge base and skilled labor force. In the end, the new jobs and economic development should also help to foster local support for the vision of making Germany climate-neutral by using hydrogen technologies (Interview NEW_4). In addition, public research organizations are important for the acquisition of R&D funding because the German national government often requires the involvement of public research organizations in research projects to grant funding (Interview PL_4).

After providing funding for the establishment of new research organizations, the national government has peaked funding in 2021, mirroring earlier hypes that went along increased public investments (Bakker 2010). As a consequence,

> “since 2019-2020 there [was] a lot of money [for hydrogen research] and all of a sudden everyone researches hydrogen … but now, there is no money anymore… there’s a huge peak [of funding] … the research capacities are increasing a lot, particularly in research institutes that did not research hydrogen … before, and there is a huge danger obviously, that there is competition for funding now and that established research institutes could be left behind (Interview EST_3)”.

A positive systemic outcome of the rising competition at the national scale could be that organizations which do not develop technologies in a mission-oriented way lose access to funding. Thereby, competition could reduce technological variety and reinforce the direction of the national innovation system in the end (cf. Sanders, Stam, and Thurik 2024). Besides the increasing competition between the research organizations, some of them are more prone to competition within the specific market segments in which they are specialized. For example, the BMDV funds the development of an Innovation and Technology Center for Hydrogen (ITZ), which consists of four branches (NOW GmbH 2023): The ITZ North will support the development of hydrogen technologies in aviation and shipping, and is being developed in four places in Northern Germany, close to the ocean and Hamburg, where Germany’s aviation industry is based. The Tryhy is dedicated to codes and regulations, which all hydrogen technologies require for successful market formation, and is co-located with the ZBT in Duisburg. In comparison, the HIC in Chemnitz (small trucks) and WTAZ in Pfeffenhausen (heavy trucks), which are also part of the ITZ, are more prone to competition with battery electric vehicles and eventually demise.

Competition for funding has not only increased between research organizations, but also industrial actors, since the government increasingly funds R&D projects concerned with commercial technology deployment and market formation. The ministries' funding lines for hydrogen research projects are not mission-oriented in so far as hydrogen technologies do not compete with other defossilization options for funding. Three national ministries fund large hydrogen R&D projects across Germany.

The BMBF funds three "lead projects", which are oriented towards basic and applied research. They constitute major research programs that consist of various projects pursued by partnerships between public research organizations and private companies. The projects reflect a place-based approach in regard to the characteristics of the German territory and established national innovation system: First, one lead project is concerned with hydrogen production from offshore wind (H2Mare), which constitutes the largest regional renewable energy resource of the German territory. Hence, making use of this resource for the defossilization of the country is of utmost importance. Second, all three lead projects try to compensate for historical path dependencies. The second lead project is concerned with the manufacturing of electrolyzers (H2Giga), while the third with hydrogen transport (TransHyDE). Thus, two of the three lead projects direct innovation towards green hydrogen production (H2Mare and H2Giga) in an attempt to compensate for the innovation system's historical focus on fuel cells, while the third project contributes to infrastructure development to support market formation (Interview PL_10). In addition, the lead projects produce data on different competing hydrogen technologies in the fields of hydrogen production and transport, which should inform policymakers to reduce the technological variety that the innovation system pursues in the future (Interviews PL_10, PL_13).

The BMDV funds the Second National Innovation Program Hydrogen and Fuel Cell Technology (NIP II). The NIP's most prominent funding scheme is the multi-stage HyLand Program, which is explicitly place-based insofar as it allocates funding according to the competences of municipalities and districts. At the first and second stage, the HyLand Program funds the development of place-based, municipal hydrogen strategies for the production, transport and use of hydrogen, primarily in the mobility market segment. Thereby, the program has considerably increased the spatial reach of the national innovation system by incorporating more and more municipalities into it. Likewise, it has contributed to the development of new capabilities regarding the spatial planning and administration of hydrogen projects at the local and regional levels of government (Interviews PL_1, OS_4). At the third stage, the BMDV subsidizes the development of hydrogen production capacities, filling stations, and fuel cell vehicles (so-called HyPerformer regions, Figure 15). By concentrating funding for infrastructural linkages and implementation regionally, the program should enable clustering and spillover effects, as well as market formation at the local and regional scale.

The BMWK funds thirteen projects concerned with technology deployment in a funding line called "Reallabore" (living labs), which focus on hydrogen production for and use in the large-scale industrial market segment, e.g., in steel or chemical plants. The policy is place-based in two regards: On the one hand, the BMWK ran a special tender for Reallabore in the coal mining regions, to integrate those regions into the hydrogen innovation system and promote their economic development. On the other hand, the tender process evaluated the project bids on the basis of existing knowhow and capabilities within the local networks that have formed around particular industrial sites. The Reallabore integrate and co-locate hydrogen production and industrial use (FfE 2023). Hence, they promote market formation at the local scale. However, local renewable energy resources will likely not suffice to defossilize large-scale industrial sites. Instead, hydrogen trade at the regional or (inter-)national scale will be necessary.

To supply hydrogen at the necessary scale to replace fossil fuels in large industrial plants, the BMWK and BMDV fund hydrogen projects as part of the European IPCEI (Important Project of Common European Interest) for Hydrogen (BMWi 2021a). The national ministries and the regional governments have identified 62 hydrogen projects as IPCEI in Germany (Figure 15). The projects are either concerned with the industrialization of technology manufacturing and the establishment of new manufacturing sites, or the deployment of hydrogen technologies and the formation of the industrial market segment. While the manufacturing sites are located mostly in Southern Germany, most places in which hydrogen should be produced and/or used are located in Northern Germany, connected by initial pipelines, which also receive subsidies (BMWi 2021b). The allocation of funds to Southern Germany for manufacturing and Northern Germany for technology deployment is place-based since it takes into account that Northern Germany offers more renewable electricity for green hydrogen production (OTH Regensburg 2022), while Southern Germany is historically specialized in technology manufacturing. Hence, the national government has reinforced regional specialization. Moreover, the concentration of funding for technology deployment and infrastructure development directs the formation of the green hydrogen market for industrial users to Northern Germany. The development of a national hydrogen pipeline network should then enable the expansion of the green hydrogen market across Germany and the integration of formerly fragmented regional hydrogen markets (see map of envisioned national pipeline network: FNB Gas 2023).

4.5. Different routes within the direction of change

The design of the IPCEI and Reallabore and their focus on large industrial sites is contested within the innovation system for two reasons. First, the IPCEI and Reallabore do not offer subsidies for the use of green hydrogen, which is why many of the Reallabore and IPCEI lack a business case and cannot support market formation (FfE 2023). While the business case will improve as the newly established research organizations, manufacturing sites, and technology deployment bring down the costs of hydrogen technologies, additional support policies seem necessary to form the large-scale industrial market segment (Agora Energiewende and AFRY Management Consulting 2021).

Second, both the Reallabore and IPCEI direct innovation within the industrial market segment towards industrial players with the largest future hydrogen demand, such as steel and chemical plants. Taking this route assumes that hydrogen technologies can be deployed at large industrial scale within the next couple of years without the prior deployment of technologies at smaller industrial scales (Interview EST_6). However, even multinationals like Linde struggle to build electrolyzers of only 20 MW today (Tix 2022), so the viability of supplying large-scale consumers, requiring several hundreds of MW is questionable.

In comparison, funding could also be allocated and directed towards energy-intensive small and medium-sized enterprises (SME), which require hydrogen to become climate-neutral as well, such as the glass, ceramics, paper, and non-iron metals industries (Interviews OS_9, OS_5, BMWK 2022). SMEs in those sectors are often located in rather peripheral places and would require an even greater spatial reach of the national innovation system. The benefit of this alternative route would be that the readiness of hydrogen technologies at the scale of SMEs is higher. Moreover, some energy-intensive SMEs could be supplied with hydrogen at their production site and would not require hydrogen pipelines and regional hydrogen markets (Interview PL_22).

5. Conclusion

The literature on MOIP (Mazzucato 2018; 2021; Robinson and Mazzucato 2019) and MOIS (Hekkert et al. 2020) still lacks geographical sensitivity (Coenen and Morgan 2020). Geographers have recently started to reflect on, and conceptualize, multi-scalar coordination challenges and place-specific path dependencies of MOIS (Wanzenböck and Frenken 2020; Bugge, Andersen, and Steen 2022). Moreover, they have advocated a place-based approach to anchor missions in regions, districts, and universities (McCann and Soete 2020; Fastenrath et al. 2023; Henderson, Morgan, and Delbridge 2024). However, directionality and the challenge of market formation have not received much attention in the geographical literature on missions yet.

Building on the place-based perspective on missions, I have proposed a two dimensional conceptual framework, which, firstly, takes the challenges of building MOIS, formulating missions, and reducing technological variety into account (Wanzenböck et al. 2020; Reale 2021; Parks 2022; Kirchherr, Hartley, and Tukker 2023). Secondly, I have argued that the spatial allocation of R&D funding can direct national innovation systems in space if the funders reflect on which innovative activities, from basic research to end-use (Liu and White 2001), they should fund in which places to support innovation and market formation at the local and regional scale. Moreover, the allocation of these research activities to different places requires the development of organizational capacities at the national scale to coordinate among different places and enable mutual benefits, so different places can contribute to the development of the national innovation system.

My conceptual framework follows the argument that successful mission implementation requires policymakers and practitioners to be attentive to the characteristics of different places that influence how actors in those places engage with missions (McCann and Soete 2020; Fastenrath et al. 2023; Henderson, Morgan, and Delbridge 2024). Such a place-sensitive approach can, on the one hand, avoid that the allocation of R&D funding to different places results in “cathedrals in the desert” (Coenen and Morgan 2020) and uneven development, which could foster resistance against transformative missions from places that are being left behind (Dreher, Kovač, and Schwäbe 2016; Cappellano, Molica, and Makkonen 2023). On the other hand, it should enable a range of systemic outcomes at the regional scale (Grillitsch and Asheim 2018) and contribute to market formation, first at the local and regional scale, then at larger scales (Dewald and Truffer 2011; 2012). Finally, I have also stressed the necessity to monitor and evaluate the effects of funding decisions for routes within the direction of change of the innovation system (Mazzucato 2016).

The framework enabled me to analyze to what extent, in which places, and in regard to which market segments and routes the German national government directs the established national innovation system for hydrogen technologies (Hekkert et al. 2005; Musiolik and Markard 2011; Musiolik, Markard, and Hekkert 2012). I have found that the national government has formulated a mission and has enhanced the organizational capacities to provide directionality. However, its funding strategy is not entirely mission-oriented but often hydrogen-technology specific and includes market segments that are disputed.

While the reduction of funding after the establishment of new research organizations has increased competition within the innovation system, the spatial allocation of funding to research organizations has two systemic outcomes at the regional scale: On the one hand, specialization in new market segments and clustering as new research organizations were co-located with existing research organizations. They should contribute to the formation of new market segments by reducing technology costs and networking among local and regional actors while attracting funding for research projects. On the other hand, the national government has increased the spatial reach of the national innovation system, particularly towards Eastern Germany, to not leave the region behind.

Funding for (industrial) innovation projects was allocated to Southern Germany, based on existing skills in manufacturing, and to Northern Germany, due to the region's renewable energy resources. The funding has two systemic outcomes: On the one hand, the specialization of places in manufacturing drives down technology costs. The technologies can then be deployed in other places at reduced costs and contribute to market formation there. On the other hand, the national government has directed funding for large-scale industrial hydrogen projects and pipelines to Northern Germany, so technology deployment and market formation in this market segment will start at the regional scale there. In comparison, funds for the – disputed – deployment of hydrogen technologies in the mobility market segment were allocated across Germany, based on previous place-based experiences within this sector.

The allocated funding for large-scale industrial sites is currently insufficient to enable the formation of local and regional markets (FfE 2023). In this regard, the current route of the innovation system is disputed because some actors would favor a more gradual approach that would direct the innovation system towards smaller, energy-intensive industries first, which would result in a more decentralized allocation of funding and, potentially, market development. In this regard, future research should develop a better understanding for competing routes within directions of innovation systems rather than competing innovation systems (cf. Dreher, Kovač, and Schwäbe 2016). From a policy perspective, pursuing various routes at the same time appears to be a less risky approach, whereas a focus on one route seems to be more risky but potentially more effective in promoting the formation of certain market segments.

Ultimately, the allocation of funding throughout Germany also reflects an attempt to strike a balance between specialization and clustering, counteracting uneven development, increasing the spatial reach of the national innovation system, and enabling widespread technology adoption, deployment, and market development. In this regard, policymakers are confronted with a trade-off between clustering in and specialization of certain places, on the one hand, and the spatial reach and cohesion of different places, on the other hand (Cappellano, Molica, and Makkonen 2023). Future research could further conceptualize these potential trade-offs and offer policy recommendations in regard to striking a balance between them.

While this article has focused on a top-down and outcome-oriented perspective on the allocation of funding to different places, future research could enable more insights into how the allocation of funding is coordinated across government-levels, and to what extent actors provide directionality to national innovation systems from the bottom-up. Moreover, research could zoom-in on the local and regional scale and investigate how funding changes place-specific characteristics, using concepts such as placemaking that focus on the sociocultural dimensions of place-based development (Pancholi et al. 2020; Courage et al. 2021).

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Article IV

Kalvelage, L., **Walker, B.**, 2024. Strategic coupling beyond borders: Germany's extraterritorial agency in Namibia's green hydrogen industry. Journal of Economic Geography lbae036. https://doi.org/10.1093/jeg/lbae036.

Strategic Coupling beyond Borders: Germany's Extraterritorial Agency in Namibia's Green Hydrogen Industry

Abstract

Amidst increasing geopolitical threats, geo-economic competition, and climate change concerns, this paper reflects on why and how states support private firms in strategic coupling processes abroad. By conceptualizing the defossilization rationale as a state project that drives extraterritorial agency, we explain Germany's involvement in Namibia's green hydrogen industry. Introducing the notion of extraterritorial institutions, we show how a state project is translated into extraterritorial state action by accompanying private enterprises with public institutional support and unveil three mechanisms through which extraterritorial agency alters strategic coupling dynamics: extraterritorial de-risking, extraterritorial asset creation, and market creation. We show that, even in liberal and coordinated market economies, states develop extraterritorial strategies to align global production networks with their strategic goals.

Keywords: global production networks, extraterritoriality, competitive dynamics, hydrogen industry, strategic coupling

1. Introduction

In a multipolar world of geopolitical blocs facing the climate crisis, the spatial organization of the global economy is increasingly influenced by state responses to geopolitical risks (Blažek and Lypianin 2024; Pavlínek 2024) and the defossilization imperative (Bridge and Faigen 2023; Coe and Gibson 2023). As a consequence, even in liberal and coordinated market economies (Kim, 2022), states develop strategies to align global production networks (GPNs) with their strategic goals not just within their territory but also extraterritorially (McGregor and Coe 2021). Trends to reshore, friendshore, and nearshore production reflect attempts to mitigate geopolitical and climate risks by actively shaping the geography of strategic production networks (Kalvelage and Tups 2024; Völlers et al. 2023). Notwithstanding, GPN research still tends to confine the role of the state to "the facilitation and regulation of GPN activities *within the territorial boundaries of the state*" (McGregor and Coe 2021, 7 emphasis added). To broaden the understanding of the role of states in GPNs outside their territorial boundaries, this paper examines why and how states exercise extraterritorial agency to alter the geographies of global production in accordance with their interests.

While we appreciate that the literature increasingly recognizes, and distinguishes between, the influence of foreign and domestic states on the spatial configuration of GPNs (Glassman 2011; Lim 2018; McGregor and Coe 2021; Smith 2015), we observe a rather narrow understanding of extraterritorial state engagement in strategic coupling concerning three caveats.

First, in regard to the drivers of extraterritorial state engagement, we note that the literature often discusses motives and interests rather implicitly, focussing on aspects such as security (Glassman 2011) or economic concerns (Lim 2018). Moreover, the literature has not engaged with defossilization as an important rationale of state action in GPNs (Blažek and Lypianin 2024; Bridge and Faigen 2023; Coe and Gibson 2023), even though such an engagement could offer insights into how different drivers of state action, such as security and socio-ecological concerns, interact and materialize (Riofrancos 2023). Therefore, we conceptualize the defossilization rationale as the intersection of three drivers of state action: socio-ecological concerns, economic development, and security threats. Foregrounding defossilization draws attention to specific GPNs (e.g., renewable energies, low-carbon technologies) and inter-state relations (e.g., the import/export of renewable energy and minerals critical for low-carbon technologies).

Second, research on strategic coupling tends to confine extraterritorial state agency to the strategic coupling of state-owned enterprises (SOEs) abroad (Lim 2018; McGregor and Coe 2021). We argue, however, that extraterritorial state agency is embedded in more complex organizational forms of state-corporate relationships that have not yet been conceptualized. Therefore, we have developed the term “extraterritorial institutions” to denote actors that pursue domestic interests in foreign states, such as development agencies, embassies, and development banks, and highlight that they can not only support SOEs but also domestic private companies in strategic coupling processes abroad. To capture these activities of extraterritorial institutions in support of private and/or public enterprises abroad, we coin the term "flanking".

Third, how extraterritorial institutions can support the strategic coupling of domestic lead firms abroad remains undertheorized. We propose a mechanism-based approach (Yeung 2019) and conceptualize three mechanisms through which states can shape strategic coupling processes by altering competitive dynamics: extraterritorial asset creation, extraterritorial derisking, and market creation.

Empirically, we analyse why and how the German state supports (or *flanks*) the strategic coupling of the fully private German-British joint venture *Hyphen Hydrogen Energy* (hereafter Hyphen) with a range of political-economic activities in Namibia and how these efforts have influenced the Namibian state to grant the joint venture a concession to develop a large-scale export-oriented green hydrogen project in the country. The case is insightful for three reasons. First, it exemplifies how the defossilization rationale can drive extraterritorial state action because industrialized states, including Germany, increasingly aim to defossilize a wide range of energy uses with green hydrogen, an emission-free energy carrier. Second, the role of the state in the green hydrogen industry is pronounced because in as much as green hydrogen can replace fossil fuels, it changes the geopolitics of energy trade (van de Graaf et al. 2020). Likewise, the development of the first export-oriented green hydrogen projects is a function of strong (foreign) state support because such projects are rife with risks and characterized by a difficult business case vis-à-vis fossil fuels. Third, the case of German-Namibian relations is particularly interesting as it occurs in a post-colonial context, which has led some researchers to warn that the green hydrogen industry could reproduce unequal power relations between the two countries (Gabor and Sylla 2023).

In the next section, we develop our theoretical arguments, focussing on the formation of the defossilization state project, the flanking activities of extraterritorial institutions, and the mechanisms of extraterritorial agency. Following the methodology, we apply these theoretical arguments to the strategic coupling process of the green hydrogen GPN in Namibia. Finally, we discuss the implications for future research in the conclusion.

2. The drivers, organizational strategies, and mechanisms of extraterritorial agency on strategic coupling processes

We develop our theoretical arguments in three steps. First, we explain how different drivers of state action coalesce in the defossilization state project. Second, we propose the term “extraterritorial institutions” to enable reflections on the agency of states to pursue their defossilization goals abroad by – what we suggest calling – flanking private lead firms. Third, we conceptualize three mechanisms through which extraterritorial institutions can influence the strategic coupling of private lead firms in other countries (cf. Figure 16).

2.1. Extraterritorial state engagement amidst security, geoeconomic, and climate-change concerns

To understand why states act abroad, we propose distinguishing between three drivers of state action that have received (more or less implicit) attention in the GPN literature on extraterritoriality. These are social forces (Phelps 2007), geopolitics (Glassman 2011), and geoeconomic competition, as capitalist states (Lim 2018; McGregor and Coe 2021) compete in the new international division of labour (Alami and Dixon 2022). We show how these three drivers coalesce in the defossilization state project to demonstrate the analytical value of distinguishing drivers of extraterritorial state action that materialize differently in relation to one another in different states and geographical contexts.

First, extraterritoriality can result from the interests of particular national or transnational classes or social forces, which mobilize states to pursue their interests (Phelps 2007). These interests range from socio-ecological (Riofrancos 2023), over religious (Hunter 2017; Kadri and Abdelsalam 2020) to ideological concerns, such as anti-communist sentiments (Callaghan, O'Connor, and Phythian 2019). Climate change constitutes a particularly important socio-ecological concern today. However, social forces can mobilize the state to drive or hinder (extraterritorial) defossilization efforts. On the one hand, when elites are beneficiaries of fossil fuel exports, states are likely to hinder (Bouzarovski and Bassin 2011) or slow down defossilization (Koch 2022). Likewise, the threat of industry relocations to "pollution havens" (Poelhekke and van der Ploeg 2015) or to countries which offer a cheaper renewable energy supply (Samadi, Fischer, and Lechtenböhmer 2023) can motivate social forces, such as labour unions (Prinz and Pegels 2018), to protest against defossilization. On the other hand, climate movements play an important role in demanding climate action from states (Jänicke and Jacob 2004), also in regard to financing climate change mitigation efforts abroad (Pickering and Mitchell 2017).

Second, geopolitical concerns, particularly military and the security of supply threats, constitute a second motive for extraterritorial state engagement (Glassman 2011; Kalvelage and Tups 2024). While several authors have argued that security concerns have incentivized states to onshore production (Riofrancos 2023) and might even signal a reversal of globalization and a trend towards regional production networks (Butollo et al. 2024; Gong et al. 2022), we argue that it might also compel states to act extraterritorially. For example, states are forced to respond to geopolitical trigger events such as violent conflicts (Blažek and Lypianin 2024), trade sanctions (Pavlínek 2024), military threats, or the weaponization of supply chain bottlenecks (Beaumier and Cartwright 2024). When such trigger events lead to the "geopolitical decoupling" (Blažek and Lypianin 2024) of domestic firms from foreign energy sources, states require the capacity to achieve new, geopolitically safe couplings to ensure security of supply. This is especially relevant for some industrialized countries, such as Germany, Japan, and South Korea, that are not able to produce enough renewable energy domestically at competitive costs (van de Graaf et al. 2020). Hence, there is a strong incentive to secure an economical and reliable renewable energy supply from abroad. Moreover, states try to anticipate and prevent geopolitical trigger events by "defensive decoupling" (Ando, Hayakawa, and Kimura 2024, 3) and building geopolitical alliances (Flint and Zhu 2019), which the development of international energy transportation infrastructures exemplifies (Sovacool 2012). In sum, the "geopolitical position of a country in the international system is thus one of the preconditions for its industries and firms to successfully decouple from the structural coupling and recouple in a more favourable strategic coupling" (Pavlinek 2024, p. 161).

Third, states increasingly compete as economic actors in "the new international division of labour" (Alami and Dixon 2022). To secure or improve their geoeconomic position, states can be compelled to act in foreign countries, for example, to ensure domestic firms' access to foreign (export) markets (Shadlen 2005). For example, defossilization offers resource-rich and advanced economies new opportunities for economic development. On the one hand, low-carbon technologies, from battery electric vehicles to hydrogen technologies, provide novel opportunities to specialize in technology development, manufacturing, and export (Baker and Sovacool 2017). On the other hand, the growing demand for energy transition minerals (IEA 2021) and renewable energy imports offers export-oriented development opportunities to mineral- and energy-rich countries (van de Graaf et al. 2020) but also puts pressure on states specializing in technology manufacturing to ensure a stable supply of these resources (Bridge and Faigen 2023; Coe and Gibson 2023).

Based on these insights, we argue that national and transnational social forces, geo-economic competition, and geopolitical concerns drive the formation of state projects that steer extra-territorial state action. However, depending on which of the three underlying drivers dominates, and how the drivers intersect in nationally specific ways, states will be inclined to interpret their extraterritorial role in different ways. In export-oriented industrialized countries with high vulnerability regarding energy imports, active climate change pressure groups, and the need to defend a position as technology leaders in a dynamic geo-economic environment, these three drivers may coalesce into defossilization as an increasingly important rationale for extraterritorial state action (Riofrancos 2023). For example, extraterritorial state action may be characterized by national industrial specializations and resources and states might therefore be willing to deviate from strictly economic goals of value creation and capture for geopolitical reasons (Lim 2018). However, in different contexts, such as countries with an authoritarian governance structure and political-economic elites that benefit from the export of fossil resources, extraterritorial state action may take different, even violent, forms. In the following section, we explore how states can organizationally pursue state projects abroad.

2.2. Flanking domestic lead firms with extraterritorial institutional support as a means of distancing in postcolonial contexts

We propose the term "extraterritorial institution" to analytically foreground foreign-state and state-linked actors involved in strategic coupling processes abroad and distinguish them from the established GPN category of "regional institutions". Following Ospina Peralta et al. (2015, 32), we define extraterritorial institutions as "organizations that are not controlled by actors in the territories where they operate". This conceptual distinction highlights actors that pursue a foreign state's interests in strategic coupling processes.

Extraterritorial institutions will often be associated with different policy fields because states are organized along policy fields, such as climate and economic policy (Neilson, Pritchard, and Yeung 2014). Considering policy fields helps to reflect on the interests and functions of different extraterritorial institutions. In all policy fields, extraterritorial institutions might exist that influence GPNs, ranging from international research efforts and the attraction of foreign scientists by national ministries of research and innovation (Zhang, Cooke, and Wu 2011), and labour ministries that regulate labour standards across transnational supply chains (Sydow, Helfen, and Auschra 2021) to foreign affairs ministries and diplomats lobbying for market access in foreign countries (Jaklič and Šešum 2019), as well as export promotion agencies facilitating this market access (Yang 2014).

Besides policy fields, extraterritorial institutions might also be linked to different government levels. Hence, assuming a multi-scalar perspective offers insights into intra-state power relations and coordination. Often, national ministries will control extraterritorial institutions, such as development banks. However, supranational organizations, by definition, have influence beyond a single nation state but are subjected to uneven influence from different national governments (Ranis, Vreeland, and Kosack 2005). Hence, they can act as extraterritorial institutions in the interest of nation states too. Likewise, GPN research has shown that local state actors can exert extraterritorial agency (Breul et al., 2019).

To understand the coordination among extraterritorial institutions, we follow a strategic-relational understanding of the state (Jessop 2016), which is often employed in the GPN literature (Dawley et al., 2019; Pavlínek, 2024; Smith, 2015; Bridge and Faigen 2023). From a strategic-relational perspective, state agency is understood as the result of struggles between state actors and underlying social forces. Hence, different extraterritorial institutions can pursue different, potentially competing goals. In this sense, coherent state action abroad constitutes an organizational achievement and outcome of intra-state coordination. The concept of state projects, which secure the "operational unity" of state action, describes this organizational achievement (Jessop 2016, 58, see as well: Bridge and Faigen 2023).

When extraterritorial institutions pursue a state project that concerns strategic coupling with a foreign region, strategic coupling encompasses the coordination of interests between foreign states, host states, and corporate entities (Lim 2018; Smith 2015). State-state coordination is important because states hold certain sovereign territorial rights, especially regarding land and resource use, policing, and defence (Bridge 2008; McGregor and Coe 2021). Hence, extraterritorial institutions will need to coordinate with regional institutions to perform certain functions in support of strategic coupling if they do not want to expand to perform those functions abroad themselves (as in colonialism) or arrange for other states to perform these functions on their behalf (as in neocolonialism) (Phelps 2007).

In regard to state-corporate relations, states can either directly participate in the strategic coupling abroad through SOEs (Lim 2018; McGregor and Coe 2021) or cooperate with private firms (e.g., Glassman 2011; Smith 2015). Both organizational strategies might allow states to achieve their interests abroad. Similar to SOEs, private firms transfer value and/or strategic commodities from territories abroad to the home region where they are headquartered (Vicol et al. 2019). Hence, when states are not in control of SOEs, states can cooperate with private lead firms. Similarly, states can cooperate with private lead firms if they offer organizational benefits over SOEs.

We argue that the greater independence of private companies from their home states compared to SOEs can constitute an organizational benefit in strategic coupling processes. McGregor and Coe (2021, 9) have already argued that concealing ownership of SOEs might benefit state-state negotiations. They call this strategy "distancing", encompassing indirect forms of ownership, e.g., through intermediary government agencies, as well as "hybrid entities" (McGregor and Coe 2021) or "state-linked actors" (McGregor and Yeung 2022), such as development agencies, cluster organizations, and research institutions.

In this vein, we propose that distancing does not need to end at hybrid entities and indirect forms of control but can also encompass the public support of entirely private companies by mobilising extraterritorial institutions. We term this mobilisation of extraterritorial institutions to support the activities of private firms that are aligned with state projects "flanking". For instance, domestic lead firms might transfer profits or commodities from abroad back home and, hence, contribute to achieving geoeconomic goals. Hence, foreign states might rely on fully private companies to create distance among themselves and the corporation in the eyes of the state hosting the strategic coupling, which an indirectly state-owned enterprise could not offer. Distancing can be especially useful in geopolitically sensitive contexts, such as in postcolonial contexts, in which firms might not want to be associated with the state where they are headquartered, e.g., because of the state's colonial heritage.

In the literature, different forms of extraterritorial state action to flank domestic lead firms in strategic coupling processes abroad can be found. These flanking efforts encompass the development of infrastructures and military interventions, diplomacy and sanctions (Glassman 2011), product and labour standards (Alford and Phillips 2018), as well as bilateral trade agreements and other forms of market integration, or tariff regimes and protectionism (Curran, Nadvi, and Campling 2019; Smith 2015). In other works, more specific functions, such as landownership, economic planning and management, strategic and portfolio investing, redistribution, and knowledge generation are emphasized (McGregor and Yeung 2022; Werner 2020).

In order to provide a more concise view on extraterritorial state action, we propose three mechanisms of extraterritorial agency through which state actors can influence strategic coupling in the following section.

2.3. Three mechanisms of extraterritorial agency

We argue that states can extraterritorially shape the competitive dynamics and risk environments that drive firms according to the GPN 2.0 approach (Coe and Yeung 2015). These competitive dynamics encompass the management of costs and capabilities, adhering to market and financial imperatives, and minimizing risk exposure (see for a short review: Coe 2021). We propose – in a non-comprehensive manner – to distinguish three mechanisms of extraterritorial agency, including asset creation, de-risking, and market creation. While asset creation can particularly support how firms manage costs and capabilities, de-risking addresses the risk environment and improves financing conditions, while the creation of new markets changes market imperatives as newly created markets gain in relative importance to established markets.

1. Extraterritorial asset creation

The concept of regional assets describes the human, technological, and institutional resource base of a region (Henderson et al. 2002). Regional assets encompass "natural assets (covering resources); infrastructural and material assets; industrial assets (covering technology and firm competencies); human assets in the shape of labour skills, costs, and knowledge; and institutional endowments of rules, routines, and norms" (MacKinnon et al. 2019, 10). Regional assets can be more generic or more distinctive in nature. For example, generic regional assets include cheap regional energy resources, labour surpluses, and the availability of industrial sites which drive down production costs (MacKinnon 2012). In comparison, more distinctive regional assets, such as specialized pools of knowledge and expertise, and a well-trained regional labour force can contribute to the capabilities of a firm. Therefore, regional assets are at the core of the GPN framework and allow regions to attract investments (Yeung 2015). Hence, extraterritorial asset creation constitutes a means to increase the competitiveness of regions in competition for foreign direct investment.

GPN studies have increasingly adopted a dynamic understanding of regional assets (Fu and Lim 2022; McGregor and Coe 2021), according to which the "state and other actors" can improve the regional asset base "through dynamic and strategic processes of asset creation and destruction" (McGregor and Coe 2021, 7). In this vein, we argue that states cannot only alter the domestic asset base but also modify and create assets abroad to alter the preconditions of strategic coupling (cf. Ospina Peralta et al. 2015).

For instance, foreign state-led exploration activities can discover natural resources (Adamson 2021) and spatial development initiatives can create infrastructural assets (Tups and Dannenberg 2021), including ports (Blanchard and Flint 2017). States can also foster knowledge, skills, and technology transfer via research cooperation and training programmes, thereby creating human and industrial assets (Pandey, de Coninck, and Sagar 2022). Lastly, improving the institutional environment, i.e., creating institutional assets, is a conventional aim of international development cooperation and widely practiced (Booth 2011).

An improved regional asset base as a result of extraterritorial asset creation may strengthen the bargaining position of regions vis-à-vis lead firms in strategic coupling processes. Hence, regional institutions might be able to negotiate more beneficial terms of strategic coupling for regional development (Coe and Yeung 2015). Therefore, regional institutions will be interested in receiving support in asset creation by extraterritorial institutions, which those extraterritorial institutions can leverage in state-state negotiations to influence the decision-making of regional institutions.

2. Extraterritorial de-risking

Besides creating regional assets abroad, states can alleviate companies from the demands of private financiers and de-risk investments in foreign territories, thus incentivizing strategic coupling in those territories. Risks hinder companies from investing in certain locations and translate to higher financing costs because financiers will require higher returns on their investments to take on financial risks (Sweerts, Longa, and van der Zwaan 2019).

De-risking refers to practices which aim to improve the overall risk-return profile of an investment and, thereby, the investment's financing conditions (Gabor 2021). De-risking has become "immensely powerful" (Gabor and Sylla 2023, 2) as various government programmes, such as the Inflation Reduction Act in the US or the European Green Deal, pursue a de-risking approach to enable private investments in strategic sectors like renewable energy. However, governments do not only de-risk investments in strategic sectors on their territory but also extraterritorially.

Two forms of de-risking can be distinguished: policy de-risking, i.e., measures to reduce underlying investment risks, and financial de-risking, i.e. underwriting private risks with public funds (Steckel and Jakob 2018). Particularly the latter type of de-risking has become the subject of critical discussions for two reasons. On the one hand, when states take on risks from the private sector while not benefitting from successful investments, they socialize risks while privatizing returns (Mazzucato 2018; 2016). On the other hand, the uneven (fiscal) capacities of states in the Global North and South imply uneven capacities to engage in financial de-risking, which could reproduce uneven development globally (Gabor 2023).

De-risking efforts are particularly important for capital-intensive investments, e.g., in large-scale infrastructures, where financing costs can amount to a considerable share of total costs (Ochieng and Papadaki 2020). Moreover, de-risking efforts are often necessary in new fields of technology and industrial sectors that are characterized by a difficult business case or long-term investments (Mazzucato 2018; 2016). Lastly, risks are more pronounced in emerging markets and places with which investors associate (socio-political) risks, e.g., Global South countries (Steckel and Jakob 2018; Sweerts, Longa, and van der Zwaan 2019).

Regarding the actors of extraterritorial de-risking, development banks play an important role (Gabor 2021). Development banks are usually majority-owned by national governments, which ensures their high creditworthiness and enables them to raise large amounts of capital on financial markets which can be offered at low interest rates to foreign governments (Shapiro, Vecino, and Li 2018). Hence, development banks constitute important extraterritorial institutions that flank private companies. Moreover, export credit agencies are an established institution undertaking de-risking efforts, e.g., by offering export credit guarantees and political insurances that aim to address political risks, while facilitating access to potential export markets (Felbermayr and Yalcin 2013; Gianturco 2001).

3. Market creation

Lastly, states can create markets which offer companies new business opportunities in the direction of economic development that is aligned with the interests of states. For example, new fields of technology might promise economic or socio-ecological benefits, such as employment opportunities or lower greenhouse gas emissions. To be able to create markets, states need to assume a more strategic and proactive role than only correcting market failures (Mazzucato 2018; 2016).

However, correcting market failures, e.g., by pricing or regulating negative market externalities, such as greenhouse gas emissions, might be a necessary part of creating new markets, e.g., for climate-neutral technologies. In addition, states are crucial for market creation for various reasons. First, states are involved in the standardization of commodities (Coe and Yeung 2015, 56) and negotiate with other states to lower bilateral import tariffs, thereby enabling suppliers and buyers to trade across territories at competitive prices (Curran, Nadvi, and Campling 2019; Smith et al. 2014). Second, market creation requires long-term, strategic investments by states in the research and development of new commodities, e.g., technology, and often hinges on place-based incentives to support their commercialization, e.g., by subsidizing the production and consumption of these commodities in different places (Walker 2024). Third, states often finance and co-develop the necessary infrastructures underpinning (international) trade. Hence, they can shape the scale at which market participants can trade goods, as exemplified by the extension of gas pipelines (Bridge and Bradshaw 2017; Walker and Klagge 2024). Fourth, market creation also encompasses the creation of market operators, e.g., trading institutions (Chandrashekeran 2022). Last, through public procurement, states actively create demand (Edler 2016).

McGregor and Yeung (2022) have recently argued that states can contribute to extraterritorial market creation. Not only do states, through economic diplomacy, negotiate for domestic firms to access foreign markets (Jaklič and Šešum 2019), they can also assist in developing the necessary infrastructure underlying markets in foreign territories, exemplified by China's Belt and Road initiative (Flint and Zhu 2019), or stimulate demand for domestically produced goods abroad (Edler 2016). In addition, states can contribute to the creation of trading institutions abroad. For instance, technical and juridical assistance by development agencies has stimulated the creation of a wholesale electricity market in Vietnam (Do et al. 2020).

Summarizing our conceptual approach, we distinguish three drivers of extraterritorial state engagement, encompassing the concerns of social forces, geopolitical threats, and geoeconomic competition. From this perspective, we understand the defossilization rationale as a state project driven by social pressure for climate action, energy security concerns, and economic development goals to varying, nationally-specific degrees. The defossilization rationale can motivate state actors and extraterritorial institutions to unite under a defossilization state project, which stimulates extraterritorial state engagement. In this case, extraterritorial institutions flank public or private companies in their strategic coupling efforts abroad through three mechanisms: extraterritorial asset creation, de-risking, and market creation (cf. Figure 16). These three mechanisms, however, are strongly interrelated and can reinforce each other.

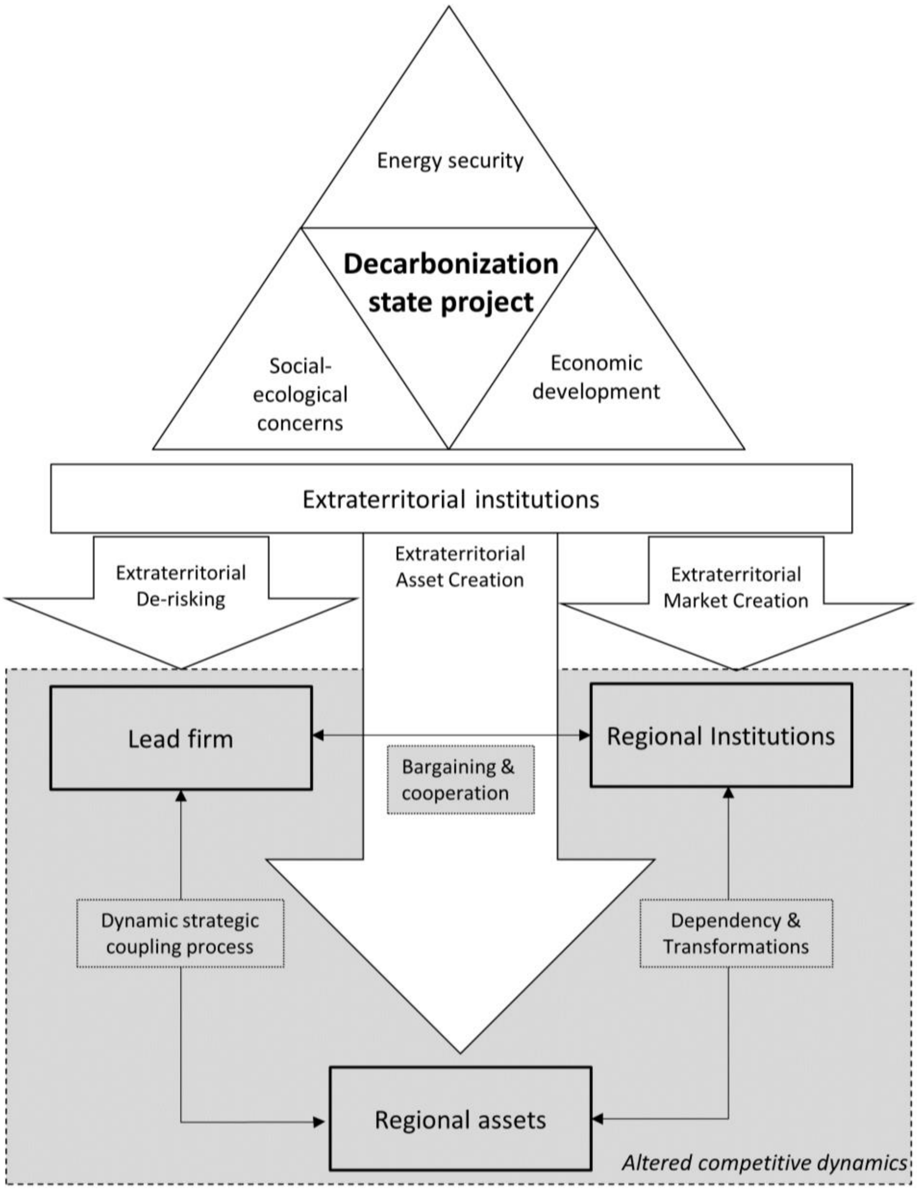

Figure 16: Expansion of the strategic coupling framework elaborated and visualized in: (Coe and Yeung, 2015, p. 19; Yeung, 2015, p. 5); the elements of the original framework are depicted in the gray rectangle and proposed expansions in white above (illustration by the authors)

3. Methodology

We developed our analytical framework in an iterative process of reviewing literature and analysing empirical data about a planned US$ 10 billion investment by the joint venture Hyphen in an export-oriented green hydrogen and ammonia production facility in Southern Namibia, near the town of Lüderitz. Hyphen plans to transform the green hydrogen into green ammonia for easier transport, which prospective buyers, such as the German energy utility RWE, could either use directly or reconvert. Hyphen consists of the German renewable energy and hydrogen project developer Enertrag and the British investment company Nicolas Holdings. The project is currently in the planning and development phase which for hydrogen projects of this size take 3-6 years. Afterwards, project developers take the final investment decision (FID), followed by a construction phase of 1-2 years, and an operation phase, which should last at least three decades to be economical (Engelmann and Rohrmeier 2022).

In light of the explorative nature of the research question, we applied a qualitative research design. To understand the agency of German extraterritorial institutions in the strategic coupling process of Hyphen, we conducted a field trip between February and April 2023 to Namibia's capital Windhoek and to Lüderitz, resulting in 29 semi-structured interviews with seven Namibian government representatives (NAMGOV), including high-ranking officials, five German extraterritorial institutions (GEREX), fifteen international and Namibian companies (PRIVATESEC), and two civil society organizations (CSO). In addition, the analysis draws from interviews with German actors (GER) conducted in Germany, including interviews with three Enertrag employees, Brandenburg's regional development agency, two German policymakers involved in the development of the German hydrogen strategy, the German subsidy mechanism for non-European hydrogen projects, H2 Global, and two employees from the German Development Cooperation (GIZ). The majority of the interviews were conducted in English and lasted approximately 60 to 90 minutes. They were recorded and transcribed. One interview was conducted in a group, two online, and one could not be recorded due to confidentiality concerns. In the latter case, we took detailed notes and supplemented with recall transcripts later.

The data collection approach also included policy documents (particularly the German and Namibian hydrogen strategies BMWi, 2020; the Ministry of Mines and Energy, 2022), site visits, conference attendances, and the observation of a German business delegation organized by the Economic Development Agency of the German state of Brandenburg, where Enertrag's headquarters are located. A qualitative content analysis of all the material was conducted, as described by Kuckartz and Rädiker (Kuckartz and Rädiker 2022).

4. The German state's extraterritorial agency in Hyphen's strategic coupling process

We start the analysis by providing background information about the strategic coupling process between the Namibian government and the green hydrogen project developer Hyphen, which was flanked by the German state (4.1). The following sub-sections further scrutinize, first, why the German state is engaged in the hydrogen industry in Namibia as part of its energy transition (4.2). We then identify the extraterritorial institutions that support Hyphen's GPN and how they coordinate among themselves (4.3). Lastly, we explain the extraterritorial agency mechanisms that have influenced Hyphen's strategic coupling process (4.4).

4.1. Extraterritorial influence as an explanation of Hyphen's the strategic coupling?

In June 2021, the Namibian government published a public request for proposals to develop a first large-scale, export-oriented green hydrogen project in a concession zone in the Tsau ǁKhaeb National Park. The concession zone includes around one-fifth of the park's total land area (NIPDB 2021). The park stretches from Lüderitz, in the South of Namibia, to the South African border. Tsau ǁKhaeb is an unpopulated historical mining area, owned by the state (Nangolo 2012) and hosts the country's best renewable energy resources (IEA 2019).

The Australian hydrogen company Fortescue Future Industries, Hyphen, and the South African petrochemical company Sasol received high rankings for their project proposals (The Presidency of Namibia 2022). Yet, although both Fortescue and Sasol represent large, diversified companies that could have invested considerable equity, the Namibian government instead declared Hyphen to be the preferred bidder. The decision-making process was criticized by a civil society organization, which claimed that the evaluation process was not transparent and questioned why the joint venture, consisting of the medium-sized Enertrag (annual turnover €250 million) and Nicholas Holdings, a rather unknown holding, investment, and project development company, should be the preferred bidder (IPPR 2022).

Our understanding of extraterritorial agency and the benefits of state-private cooperation can explain why choosing Hyphen as the preferred bidder has two advantages for the Namibian state. On the one hand, Enertrag's involvement in the consortium ensured continuing support for Namibia's green hydrogen industry by the German state, which had already invested considerably in Namibia at the time of the tender (see 4.4). In comparison, neither Sasol's nor Fortescue's bids were supported with comparable extraterritorial efforts by their home states. On the other hand, the relatively small size of the two companies invested in Hyphen and the EIB's concessional loan ensured that the Namibian state could acquire shares in the Hyphen project (NAMGOV1). Hence, extraterritorial agency is relational insofar as it depends on the capacities of other, competing foreign states to assert their interests, as well as host states to amplify asset creation, de-risking, and market creation efforts or conduct these efforts themselves.

Following more than a year of negotiations between Hyphen and the Namibian national government, the two parties signed a Feasibility and Implementation Agreement (FIA) in May 2023. The FIA grants the Namibian government the opportunity to acquire a 24% equity share in the project (Hyphen and Government of Namibia 2023), thus sharing both investment risks and benefits. On the one hand, the shares of the Namibian state would increase its value capture if the project is realized and operates successfully. On the other hand, if the project fails after the investments have been realized, the Namibian state would need to service its debt to the EIB, which would prove difficult given Namibia's state budget of less than €4 billion (IPPR and Hanns Seidl Foundation 2023). In addition, Hyphen has committed to procuring 30 percent of goods and services locally and filling 90 percent of jobs with Namibians throughout the construction and operational phases (Hyphen and Government of Namibia 2023). Reaching these very ambitious goals will crucially depend on the German state's extraterritorial agency, particularly the creation of an educated Namibian workforce, as we explore in the next sections.

4.2. Defossilization as a rationale for the German state's engagement for green hydrogen and Hyphen in Namibia

The German state's extraterritorial engagement in Namibia's green hydrogen industry can be explained as an interplay of the three drivers introduced earlier: social pressure for climate action, economic development opportunities, and energy security concerns. Facing very limited oil and gas resources and economic stagnation due to the oil price crises of the 1970s, social forces emerged in Germany in the late 1970s that warned against pollution, dependence on fossil fuel imports, and nuclear accidents (Krause, Bossel, and Müller-Reißmann 1980). With the formation of the Green Party, these social forces gained a political voice in local and national parliaments. Opposition to nuclear power spawned the development of wind, solar, and hydrogen technologies by private entrepreneurs and companies from powerful industrial sectors, such as automotive, mechanical engineering, and chemicals, offering necessary capabilities (Rechsteiner 2021; Walker, Becker, and Klagge 2021).

The intersection of environmental and energy security concerns with opportunities for economic development created a strong political force that increasingly gained hold in the German state. Hence, from the 1980s onwards, first federated state governments, then the national government adopted policies supporting green hydrogen and renewable energies (BMWA 2005; von Hirschhausen 2018).

By 2010, Germany had become a world market leader in the production of renewable energy and hydrogen technologies, which represented a significant growth factor for peripheral areas in East Germany (Brock, Sovacool, and Hook 2021). While the national government decided to phase out nuclear power in 2011 after the Fukushima accident and, thereby, increasing demand for alternative energy sources, the German renewable energy market showed the first signs of maturation due to increasing political resistance from citizens dwelling in the vicinity of renewable energy installations (Walker 2022) and industrial associations and labour unions associated with fossil fuels (Prinz and Pegels 2018). Hence, it became increasingly apparent that the potential for domestic renewable power generation was insufficient to satisfy German energy demand (Walker 2022).

Social pressure for defossilization persisted and growth opportunities for renewable energy technology abroad opened up. On the one hand, German renewable energy lead firms started to explore new business fields, e.g., green hydrogen production to store renewable electricity, and project development abroad to access new markets (Franz and Vogel 2015). The corporate history of Enertrag exemplifies these developments. Headquartered in one of the structurally weakest regions of East Germany, the company developed its first green hydrogen project in Germany in 2011. Driven by a stagnating market in Germany, in 2017, Enertrag entered the growing southern African renewable energy market (GER1). The German national government, the government of Enertrag's federated home state Brandenburg, and Brandenburg's regional development agency see support for Enertrag as a means to address the region's political and economic challenges and hope that Enertrag will transfer part of the value it captures abroad back to its home region (GER5).

On the other hand, the German Ministry of Economic Affairs commissioned the German Development Cooperation (GIZ) to investigate whether green hydrogen imports from regions such as Southern Africa could substitute fossil fuel imports and, thus, contribute to energy security in the face of the twin challenges of defossilization and nuclear phase-out (Interview GER6, GER7). Energy security concerns became even more pressing when Germany sanctioned fossil fuel imports from Russia to use its purchasing power in the trade war that resulted from the outbreak of the Russia-Ukraine war. Consequently, the German national government is interested in accessing Namibia's worldclass renewable energy resources to friendshore energy production (Kalvelage and Tups 2024). However, extraterritorial engagement in Namibia takes place in a sensitive geopolitical context, due to the colonial history of the two states. 30,000 ethnic Germans live in Namibia, resulting in strong German extraterritorial institutions but also in diplomatic tensions caused by claims for reparation (Melber 2022). In the next section, we show how the German state's ambition to import green hydrogen from Namibia cumulates in a coordinated state project.

4.3. Unified extraterritorial support for a private company

The intersection of different state drivers in the defossilization rationale facilitates the emergence of state projects as state actors with different political mandates can unite behind a common goal for different reasons. (Importing) green hydrogen is an example of a state project that is shared by various political parties across subsequent legislative periods. The German National Green Hydrogen Strategy (BMWi 2020) is an expression of this state project and five German ministries[16] are currently working on a hydrogen import strategy that further guide the political mandates of extraterritorial institutions (BMWK 2024).

The state project of green hydrogen imports requires coordination between the German and the Namibian states, among different government levels, and encompasses various extraterritorial institutions. In August 2021, the German Federal Minister of Education and Research had already signed a joint communiqué of intent to establish a hydrogen partnership with Namibia, which the Green Party Minister for Economic Affairs signed in 2022 (BMWK 2023). The partnership represents the national-level strategic platform to coordinate the activities of different German ministries and the extraterritorial institutions they control in Namibia and to negotiate the German State's involvement in Namibia's green hydrogen industry with the Namibian government.

These state-state negotiations encompass the potential use of the German State's extraterritorial agency, e.g., its ability to create regional assets. They have improved Hyphen's position vis-à-vis its competitors for access to Namibian land because the German state can offer the Namibian government benefits that private companies cannot offer (see 4.1, 4.4). The German Embassy in Windhoek represents a classic extraterritorial institution organizing and executing such negotiations (cf. Jaklič and Šešum 2019) and is assisted by the German Development Agency (GIZ).

The German extraterritorial institutions in Namibia are composed of ministries from different policy fields, implementing organizations, which the ministries control directly, and supporting state-linked organizations that are formally independent but strongly aligned with the state (Table 7). Implementing organizations primarily support Hyphen within the political mandate that the policy field defines. For example, the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) offers resource exploration services, the Federal Institute for Materials Research and Testing (BAM) material science capabilities, and the German development bank (KfW), which is jointly owned by the German federal and federated states and controlled by the German Ministry of Finance (BMF), supports Hyphen in acquiring (grant) financing from international donors (Parkes 2023). Hence, extraterritorial institutions can take over tasks from the private companies they support, i.e., securing their financing.

[16] The Federal Ministry for Economic Affairs and Climate Action, the Federal Ministry of Education and Research, Federal Ministry for Economic Cooperation and Development, the German Federal Ministry of Digital and Transport, and the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection.

German extraterritorial institutions in Namibia					
Policy field	Foreign Policy	Climate politics and export promotion	Development cooperation	Research and Development	Public Financing
Ministries	German Federal Foreign Office (AA)	Ministry for Economic Affairs and Climate Action (BMWK)	Federal Ministry for Economic Cooperation and Development (BMZ)	Federal Ministry for Education and Research (BMBF)	Federal Ministry of Finance (BMF)
Implementing organizations	German Embassy in Windhoek; GIZ	German Export Promotion Agency (GTAI), Federal Institute for Materials Research and Testing (BAM)	German Development Agency (GIZ)	Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL)	German Development Bank (KfW)
Supporting state-linked actors	Political foundations (Hanns Seidler, Konrad Adenauer, Friedrich Ebert), Research institutions (Fraunhofer, ISOE), Business association (AHK)				

Table 7: Summary of German extraterritorial institutions (Sources: interviews, document analyses)

A number of state-linked actors is active in Namibia: the German Chamber of Commerce Abroad (AHK) represents German corporate (trade) interests and is co-funded by BMWK and GTAI. Similarly, political foundations such as Hanns Seidel, Konrad Adenauer, or Friedrich Ebert are strongly aligned and funded by German political parties. They contribute to building technology legitimacy in Namibia and offering information services for German policy makers. Last, German research institutions, such as Fraunhofer or the Institute for Social-Ecological Research (ISOE), are largely dependent on German government funding and provide socio-technical research services, e.g., regarding technology testing or stakeholder engagement.

Besides this horizontal coordination across various policy fields, the German national government also coordinates its extraterritorial activities vertically, with the German federated states that are active in Namibia which, however, only have limited resources for extraterritorial engagement. More importantly, the German national government coordinates with the EU. In October 2022, the EU Commission President and the Namibian President announced the EU-Namibia Strategic Partnership in sustainable commodity value chains and renewable hydrogen. As part of the partnership, the Global Gateway Initiative, the EU's equivalent of the

Chinese Belt and Road initiative (Heldt 2023) will invest €1 billion to mobilize funding for infrastructure, capacity building, research, and regulatory changes, partly in support of Hyphen (see 4.3, 4.4).

German extraterritorial institutions flank private companies like Hyphen because the German state cannot participate through direct ownership[17] in GPNs for green hydrogen. Historically, the German state has never controlled major energy SOEs compared to other European states (Karlsch and Stokes, 2003). Hence, for the German state, as an example of a coordinated market economy (Weiss 2021), organizational distance from Hyphen resulted from a lack of alternatives. Hence, the nationally specific institutional context defines the state's extraterritorial engagement. However, in the postcolonial context of German-Namibian relations, the organizational distance between Hyphen and the German state also constitutes an organizational advantage as it has increased the trust and confidence of the Namibian state that it remains in control of the strategic coupling process (NAMGOV1, see 4.4). In the next section, we analyse the different forms of support with which German extraterritorial institutions shape the strategic coupling process.

4.4. Mechanisms of extraterritorial agency in postcolonial contexts

The German state's extraterritorial engagement intends to improve Hyphen's cost-capability ratio and financing conditions in Namibia, so that the company can produce green hydrogen at a competitive cost there. To this end, German extraterritorial institutions worked towards extraterritorial asset creation, extraterritorial de-risking, and market creation (Table 8).

Extraterritorial asset creation started with the exploration of Namibia's natural resources. In 2020, the German Ministry of Education and Research (BMBF) commissioned SASSCAL to evaluate Southern Africa's, including Namibia's, renewable energy resources and the potential to produce green hydrogen in the region (GEREX4). As a result, "[e]veryone involved became aware that Namibia has perfect location conditions and could become a hotspot for green hydrogen production" (GEREX1).

Extraterritorial asset creation is particularly necessary because Namibia is only sparsely industrialized and, hence, lacks crucial industrial assets and human resources. In order to address skills and technology shortages, the BMBF and the EU made €40 and €25 million, respectively, available in grants to the Namibian government to fund five green-hydrogen pilot projects in August 2021 (BMBF 2022; Gabor and Sylla 2023). These projects are much smaller than the Hyphen project, are dispersed throughout the country, and provide opportunities for the creation of a domestic green hydrogen market, R&D, human resource development, and green

[17] While there are discussions in Germany about increasing state ownership in the energy sector, there are no initiatives yet to create a state-owned hydrogen multinational.

industrialization. Due to their smaller size, their development is much faster. They contribute to the creation of industrial and human assets in Namibia, which both the Namibian state and Hyphen can harness in the coupling process later on.

Mechanisms of extraterritorial agency	**Activities**	**Involved Extraterritorial institutions**
Asset creation	• Analysis of green-hydrogen production potential • Green hydrogen pilot projects • Research programme • Infrastructure development	• SASSCAL (Southern African Science Service Centre for Climate Change and Adaptive Land Management) • BMBF (Ministry of Education and Research) • BAM (Federal Institute for Materials Research and Testing) • German Embassy
De-risking	• Funding of national green hydrogen strategy • Special hydrogen envoy • Concessional loan	• BMBF • BMWK (Ministry for Economic Affairs and Climate Action) • EIB, KfW (European Investment Bank, German Development Bank)
Market creation	• H2 Global funding mechanism • Carbon border tariff (CBAM) & regulation for green-hydrogen use	• GIZ (German Development Agency), BMWK • EU

Table 8: Overview of mechanisms of extraterritorial agency, empirical examples, and executing extraterritorial institutions (Source: interviews, document analyses)

To create human resources, the BMBF also funds the development of the Green Hydrogen Research Institute at the University of Namibia and pays German hydrogen experts to teach there. Similarly, the Federal Institute for Materials Research and Testing (BAM) runs a scholarship programme, which gives Namibian Ph.D. students the opportunity to pursue their studies in Germany (NAMGOV2). Besides skills transfer, these asset creation efforts garner political support for the green hydrogen industry: “We would like to capacitate the Namibian youth in regard to green hydrogen and anchor technical expertise and knowledge here in Namibia. (…) We (…) want to use this programme to create excitement among the Namibian youth for green hydrogen” (GEREX1).

Lastly, the Hyphen project depends on the creation of infrastructural assets. Among them is the construction of a new port to import wind turbines and other technological components and export ammonia (Kinyua 2023). Moreover, the peripheral town of Lüderitz has a population of around 15,000 people, but Hyphen envisages employing around 15,000 people during construction and 3,000 people in operation. Therefore, Lüderitz will need to invest in urban development to accommodate workers and their families. To this end, the German Embassy has granted the local council €5 million to develop a new urban development plan (German Embassy Windhoek 2023).

Extraterritorial de-risking has two main objectives: the mitigation of policy risks and the reduction of financial risks. To develop a stable regulatory and political environment in Namibia, the BMBF has funded the Namibian green hydrogen and derivates strategy to integrate green hydrogen into the long-term economic planning of the Namibian government (Ministry of Mines and Energy of Namibia 2022). Moreover, various extraterritorial institutions from the German state and the EU provide technical and legal assistance to the Namibian government. Among them, for example, is a special hydrogen envoy who was appointed by the Minister of Economic Affairs (BMWK 2022).

Extraterritorial de-risking in Namibia also addresses financial risks (cf. Gabor and Sylla, 2023). These de-risking efforts are necessary because Hyphen is a private company and, hence, the German state does not vouch for the company's finances directly, as it would for an SOE (cf. Gabor 2021). Hydrogen production in Namibia faces unfavourable financing conditions due to the perceived risks that investors associate with Namibia and other Global South countries (Parkes 2023). To reduce Hyphen's dependence on more expensive private finance, the European Investment Bank (EIB) has granted the Namibian government a €500 million concessional loan to invest in the Hyphen project.

Lastly, market creation is crucial to address (economic) offtake-risks and to drive corporate investments abroad, as market development constitutes one of the corporate drivers identified by Coe and Yeung (2015). To stimulate international market development, the German national government instructed the GIZ to develop the H2 Global funding mechanism. Through the mechanism, several ministries subsidize the gap between the best price that green hydrogen producers offer and the highest price that buyers in Germany are willing to pay in a double auction. HINT.CO will then offer long-term purchase agreements to producers like Hyphen to provide them with the necessary investment security to bring export-oriented green hydrogen projects to financial close (GEREX2). In this way, the national government contributes to the creation of a global hydrogen market and provides valuable financial assets for project developers that are located in states like Namibia which cannot provide subsidies.

In addition, the EU has decided that European industries which already use hydrogen made of fossil fuels today, such as the refinery, chemicals, and metals industries, will be obliged to use at least 42% of green hydrogen by 2030 (European Parliament 2023, 6). Hence, the EU has effectively created a potential export market that green hydrogen projects in countries such as Namibia can target. Since green hydrogen is still uncompetitive with fossil fuels on a cost basis, the EU has also passed a new tariff scheme (CBAM) for the import of energy-intensive products which should shield European industries from foreign competitors that have lower production costs since they do not need to use green hydrogen (European Parliament 2023). Thereby, the EU has consolidated the market for low-emission products and, by extension, demand from European industries for green hydrogen.

International market creation efforts complement attempts to foster hydrogen offtake in Namibia via the funding of pilot projects described above. In this sense, different mechanisms of extraterritorial agency are interrelated and address corporate drivers in interrelated ways, reinforcing each other when combined successfully.

5. Conclusion

The GPN literature has not yet systematically engaged with the extraterritorial agency of the state in strategic couplings abroad (McGregor and Coe 2021). While previous contributions have foregrounded geopolitics as a driver of state involvement (Glassman 2011; Kalvelage and Tups 2024), we have argued that geopolitical drivers can intersect with other drivers to culminate in rationales of state action, in our case defossilization, which motivate states to engage with other states and selected GPNs.

Acknowledging that bargaining in strategic coupling processes can encompass foreign states (Lim 2018; Smith 2015), we have expanded the strategic coupling framework by proposing the term "extraterritorial institutions". Extraterritorial institutions provide a conceptual distinction from the established concept of regional institutions (Yeung 2015) which helps to understand how states can flank strategic coupling processes abroad.

In addition, we have deduced three mechanisms through which the state, but potentially also other actors, can shape competitive dynamics and risks and, subsequently, influence firm behaviour to achieve couplings instead of decouplings (Blažek and Lypianin 2024; Pavlínek 2024). These mechanisms are extraterritorial asset creation, extraterritorial de-risking, and market creation. Thereby, we offer a conceptual – albeit not comprehensive – understanding of extraterritorial state agency in GPNs.

Our study shows that defossilization presents a rationale for extraterritorial state engagement in strategic coupling processes, as the German state (and the EU) have mobilized considerable resources to support Hyphen in Namibia. While Germany depends on renewable energy imports to defossilize (van de Graaf et al. 2020), future research on extraterritorial state action could explore different rationales for extraterritorial state action and, for example, focus on energy transition minerals (Bridge and Faigen 2023) or low-carbon technologies (Kleimann et al. 2023) in cases where countries do not rely on renewable energy imports. At the same time, the energy transition provides an opportunity for countries to decouple from extraterritorial fossil fuel resources and, in this sense, provides ample opportunities to research decoupling processes in the face of the defossilization rationale (Blažek and Lypianin 2024).

Our focus on the flanking of Hyphen's activities in Namibia by the German state (and the EU), complements but also complicates the literature on state capitalism (Alami and Dixon 2022; Lim 2018). While our findings reflect the strong role of the state in contemporary capitalist development, we have shown that states might take over certain roles from (fully) private companies, e.g., financing, and strategically use private companies for their ends. Hence, our research points to the need to expand and critically reflect on the –already controversial – boundaries of the state (Alami and Dixon, 2022). States might cooperate with (fully) private firms in sectors in which they do not control SOEs, as is often the case particularly in coordinated market economies like Germany (Weiss 2021). Cooperation with private firms can even be an organizational advantage in sensitive geopolitical, e.g., postcolonial contexts, as part of a distancing strategy (cf. McGregor and Coe 2021).

The case study reflects the importance that GPN research should engage more with the urgent need for defossilization, since the restructuring of global energy GPNs is already underway (Coe and Gibson 2023). Building on our approach, we think that future research could, first, develop a more comprehensive picture of the mechanisms through which the state – but also other actors such as private financiers (Newell and Paterson, 2010) - can shape firm-level drivers. Second, future research could focus on the response of host states to extraterritorial agency, analysing why and how they reinforce or impede coupling attempts by foreign states. Third, we did not elaborate in more detail what type of strategic coupling and (regional) value capture trajectories might result from extraterritorial agency, not least due to the methodological limitation that we observed a coupling process in its early stages. In this regard, the hydrogen industry constitutes an insightful research object, given that many large-scale, export-oriented projects are located in some of the most peripheral regions of the world (IEA 2023).

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Manuscript I

Walker, B., Coulomb, F. Climate action driving competitive dynamics and recoupling? Why cement lead firms plan to produce jet fuels in Germany. Unpublished manuscript, in peer review at Progress in Economic Geography. The article is intended to be licensed under the CC BY-NC-ND 4.0 license.

Climate action driving competitive dynamics and strategic couplings? Why cement lead firms plan to produce jet fuels in Germany

Abstract

Climate change mitigation is crucial, yet the factors influencing where and why emission-intensive firms in global production networks reduce or fail to reduce emissions remain insufficiently explored. We apply the materiality concept to examine the challenges firms face in adopting climate-friendly processes across different industries and places. To conceptualize how actors can address these challenges, we integrate the GPN 2.0 framework with related research, identifying four mechanisms through which actors can enhance the competitiveness of and mitigate risks associated with climate-friendly processes. We argue that the legitimacy of employing these mechanisms depends on their economic impact, particularly the effects of strategic (de-)/(re-)couplings by global lead firms on local firms and buyers. Empirically, we analyze how and why different actors, particularly state institutions, have increased the competitiveness of climate-friendly cement and synthetic jet fuel production in Germany, encouraging global cement lead firms to plan the production of synthetic jet fuels from cement plant emissions and green hydrogen. Our findings reveal that climate action in global production networks depends on the agency of the involved actors to align climate action with economic development.

Keywords: global production networks, competitiveness, energy-intensive industries, synthetic jet fuels, cement industry, green hydrogen

1. Introduction

While the need for urgent climate action is well understood, a considerable action gap still exists (Bushell et al. 2017). This gap is particularly pronounced in emission-intensive industries such as steel, cement, and chemicals. Since firms in these sectors are often organized in global production networks and compete globally, governments have shied away from climate policies that might endanger national competitiveness and trigger divestment by global lead firms (Bataille et al. 2018).

Given these challenges, the global production networks (GPN)[18] literature should grant more attention to climate action (Coe and Gibson 2023). A global production network can be

[18] We use the abbreviation GPN to denote theory or literature, and global production networks to refer to the empirical phenomenon

defined as “an inter-organizational structure that is coordinated and controlled by a globally significant lead firm (usually a multinational corporation) and involves the geographically dispersed network of overseas affiliates, strategic partners, key customers, and non-firm institutions” (Yeung 2016, 16). While Blažek and Lypianin (2024, 37) expect a “significant restructuring of global production […] in connection with decarbonization”, and Coe and Gibson (2023, 3) suggest that “it may be the complex interplay between ‘economic’ value and carbon intensity that ultimately drives GPN dynamics“, the literature provides little insights into these processes.

Other branches of economic geography, particularly the (challenge-oriented) regional innovation systems (CoRIS) and path development literatures, are leading the discourse on industrial defossilization (Trippl et al. 2020; Zhou, Chung, and Xu 2023). However, these literatures lack a dedicated framework to analyze the “competitive disadvantages of green industries compared to brown industries” (Trippl et al. 2020, 186), how actors can make climate-friendly processes competitive (cf. Sotarauta et al. 2021), and to “assess under what conditions [actors can] reconcile broader societal goals [such as climate change mitigation] with narrower economic ones” (Tödtling, Trippl, and Desch 2022, 2153).

We contend that the GPN approach can provide a dedicated framework to analyze the competitive dynamics of green industrial reconfiguration. Therefore, we apply the GPN framework – to our knowledge for the first time – for analyzing climate action. In doing so, the core contribution of this article is to highlight competitive dynamics as an explanation for why and how emission-intensive firms organized in global production networks reduce their emissions or fail to do so.

We make three specific contributions to the GPN literature. First, we use the materiality concept (Bridge and Bradshaw 2017; Njøs et al. 2024) to understand the competitive challenges faced by energy-intensive firms across different sectors and locations in adopting climate-friendly processes. We posit that as long as firms lack the capabilities to adopt cost-effective climate-friendly processes, states play a pivotal role in making these processes competitive and mitigating investment risks (Kalvelage and Walker 2024).

Second, we integrate the GPN 2.0 framework with related research to conceptualize how actors can make climate-friendly processes competitive with climate-damaging processes and mitigate associated risks. Thereby, we highlight a less-explored dimension of agency – the ability of making (low-emission) processes competitive – and power – the ability to exercise this agency despite opposition (Kalvelage and Walker 2024; MacKinnon, Dawley, Pike, et al. 2019; Neilson et al. 2018).

Third, drawing from the path creation literature (Binz, Truffer, and Coenen 2016; Heiberg, Binz, and Truffer 2020), we examine why actors make climate-friendly processes competitive and mitigate associated risks. We argue that the legitimacy of such climate action depends on the ability of the involved actors to reconcile climate action with economic development, which we evaluate in terms of the effects of strategic (de-)/(re-)couplings by global lead firms on local firms and buyers (Yeung 2016).

Empirically, we explore the economic challenges faced by climate-friendly cement and synthetic fuels and how the EU, German state, and firms in three global production networks have increased the competitiveness of these products in Germany. We also assess the economic legitimacy of these developments around three cement plants to explain why the actors have increased the competitiveness the way they did.

The three global lead firms operating these plants, in partnership with other lead firms, plan to capture carbon emissions and use them with green hydrogen to produce synthetic jet fuels. These efforts are insightful because the cement lead firms have nearly exhausted opportunities for efficiency improvements at their German cement plants (VDZ 2020), while the new measures would increase production costs by over 50% (Cavalett et al. 2024, 7; Markewitz et al. 2019, 10). Nevertheless, the lead firms have made significant investments to further reduce their emissions, providing insights into how actors shape competitive dynamics to justify such investments. Moreover, comparing strategic coupling dynamics around three production sites within Germany allows us to identify regional assets that offer competitive advantages, contributing to uneven development as global production networks transition to net zero.

The next section outlines our conceptual framework, followed by our methodology and the analysis, which addresses the research questions. The conclusion reviews our contributions to the GPN literature, summarizes our findings, and suggests future research directions on climate action in global production networks.

2. Shaping Competitive Dynamics and Mitigating Risks for Climate Action

Following the environmental upgrading literature, we assume that actors aim to reconcile climate action with value capture (Krishnan, De Marchi, and Ponte 2023). Based on this, we develop our framework in three steps. First, we highlight the role of materiality in shaping the (cost-)competitiveness of climate-friendly versus climate-damaging processes. Second, we conceptualize four mechanisms through which actors can enhance the competitiveness of climate-friendly processes and mitigate associated risk. Third, we examine why and to what extent actors can use these mechanisms, arguing that the legitimacy of climate action depends on its economic effects in terms of re(- investments), divestments, and price increases.

2.1. How the Materiality of Low-Emission Processes Shapes Their Competitiveness

Emission reduction options vary across industrial sectors due to the sector-specific materiality of economic processes (Coe and Gibson 2023). Materiality refers to "the (biological, chemical, physical) qualities of materials [that] shape strategies for value capture" (Bridge and Bradshaw 2017, 221). To understand how the materiality of processes like cement production and aviation shapes the competitiveness of climate-friendly processes, we apply the GPN 2.0 approach (Coe and Yeung 2015). This approach distinguishes three interrelated competitive dynamics: the cost-capability ratio of firms, the goal of accessing and dominating markets, and the need to create value for financiers to secure affordable financing. Additionally, firms need to manage various types of risks (Coe and Yeung 2015).

The materiality of climate-friendly processes conditions their competitiveness in geographical and sectoral contexts. Important resources for climate-friendly processes, such as renewable energy and carbon sources, are geographically unevenly distributed and more costly to transport than fossil fuels (so-called "Renewables Pull Effect", Samadi, Fischer, and Lechtenböhmer 2023). Hence, they create cost-based advantages or disadvantages based on access to these resources. Here, renewable carbon, sometimes also called circular carbon, refers to carbon that was captured from the atmosphere before being used (so-called carbon capture and use, CCU), either by plants or machines (so-called direct air capture technologies). When being emitted again, renewable carbon does not increase the atmospheric CO_2 concentration (Becattini, Gabrielli, and Mazzotti 2021).

Sectors lacking the necessary capabilities to cost-effectively transition to net-zero face higher costs (Wesseling et al. 2017). Energy-intensive sectors, specifically, often cannot use renewable electricity but rely on green hydrogen and synthetic fuels to lower their emissions, which are being produced by "emerging industries" (Gong, Binz, et al. 2022) at high costs (Kasten 2025; Wappler et al. 2022). Moreover, some industries produce so-called process emissions that result from chemical reactions in production processes that these industries cannot substitute (yet). Process emissions need to be compensated by carbon sinks or captured and stored (so-called carbon capture and storage, CCS), which constitute additional processes that incur additional costs on producers (Roussanaly et al. 2021).

Cost increases are not in the interest of firms in competitive dynamics (Coe and Yeung 2015). Without state support, additional costs for climate action either endanger profits, if producers cannot pass them on to buyers, or market growth (Cludius et al. 2020), if producers can pass them on and increase prices, which face uncertain demand (Nazarenko and Saleh 2024; Oerlemans, Chan, and Volschenk 2016). Therefore, investors associate risks with investments in cost-ineffective climate-friendly processes, which can make financing difficult (Karltorp and Maltais 2024).

In more detail, risks in global production networks arise when decision-makers perceive the "value of something […] to be at stake" (Völlers et al. 2023, 6). Focusing on the organizational level, we examine risks that firms and their financiers associate with investments in low-emission processes, so they do not invest or financiers increase capital costs (Karltorp and Maltais 2024). These risks can emerge both within and between GPNs (Bryson and Vanchan 2020; Völlers et al. 2023): within GPNs, they include uncertain demand for climate-friendly products and inconsistent or unreliable climate policy frameworks (Brunner, Flachsland, and Marschinski 2012); between GPNs, concerns arise about the cost-competitiveness with competitors (Semieniuk et al. 2021).

In summary, the materiality of climate-friendly processes conditions their competitiveness in different locations and sectors. Firms lacking the capabilities to implement climate-friendly processes cost-effectively will not do so, as they would face competitive disadvantages. However, firms and other actors, particularly states, can enhance the competitiveness of climate-friendly processes and mitigate associated risks.

2.2. Competitiveness Adjustment and Risk Mitigation Mechanisms

To conceptualize how different actors can enhance the competitiveness of climate-friendly processes and mitigate associated risks, we integrate GPN research (Kalvelage and Walker 2024; MacKinnon, Dawley, Pike, et al. 2019) with related literature (Binz, Truffer, and Coenen 2016), identifying four competitive adjustment and risk mitigation (CARM) mechanisms:

Cost-Capability Transformation

Cost-capability transformation involves improving the cost-capability ratio of climate-friendly processes or deteriorating the ratio of climate-damaging processes. Costs include material inputs, fixed assets, transaction, or financing costs. To reduce their costs, firms can improve their capabilities, e.g., regarding technological knowhow and organizational capacities. However, increased costs might as well outweigh the value of new capabilities; hence, the task of optimizing both in relation to each other (Coe and Yeung 2015).

Besides firms, state agencies, public research institutions, and buyers that adopt innovations and provide feedback facilitate cost reductions and capability development at different scales (Asheim, Isaksen, and Trippl 2019; Binz and Truffer 2017; Chaminade, Lundvall, and Haneef 2018). In particular, subsidies can offset the "green premium", i.e. the cost difference between climate-damaging and climate-friendly products (Caldeira, Duan, and Moreno-Cruz 2023).

In addition, different actors, particularly state institutions, can modify regional assets, meaning they can re-use existing assets, create new ones, or destruct assets (Trippl et al. 2020). Access to regional assets can reduce the costs or contribute to the capabilities of firms (Fu and Lim 2022; McGregor and Coe 2021), depending on whether assets influence costs or capabilities. For example, natural and infrastructural assets influence production costs, whereas regional research institutes can contribute to the capabilities of firms (MacKinnon, Dawley, Steen, et al. 2019).

Besides destructing regional assets, other means of deteriorating the cost-capability ratio of climate-damaging processes exist. Most importantly, an increasing number of states uses carbon pricing to increase the costs of emission-intensive processes and, thereby, create incentives for firms to develop capabilities in climate-friendly alternatives (Steinebach, Fernández-i-Marín, and Aschenbrenner 2021; van den Bergh and Savin 2021).

Market Creation

While the GPN literature focuses on lead firms and customers as market makers (Coe and Yeung 2015, 96; Yeung 2022), other research strands, especially those on challenge- or mission-oriented industrial policies and lead markets, highlight the agency of states in market creation through instruments like price supports and procurement policies that aim to articulate demand (Jänicke and Jacob 2004; Mazzucato 2016; Uyarra et al. 2020).

In addition to supply and demand incentives, the technological innovation system (TIS) literature underscores that market formation also relies on institutions that regulate markets and customers willing to adopt new products, often facilitated by spatial proximity (Boon, Edler, and Robinson 2022; Dewald and Truffer 2012; 2011). However, when firms have not developed cost-competitive climate-friendly processes and both the state and buyers are unwilling to cover the green premium, market formation depends on the agency of firms to pass on cost increases to buyers.

Firms can pass on cost increases to buyers against their will in two cases. First, firms have achieved a high level of market control as a result of market concentration (Cludius et al. 2020; Ponssard and Walker 2008). Second, the state uses mandates or obligations, which establish minimum quotas for the use of environmentally-friendly goods (Beise and Rennings 2005). Alternatively, states can deteriorate the costs of climate-damaging goods and services in combination with instruments of “green protectionism”, such as tariffs, that undermine the cost-competitiveness of unsustainable imports (Lewis 2014; Lottici, Galperín, and Hoppstock 2014; Magacho, Espagne, and Godin 2024).

Mobilizing Investments and Financing

Mobilizing investments is essential for industrial development (Binz, Truffer, and Coenen 2016) and its greening (Trippl et al. 2020). Investments require financing (Coe and Yeung 2015), which climate finance tries to provide (Amighini, Giudici, and Ruet 2022; Giglio, Kelly, and Stroebel 2021). Climate finance refers to efforts to provide financing from local, national or transnational, public, private and alternative sources to support climate change mitigation and adaptation (Hong, Karolyi, and Scheinkman 2020).

While states are an important source of climate finance, they may face fiscal constraints from tax revenues, debt relations, credit ratings, and fiscal rules (Gabor 2023; Gabor and Sylla 2023). Therefore, among other reasons, some states have developed sustainable finance taxonomies that set criteria for sustainable investments (Schütze and Stede 2024), enabling firms to finance investments through dedicated financial products, such as climate/green bonds. Ideally, financiers provide capital at lower costs to issuers of these financial products, thus facilitating climate-friendly investments (Bhandary, Gallagher, and Zhang 2021).

Risk mitigation

Different actors can mitigate the political and economic risks that firms and investors associate with climate-friendly processes. States can mitigate political risks that investors associate with climate policy frameworks by making climate policies coherent across scales, incorporating a long-term perspective and clear enforcement mechanisms (Brunner, Flachsland, and Marschinski 2012; Steckel and Jakob 2018).

States increasingly try to mitigate investment risks by covering a part of the investment costs through public funding, as the de-risking state literature argues (Gabor 2023; 2021; Hunt and Tilsted 2024). Nevertheless, Gabor (2023) highlights that demand uncertainties may persist in the absence of regulations that enforce the adoption of climate-friendly processes. However, even with regulation in place, we show that investors can still associate economic risks with investments in cost-uncompetitive processes due to demand uncertainties, especially when private buyers refuse to sign binding long-term offtake agreements (Bridge and Bradshaw 2017). Hence, buyers also play a crucial role in mitigating risks.

In short, different actors can make climate-friendly processes competitive and mitigate associated risks. In the next section, we theorize in more detail why and to what extent different actors make use of the CARM mechanisms for climate action.

2.3. Negotiating the Legitimacy of CARM Mechanisms in Strategic Coupling Processes

To understand the extent to which the involved actors – particularly states – can use the CARM mechanisms, we draw on the path creation literature, which identifies (technology) legitimation as an important condition for the adoption of new technologies (Binz, Truffer, and Coenen 2016; Heiberg, Binz, and Truffer 2020; MacKinnon, Afewerki, and Karlsen 2022). Actors bargain over the mutual legitimacy of their actions (Coe and Yeung 2015, 151), reflecting a multi-scalar process (Heiberg, Binz, and Truffer 2020; MacKinnon, Afewerki, and Karlsen 2022). Legitimacy broadly refers to "a generalized perception or assumption that the actions of an entity are desirable, proper, or appropriate within some socially constructed system of norms, values, beliefs, and definitions" (Suchman 1995, 574). Following MacKinnon et al. (2022), we focus on "pragmatic" legitimacy, which "rests on the self-interested calculations of an organization's most immediate audiences" (Suchman 1995, 578), primarily economic interests.

Building on these insights, we argue that the perceived appropriateness and desirability of using CARM mechanisms for climate purposes depend on the extent to which involved actors can reconcile climate action with economic development (cf. Tödtling, Trippl, and Desch 2022). Drawing on the GPN literature, we suggest investigating the economic implications of the CARM mechanisms through the lens of strategic coupling (Yeung 2016). Strategic coupling refers to "the dynamic processes through which actors in regions coordinate, mediate, and arbitrage strategic interests between local actors and their counterparts in the global economy" (Yeung 2009, 332). Local actors include firms and regional institutions, which are "not only regionally specific institutions, but also local arms of national/supranational bodies (e.g., a trade union's 'local' chapters), and extra-local institutions that affect activities within the region without necessarily having a presence (e.g., a national tax authority)" (Coe et al. 2004, 474).

In strategic coupling processes, global lead firms and local actors negotiate access to and use of regional assets, thereby connecting regions to global production networks (Coe et al. 2004; Yeung 2015). From a temporal perspective, three forms of strategic coupling can be distinguished: initial strategic couplings, followed by later recouplings or decouplings (MacKinnon 2012). Initial strategic couplings emerge when global lead firms gain access to assets of regions in which the lead firms have not been active before, either through (foreign) direct investments, the acquisition of, trading or contracts with local firms (Coe and Yeung 2015, 180). Initial strategic coupling can later evolve into recouplings, referring to reinvestments into a firm's industrial assets and/or the reconfiguration of trade and contractual relations with local firms, or decoupling, referring to divestment from regional assets and/or the termination of trade and contracts with local firms (Horner 2014; MacKinnon 2012; MacKinnon, Dawley, Pike, et al. 2019). These processes may be partial, with multiple sourcing decisions and reconfigurations of production networks over time (Lund and Steen 2020).

Regions may be connected to multiple global production networks (Bridge and Dodge 2022) and global production networks can intersect with each other (Coe 2021). In light of new intersections between emerging industries supplying renewable energy and carbon and established industries in need of emission mitigation (see section 2.1.), we argue that industrial climate action will often require the strategic (re- /de-)couplings of multiple lead firms and the creation of new intersections between their global production networks. Specifically, global lead firms active in emerging and established industries are likely to form strategic partnerships to share capabilities and investment costs (cf. Coe and Yeung 2015, 144).

We contend that the use of the CARM mechanisms for climate action hinges on whether they, first, incentivize firms to undergo new strategic couplings or recouplings. Through these couplings, lead firms should mobilize investments in emerging green industries, enabling local firms to diversify into new business areas (Trippl et al. 2020) or create (inter-industrial) synergies (Frangenheim, Trippl, and Chlebna 2020). Likewise, reinvestments into existing industrial assets, such as branch plants, are an important form of recoupling (MacKinnon 2012), enabling the greening of existing production processes and services (Trippl et al. 2020). Such reinvestments can lead to path renewal[19], not only of the local branches of lead firms but also of suppliers, which may receive new contracts as part of the reinvestments (Trippl et al. 2020). Moreover, local branches may undergo a functional upgrading process, i.e. acquire "new functions which generate higher incomes" (Humphrey and Schmitz 2002, 1020).

Second, from the perspective of regional institutions, CARM mechanisms should incentivize firms to decouple from extra-regional fossil fuel supplies and recouple with regional renewable energy and carbon supplies (Furnaro 2020). In contrast, the legitimacy of using the CARM mechanisms becomes more contested when the transition does not involve extra-regional decoupling and regional recoupling but a "switching" (Bridge and Dodge 2022) from regional fossil-fuel to renewable-energy resources.

Third, the legitimacy of using CARM mechanisms will be questioned by firms if they fear having to decouple from regions. For example, firms may not be able to pass on cost increases to buyers if those buyers are able to buy climate-damaging products or services elsewhere (Grubb et al. 2022). Moreover, if firms finance investments in cost-ineffective but climate-friendly processes by passing on cost increases, the resulting price hikes may undermine the legitimacy of the CARM mechanisms in the eyes of buyers and potentially regional institutions

[19] Path renewal can be defined as "the revitalization and enhancement of a region's industrial base through the infusion of new technologies or introduction of new products and services" (Martin and Sunley 2006, 420).

(Drews and van den Bergh 2016). Hence, legitimizing the use of CARM mechanisms will require minimizing price increases.

In this context, we argue that the creation of "lead markets" – defined as the "most competitive market in which the nature of impending global changes is mirrored" (Barlett and Ghoshal 1990, 242) – is insufficient to provide legitimacy for the establishment of new industries, as argued by Heiberg et al. (2020). This is because such lead markets may imply higher prices for buyers.

Summarizing our framework, we argue that energy-intensive industries often still miss the capabilities to adopt cost-effective, climate-friendly processes due to the materiality of economic processes (section 2.1.). Therefore, the adoption of climate-friendly processes depends on the use of the CARM mechanism (section 2.2.). In global production networks, actors negotiate the use of these mechanisms based on the anticipated economic outcomes of strategic coupling processes (section 2.3.). In the following sections, we use this framework to analyze the economic challenges faced by climate-friendly cement and synthetic fuels, how the EU, the German state, and three global production networks have increased the competitiveness of these products, and to what extent the resulting developments around three cement plants in Germany are considered legitimate by the involved actors (Figure 17).

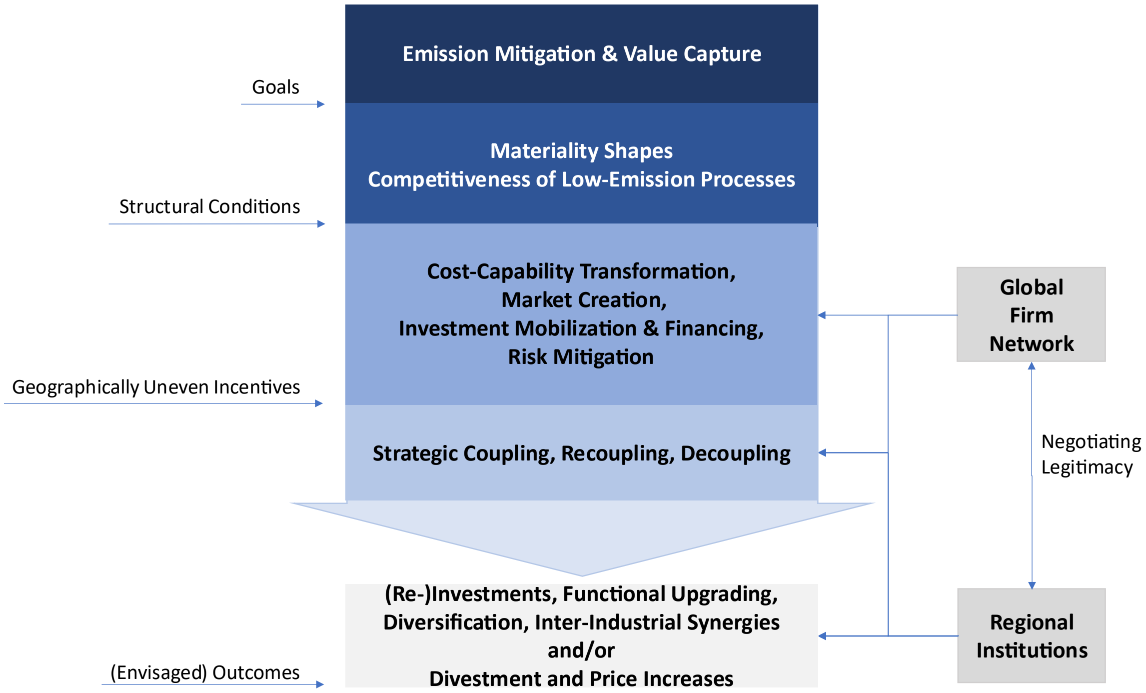

Figure 17: Visualization of the theoretical framework (illustration by the authors)

3. Methods and Data Collection

The data collection process involved three steps. First, we explored the German cement industry through desk-based research and exploratory interviews with industry representatives. The objective was to identify cement plants that different lead firms are aiming to make climate-neutral and to assess similarities and differences among them. Cement production entails extracting minerals and transporting them to clinker plants, where the raw materials are ground into powder. This powder is then heated to very high temperatures, releasing geologically stored carbon and forming clumps known as clinker, which is later ground and mixed with supplementary materials to create cement (Ruppert et al. 2020, 101). The German cement industry comprises 23 companies operating 52 plants, with 32 producing clinker and cement and 20 solely processing clinker into cement (VDZ 2020). Given that clinker production accounts for the majority of the German cement industry's emissions (see section 4.1.), our further research focused on six cement-clinker plants targeted for climate-neutral operations (Figure 18).

In the second step, we refined our understanding of the differences among the six cement-clinker plants using the exploratory data. We developed a multiple case study research design (Yin 1994) and adopted a variance-oriented approach (Bartlett and Vavrus 2017, 28) to increase the reliability of our findings and to account for variations across cases. We focused our data collection on three networks and cement-clinker plants located in Rüdersdorf (North-East), Lägerdorf (North), and Mergelstetten (South-West; Figure 18). The networks and locations reflect the largest possible variance in regional assets for synthetic fuel production, subsidies, and the capabilities of firms within each network. This variation provides insights into organizational strategies and competitive advantages and disadvantages at the regional scale.

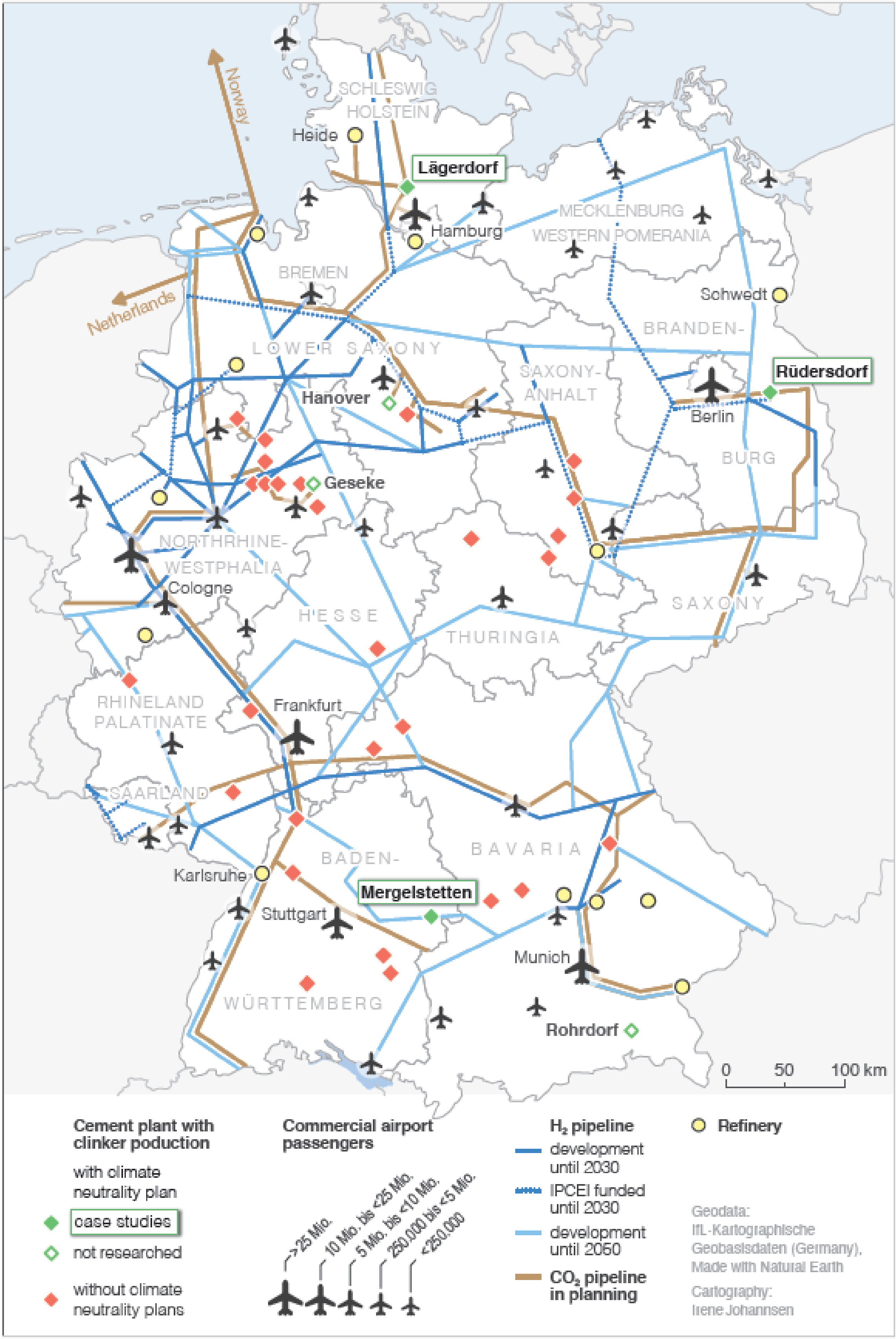

Figure 18: Map of cement plants with clinker production, refineries, commercial airports, planned hydrogen and carbon pipelines in Germany (Source: interviews, websites, publications of infrastructure providers and industrial associations)

The three cement plants identified are operated by the global lead firms Cemex (headquartered in Mexiko, active in around 50 countries), Holcim (Switzerland, 70 countries), and Schwenk (Germany, 7 countries). Of the 32 clinker-producing plants in Germany, Cemex operates two (in the East), Holcim three (in the North-West), and Schwenk four (Center-South).

These cement firms have formed strategic partnerships with other global lead firms and specialized suppliers offering capabilities and access to regional assets, such as renewable energy sources. In Rüdersdorf, the renewable energy and green hydrogen project developer Enertrag (Germany), and the synthetic fuel technology supplier Sasol EcoFT (South Africa) are strategic partners. In Lägerdorf, Holcim collaborates with the Heide refinery, hydrogen specialist Hynamics (France), synthetic fuel technology supplier CAC Engineering (Germany), and renewable energy and green hydrogen supplier Ørsted (Denmark). In contrast, Schwenk in Mergelstetten partners with three global cement lead firms, namely Vicat (France), Heidelberg Materials (Germany), and Buzzi Dyckerhoff (Italy) but lacks partners with complementary capabilities for synthetic fuel production (Table 9).

In the third step, we collected and analyzed data on the three cases from websites and gray literature, field site visits, participation in industry events, and 44 semi-structured expert interviews with stakeholders of the three networks. Between February 2022 and June 2023, we interviewed representatives from the three focal cement firms and cement industry associations (Cement 5x), strategic partners (Partner 4x), infrastructure providers (Infrastructure 5x), energy and technology suppliers (Supplier 6x), potential buyers of synthetic jet fuels (Buyer 3x), government representatives at different levels (Government 10x), competitors offering or planning to produce synthetic jet fuels (CompetitorFuel 5x), and civil society and research organizations working on low-emission solutions for the cement industry (CSOs 6x). Most interviews were conducted online, with five conducted on-site during field site visits or conferences. All interviews were recorded and transcribed.

We organized all the data using MaxQDA, categorizing it by the three cases and overarching industry information, such as EU-level regulation and techno-economic aspects. We analyzed the data using Kuckartz's structuring content analysis (Kuckartz 2014). Following this qualitative method, we first derived analytical categories from our conceptual framework, such as cost-capability improvements, and specified them inductively with codes from the empirical material (e.g., energy costs).

Firm Operating Cement Plant / Location of Plant (Municipality)	**CEMEX / Rüdersdorf**	**HOLCIM / Lägerdorf**	**SCHWENK / Mergelstetten**
Region / Federated State	East-Germany / Brandenburg	Northern Germany / Schleswig-Holstein	South-West Germany / Baden-Württemberg
Regional Assets			
Distance from closest refinery	100 km	50 km	150 km
Distance from closest airport	50 km	50 km	80 km
Expected Connection to Hydrogen Pipeline	Before 2030	Before 2030	After 2030
Expected Connection to Carbon Pipeline	After 2030	Before 2030	Unclear
Regional Renewable Energy Resources	Good	Very Good	Insufficient
Inter-Firm Partnership			
Between Competitors			
With Green Hydrogen Supplier			
With Synthetic Fuel Technology Supplier			
With Refinery			
Subsidies			
EU (Innovation Fund)	For Carbon Capture	For Carbon Capture	
National / Federated State Government (IPCEI)	For Synthetic Fuel Production (approved by EU)	For Synthetic Fuel Production (not approved by EU yet)	

Table 9: Similarities and differences between the three cases; green coloration signals applicability, black indicates non-applicability (Source: interviews)

4. Climate Action Driving Competitive Dynamics and Strategic Coupling in the German Cement Industry

In the following sections, we analyze the challenges posed by the materiality of climate-friendly cement and synthetic fuel production and their implications for competitiveness with the traditional, climate-damaging processes (section 4.1.). We then discuss how firms, the German national government, and the EU have used the CARM mechanisms to address these challenges (section 4.2.). Finally, we explain why the involved actors have or have not used the mechanisms as they try to align climate action with economic development in strategic coupling processes to create legitimacy (section 4.3.).

4.1. How the Materiality of Climate-Friendly Cement and Synthetic Fuel Production Shapes Their Competitiveness in Germany

The materiality of climate-friendly cement production significantly impacts its competitiveness. Cement is produced from carbonaceous minerals like limestone and marl. During clinker production, these minerals are heated to high temperatures, releasing CO_2, which represents around two-thirds of the German cement industry's emissions. Energy use, primarily for heating limestone and marl, only accounts for the remaining third (VDZ 2020, 5). Hence, transitioning to climate-neutral energy sources alone is insufficient; cement firms must also capture the carbon emissions from processing limestone and marl, and store them, e.g., in underground caverns, to achieve climate-neutrality (Cavalett et al. 2024). However, CCS adds significant costs, which firms are inclined to minimize in competitive dynamics.

While carbon storage raises production costs, using captured carbon presents a potential revenue stream that could help to finance the investment in capture technologies (León et al. 2024). In this sense, the materiality of low-emission production does not only imply challenges but also opportunities for value creation and capture (Njøs et al. 2024). Although carbon from limestone and marl is not climate-neutral if emitted, it could gain value due to Germany's limited biogenic carbon sources, compared to the estimated future carbon demand, and the prohibitively high costs of direct air capture (Schmid and Hahn 2021). Therefore, the cement lead firms plan to use captured carbon, initially for synthetic fuel production and, eventually, for construction purposes, though they currently lack the necessary capabilities (VDZ 2020).

Besides carbon, green hydrogen constitutes the second feedstock for synthetic fuel production. The energy-intensive materiality of producing green hydrogen and synthesizing it with carbon into synthetic fuels defines their competitiveness (Njøs et al. 2024). Currently, synthetic jet fuels are at least four times more expensive than fossil jet fuels (Dahal et al. 2021, 9). Hence, their use would increase flight costs considerably, which would reduce demand and impede market growth (Scheelhaase, Gelhausen, and Maertens 2021). Consequently, prospective producers and financiers face the risk that airlines will not buy synthetic fuels (EIB 2024; Scheelhaase, Maertens, and Grimme 2019).

The materiality of green hydrogen production also creates location-specific competitive advantages and disadvantages (Njøs et al. 2024). The EU Commission demands that green hydrogen used in synthetic fuels must be produced from renewable electricity (excluding nuclear energy) (Laprévote 2023). Thus, the cost-effectiveness of synthetic fuel production depends on access to large amounts of cheap renewable electricity (IRENA 2022, 21). In Germany, electricity grid bottlenecks limit access to extra-regional renewable electricity throughout the country, although Northern Germany, particularly around Lägerdorf, has a surplus of renewable energy, particularly from offshore wind (Walker and Klagge 2024). Therefore, the region around Lägerdorf offers the best renewable energy sources for green hydrogen production, followed by Rüdersdorf (OTH Regensburg 2022).

Overall, the distinct materialities of emission mitigation in the cement and aviation industries result in very different mitigation costs, with CCS in the cement industry ranging from 50-150 €/tCO_2, compared to 400-1200 €/tCO_2 for synthetic fuels in aviation (Bachorz et al. 2024, 8). In both industries, the materiality of production constrains the agency of firms to adopt cost-effective, climate-neutral processes, presenting significant challenges in aligning climate action with economic development.

4.2. Making Climate-Friendly Cement and Synthetic Fuel Production Competitive and Mitigating Associated Risks

This section examines how firms and the state employ four mechanisms to enhance the competitiveness of climate-friendly cement and synthetic jet fuel production while mitigating associated risks. Notably, the state's influence is pivotal when firms lack the capabilities to implement cost-effective, climate-neutral processes: "*The solution to the corporate problem of decarbonization does not lie within companies, it lies clearly outside them, with the state*" (Cement_2).

Cost-Capability Transformation

Firms and the state collaborate to improve the cost-capability ratio of climate-friendly cement production. Cemex, Holcim, and Schwenk, like most cement firms, are vertically integrated and coordinate production from mining to distribution. However, they rely on specialized suppliers to develop the necessary (technological) capabilities for climate-friendly cement production, such as carbon capture[20] (Wesseling et al. 2017). Cement firms can then adopt new technologies and provide feedback on them, which is essential for technology development and the formation of markets for climate technologies (cf. Dewald and Truffer 2011).

In Germany, technology suppliers like Thyssenkrupp and Linde have developed technologies to reduce carbon capture costs at cement plants (Holcim 2024b). These capabilities provide geographical incentives for cement firms to invest in Germany, as capability development can occur geographically uneven in global production networks (cf. Binz and Truffer 2017):

„*Linde, Thyssenkrupp, the major innovation and technology providers are all based here [in Germany]. They have the management and consulting capacity, they can supply the technologies and also build the associated plants*“ (Cement_3).

Subsidies also play a crucial role in reducing the costs of climate-friendly cement and synthetic fuel production, providing another geographical incentive for investments in the EU and Germany:

“*We looked at the individual countries [globally] to see where there is appropriate political support, a political will to implement such projects. And Germany, even within the EU, is a pioneer in implementing such measures because there is a lot going on regarding funding, which we depend on if we want to be a first mover*” (Cement_2).

The state and several firms also support the development of CCS and CCU by re-using and creating regional assets. The German government facilitates access to green hydrogen through subsidies for pipeline development in Northern Germany under the Important Projects of Common European Interest (IPCEI) scheme (BMWK 2024b). The German development bank KfW has also established a financing scheme for the rest of the pipeline network, which will partially re-use natural gas pipelines (KfW 2024). However, hydrogen pipeline connections to Lägerdorf and Rüdersdorf are prioritized over Megelstetten, creating a temporary competitive advantage for the former (Figure 18).

Second, the development of a national CO_2 pipeline network could reduce the costs of transporting carbon from cement plants to synthetic fuel plants and storage sites in Germany and abroad (Fink et al. 2025). The costs of CO_2 storage will be higher in Southern Germany than in Northern Germany due to the larger distance to storage sites, which are currently only in development in the Netherlands and Norway, and could be developed offshore in Germany in the future (BMWK 2024a). Therefore, pipeline development will also start in Northern

[20] Cement firms also increasingly develop capabilities for climate-friendly cement production by investing in firms that develop climate technologies (Cemex Ventures 2022; Holcim 2024a), thereby providing climate finance. Cemex has even created an investment arm for this purpose (Cemex 2017).

Germany (Supplier_2), creating a competitive advantage for Lägerdorf and Rüdersdorf since CO_2 transport by train – in the absence of CO_2-pipelines – would be very expensive (Cement_4).

While the German state and firms primarily improve the cost-capability ratio of climate-friendly cement and synthetic fuel production, the EU deteriorates the cost-capability ratio of climate-damaging cement production and the use of fossil jet fuel. The EU's Emission Trading System (EU ETS) incentives the development and adoption of climate-friendly processes. Emission certificate prices have reached heights of 100 €/tCO_2 in 2023 (UBA 2024), approaching the costs of CCS in the German cement industry but still being too low to drive the use of synthetic jet fuels (compare with 4.1.).

Market Creation

The creation of lead markets in both industries hinges on the ability of firms to pass on cost increases that result from the adoption of climate-friendly processes to buyers. In this regard, cement firms have more agency because cement markets are characterized by a regional scale resulting from high transport costs (Cludius et al. 2020). For example, the three cement plants that we studied mostly produce for their respective region (Hübner et al. 2019). Hence, it is often not cost-effective for buyers to switch to cheaper cement sources from further afar.

In addition, EU policies restricting imports of unsustainable products also boost demand for climate-friendly but more expensive cement (De Almeida and Esposito 2023). So far, the cement industry still receives a part of its emission certificates for free because policymakers wanted to mitigate the perceived risk that cement firms decouple from Europe, produce cement elsewhere, and export it to Europe.[21] In response, the EU gradually introduces a carbon tariff for selected goods, such as cement, and simultaneously ends the free allocation of emission certificates (Dröge 2021).

To stimulate demand for synthetic jet fuels, the EU has integrated airlines into the EU ETS and ends the free allocation of allowances as well (European Commission 2023b). Since the costs of using synthetic fuels still far outweigh the costs of emission certificates, the EU mandates that jet fuel suppliers and airlines progressively use synthetic fuel at all European airports (1.2% in 2030, 2% in 2032, 5% in 2035, 35% in 2050; European Parliament 2023). The German government's mandate is slightly more ambitious (0.5% in 2026, 1% in 2028, 2% in 2030;

[21] While the perceived threat of decoupling in the cement industry, given the high transport costs of cement (Interview CSO_3), is arguably more a result of lobbying than real, it reflects the subjectiveness of the risk perceptions of different actors (Völlers et al. 2023).

BMUV 2021) to provide an incentive for synthetic fuel production in Germany (Government_4).

Mobilizing Investments and Financing

By employing the EU ETS, tariffs, and mandates, the EU and the German state do not offset the green premium for climate-friendly processes in contrast to demand-articulation policies like subsidies or public procurement (cf. Uyarra et al. 2020). Hence, buyers need to cover the full green premium. The use of the EU ETS, tariffs, and mandates, along with selective subsidies for two of the three networks (Table 9), reflects the financial limitations imposed on the EU and the German government by fiscal rules (Government_3, Gabor 2023). Since subsidies are an important source of funding that reduces the need to mobilize and finance private investments, they create uneven competitive (dis-)advantages among the networks.

To finance the very capital-intensive investments, often reaching hundreds of millions of Euros, larger cement lead firms like Cemex, Holcim, and Heidelberg Cement (a partner of Schwenk) increasingly use climate finance instruments and try to align their investments with the EU taxonomy (Cemex 2023; Holcim 2023). For instance, Heidelberg Cement plans to finance up to 70% of its investments through sustainable financing tools by 2025 (Heidelberg Materials 2024). In contrast, smaller firms like Schwenk face a competitive disadvantage in global climate financing markets, as they lack the capabilities to use new financing instruments (Karltorp and Maltais 2024).

Risk Mitigation

Beyond providing financing and lowering costs, subsidies are important to signal political commitment to climate policies: *„If we [cement lead firm] plan to invest risk capital, we first of all apply for subsidies to make sure that a certain political commitment to the project exists*" (Cement_1). However, despite the German national government's promise to subsidize the development of synthetic fuel plants at the Lägerdorf and Rüdersdorf cement plants, the partners – and their financiers – still associate considerable risks with investments in synthetic fuel plants due to demand uncertainties (EIB 2024). In contrast, they consider the creation of a climate-friendly cement market as certain.

Unlike in the cement industry, the governments cannot ensure that prospective producers of synthetic jet fuels in Germany or the EU find buyers because of the importance of global markets in the synthetic fuel and aviation industries. Hence, the agency of states is constrained by markets transcending their borders (cf. Kalvelage and Walker 2024).

Demand for synthetic jet fuel depends solely on the mandate, which will create only a small market. This market would already be oversupplied if all synthetic fuel plants currently under development in Germany are built (PtX Lab Lausitz 2023). For example, emissions from just two or three cement plants would suffice to produce enough synthetic jet fuel to meet 5% of the jet fuel demand at German airports (Wassermann et al. 2022).

Moreover, the cement firms and their partners compete with synthetic jet fuel producers in other countries that could supply the emerging German and European lead market. Imported synthetic fuels from outside Germany or Europe, where renewable energy costs are lower, pose a risk to domestic producers, since transport costs constitute a relatively small cost factor (IRENA 2022, 21; Verpoort et al. 2024). Therefore, airlines in Germany currently plan to source synthetic fuels at least partially from outside Europe, e.g., South Africa (Partner_2, Chireshe et al. 2025). In addition, airlines are lobbying the European Commission to develop a book and claim system that would allow them to use synthetic fuels outside the EU and count them towards their synthetic fuel mandate (European Parliament 2024).

In addition, flights from and to Europe are of considerable economic importance (Federal Statistical Office of Germany 2024). Therefore, airlines perceive the risk of being unable to pass on cost increases because passengers and other airlines could reroute flights to avoid Europe (Buyer_2; Dray and Doyme 2019).

As a result, the three networks face demand risks as long as buyers do not commit to long-term offtake agreements, which the aviation industry has refused so far (Cement_5). Therefore, the cement firms have taken final investment decisions for carbon capture but not synthetic fuel plants yet.

4.3. Negotiating the Legitimacy of Using CARM Mechanisms

This section explores the aforementioned investment dynamics as part of multi-scalar negotiation processes, in which actors seek to legitimate the use of the CARM mechanisms for climate action (cf. Heiberg, Binz, and Truffer 2020). Understanding legitimacy as depending on the agency of the involved actors to align climate action with economic development (cf. MacKinnon, Afewerki, and Karlsen 2022; Tödtling, Trippl, and Desch 2022), we analyze to what extent the CARM mechanisms could propel desired investments and minimize price increases, thereby legitimating their use.

Creating Legitimacy by Enabling Investments

First of all, the CARM mechanisms should enable firms to invest in climate-friendly processes. Indeed, the use of the CARM mechanisms explains why the cement lead firms want to reduce their emissions in Europe rather than elsewhere, as in “*Europe [...] the pressure is already greatest, politically and also concerning the emissions trading perspective*” (Cement_1).

To minimize their emissions, the three cement lead firms decouple from (international) natural gas supplies and couple with (regional) biogas and (bio-)waste resources to reduce energy-related CO_2 emissions. Additionally, they are recoupling with their cement plants. Holcim has made a final investment decision to build a new kiln at its Lägerdorf plant, using novel carbon capture technologies developed by Linde and Thyssenkrupp. Similarly, the partners in Mergelstetten are constructing a new, non-commercial demonstration kiln with Thyssenkrupp's technology (Schwenk 2024). In Rüdersdorf, Cemex plans to deploy carbon capture technology by Linde but has not made a final investment decision yet (Cemex 2024).

These investments create demand for carbon capture technologies, fostering synergies with German technology suppliers (cf. Frangenheim, Trippl, and Chlebna 2020). Consequently, climate policies align with the interests of German technology suppliers, which increases the leeway for German policymakers. From their perspective, rising cement prices as a result of investments in climate-friendly cement production could be partially compensated by the development of a lead market for carbon capture technologies, laying the foundation for future exports:

"*If Germany still wants to outcompete the USA and China in climate technology sectors, then it must do so in the area of industrial decarbonization […] we have excellent technology providers in Germany that could play an important role in future export markets*" (Government_4).

Here, the lead market does not provide legitimacy for new technologies directly, but rather through the opportunities it offers German firms to gain competitive advantages in future export markets (cf. Heiberg, Binz, and Truffer 2020).

In addition, recoupling processes have led to the renewal and functional upgrading of the three cement plants, as they receive reinvestments in competition with other plants around the world and develop new capabilities, which they are supposed to transfer in the future:

"*We receive visitors from other cement plants around the world every other month now. Just last week, a delegation from [country] was here. […] One of [our] corporate principles […] is that we can replicate everything we do somewhere else and try to develop everything as modularly as possible, because we have a lot of locations worldwide*" (Cement_1).

Since the cement lead firms lack the capabilities to use captured carbon for synthetic fuel production themselves, their plans depend on the willingness of other firms with complementary capabilities to strategically couple with their cement plants (Table 10). Indeed, the use of the CARM mechanisms has incentivized a variety of global lead firms and specialized suppliers to strategically couple with the cement plants in Northern Germany.

Network/ Firms	**Type of coupling that firms are undergoing**	**Envisaged investments as part of strategic coupling**
Holcim	Partial decoupling from extra-regional natural gas supply, recoupling with region (cement plant, renewable energy resources)	Transition from extra-regional natural gas resources to (regional) biogas and (bio-)waste, carbon capture at its existing cement plant, co-investment in synthetic fuel plant
Hynamics (Subsidiary of EDF)	Initial strategic coupling	Green hydrogen infrastructure development and integration with refinery, co-investment in synthetic fuel plant
Ørsted	Recoupling with region (renewable energy resources)	Investments in renewable electricity supply from offshore and onshore wind turbines, co-investment in synthetic fuel plant
CAC Engineering	Initial strategic coupling	Supply of the synthetic fuel production technology
Heide Refinery (Subsidiary of Klesch Group)	Partial decoupling from (extra-)regional mineral oil supply and partial recoupling with region (refinery and energy/carbon supply)	Re-using refinery infrastructures for the purpose of refining synthetic fuels made of regional renewable energy and carbon sources
Cemex	Partial decoupling from extra-regional natural gas supply, recoupling with region (cement plant, renewable energy resources)	Transition from extra-regional natural gas resources to (regional) biogas and (bio-)waste, carbon capture at its existing cement plant, co-investment in synthetic fuel plant
Sasol EcoFT (Subsidiary of Sasol)	Initial strategic coupling	Supply of synthetic fuel technologies, marketing and retail of synthetic fuels, co-investment in synthetic fuel plant
Enertrag	Recoupling with region (renewable energy resources)	Investments in renewable electricity supply from onshore wind turbines and photovoltaic plants, green hydrogen supply
Schwenk	Partial decoupling from extra-regional natural gas supply, recoupling with region (cement plant, renewable energy resources)	Switch from fossil fuels to (biogenic) waste fuels, carbon capture at its existing cement plant, co-investment in synthetic fuel plant
Vicat	Initial Strategic Coupling	Co-investment in carbon capture and synthetic fuel plant
Heidelberg Materials	Recoupling (already active in region but was not coupled with Schwenk's cement plant before)	Co-investment in carbon capture and synthetic fuel plant
Buzzi Dyckerhoff	Initial Strategic Coupling	Co-investment in carbon capture and synthetic fuel plant

Table 10: Overview of the three networks and the strategic coupling processes the involved partners are undergoing (Source: interviews)

Together with Holcim and Cemex, the firms have formed strategic partnerships through joint ventures to develop synthetic fuel plants. These joint ventures allow the involved firms to share costs and capabilities, creating intersections between the global production networks of the involved lead firms. This highlights how industrial climate action drives the creation of new intersections due to the variety of necessary capabilities (cf. Coe 2021).

The organization of the three networks reflects the specific competitive (dis-)advantages each network faces. Insofar, the competitive dynamics of global production networks can explain organizational strategies (Coe and Yeung 2015) and the reconfiguration of global production networks (Blažek and Lypianin 2024). Potential synthetic jet fuel production sites in Northern Germany enjoy competitive advantages (see section 4.2.). Since the capabilities to reduce emissions are becoming critical in competitive dynamics and risk environments shaped by climate action (cf. Coe and Gibson 2023), firms in Southern Germany must prevent companies in Northern Germany from exclusively developing new capabilities in climate-friendly processes. This situation has prompted a coalition of otherwise competing cement lead firms to strategically (re-)couple with Schwenk's cement plant in Southern Germany despite the region's competitive disadvantages (Cement_5). However, the lack of involvement of other (lead) firms capable of producing synthetic fuels reflects the region's missing attractiveness for global lead firms that are not primarily interested in the cement market.

In comparison, the two cement firms in Northern Germany have created strategic partnerships with non-competing lead firms and specialized suppliers, avoiding sharing their capabilities with competitors. One important difference among the two networks is the involvement of a refinery in the network around Holcim's Lägerdorf plant. Synthetic jet fuel production in existing refineries promises cost advantages, as parts of refining assets can be re-used (Wassermann et al. 2022). In this context, spatial proximity between cement plants and existing refineries reduces the costs of transporting captured carbon. Moreover, the involvement of the Heide refinery constitutes a competitive advantage (Figure 18), particularly since other refineries have yet to signal their intention to (partially) decouple from international mineral oil supplies and switch to regional renewable energy and carbon sources.

Creating Legitimacy by Minimizing Price Increases

The reluctance of airlines to sign binding offtake agreements reflects ongoing multi-scalar negotiations to minimize price increases for climate-friendly cement and synthetic jet fuels. These looming price increases undermine the legitimacy of using the CARM mechanisms (Drews and van den Bergh 2016) and explain the cautious use of the market creation mechanism for synthetic jet fuels:

"*Synthetic fuels will be at least 10 times more expensive than fossil jet fuel initially, so a fuel mandate of 1% amounts to a fuel cost increase of 10% [...] Do you [the interviewer] really think that the average voter will accept that he [masculine in original] cannot longer fly on vacation once a year with his family*?" (CSO_6)

Climate policies that increase construction material prices are also "*very unpopular*", particularly given Germany's housing crisis (Government_7) and the large share of cement demand from private housing construction (WWF 2019, 11). Thus, when lead markets imply higher prices, their creation may undermine the legitimacy of novel technologies instead of supporting it (cf. Heiberg, Binz, and Truffer 2020).

Both the state and firms aim to foster legitimacy by minimizing price increases. Hence, the market imperative explains not only the behavior of firms but also state institutions (cf. Coe and Yeung 2015). Synthetic fuel production from cement plant emissions could minimize price increases because cement firms could finance investments in carbon capture technologies with revenues from synthetic fuels instead of passing on increased cost to cement buyers.

However, not all cement plant emissions are climate-neutral because carbon from limestone and marl was geologically stored before being emitted through the use of synthetic fuels (Cavalett et al. 2024). Hence, only the share of the cement plant emissions from bio-waste and bio-fuel use can be considered climate-neutral (Cavalett et al. 2022), highlighting the importance of CO_2 accounting regulations (Coe and Gibson 2023) and distinguishing between processes of value creation and capture and outcomes in terms of atmospheric CO_2 concentration (cf. Krishnan, De Marchi, and Ponte 2023).

Despite the questionable climate benefit of using all cement plant emissions for synthetic fuel production, the governments of the federated states where the three cement plants are located wanted to subsidize synthetic fuel production from all emissions as part of the EU's IPCEI program. In contrast, the German national government only wanted to subsidize synthetic fuel production from all the emissions of the Northern German cement plants (Lägerdorf and Rüdersdorf), considering the worse regional assets for synthetic fuel production in Southern Germany (BMWi 2021).

The European Commission declined the request of the German governments to authorize subsidies for synthetic fuel production from all cement plant emissions (BMWK 2024c), even though it decided, after lengthy negotiations, that it accounts all cement plant emissions for the production of synthetic fuels as climate-neutral until 2041 (European Commission 2023a). Thereby, the European Commission wants to provide an economic incentive for investments in synthetic fuel production plants in Europe and reduce the costs of sourcing carbon, while making clear that synthetic fuel producers need to switch to climate-neutral carbon sources (biogenic or air-captured) eventually (Government_9).

The incoherent and evolving policy framework has failed to mitigate the risks that the involved firms associate with investments whose returns are contingent on climate policies (cf. Steckel and Jakob 2018). Given that the development of synthetic fuel plants at commercial scale requires several years and the considerable capital investments would take decades to finance, one interviewee commented that "*[i]f the EU implements this [the 2041 deadline] in its current form, then all CCU projects would be dead. Then they will have to do CCS*" (Cement_5).

However, the network in Rüdersdorf has adapted its project. Instead of using all the cement plant emissions, it plans to only use the share of carbon emissions that result from biogas and biowaste combustion, which can be considered climate-neutral. The revised project has found the support of the EU Commission, which has ultimately authorized the German government to subsidize the project with 350 million Euros (Collins 2024).

Whether these subsidies will persuade an airline to sign a binding offtake agreement remains uncertain by late 2024. The outcome will depend on whether these subsidies can reduce the envisaged production costs of Cemex's network more than better renewable energy and carbon sources promise to reduce the costs of producing synthetic fuels abroad. As long as airlines do not decouple from fossil jet fuel supplies and couple with synthetic fuel sources, it is unlikely that commercial synthetic fuel plants will be built. Without a synthetic fuel industry in Europe, cement firms would lose an opportunity to finance investments in carbon capture through synthetic fuel revenues, forcing them to pass on the full investment costs on cement buyers, which would undermine the legitimacy of climate action. Similarly, the legitimacy of climate policies leading to price increases in the aviation industry would be further undermined, as these could not be partially offset by new investments in Germany and Europe.

5. Conclusion

While the GPN approach has not been used to analyze climate action in energy-intensive industries yet (Coe and Gibson 2023; Coe 2021, 148), we have demonstrated its potential to offer novel insights into the motivations and strategies of global lead firms regarding emission reductions. Specifically, the GPN 2.0 approach offers a framework to analyze competitive dynamics (Coe and Yeung 2015), an aspect that remains underexplored in existing analytical frameworks such as the (green) path development literature, which are more advanced in analyzing industrial climate action (Tödtling, Trippl, and Desch 2022; Trippl et al. 2020).

To employ the GPN approach for analyzing industrial climate action, we made three contributions. First, extending Coe and Gibson's (2023) argument that the sector-specific materiality of production shapes climate action, we identified two ways in which the materiality of climate-friendly processes shapes their competitiveness. On the one hand, some industrial sectors still miss the capabilities to adopt climate-friendly processes cost-effectively (Bachorz et al. 2024; Wesseling et al. 2017). On the other hand, the uneven geographical distribution of renewable energy and carbon resources, which are more costly to transport than fossil fuels (Samadi, Fischer, and Lechtenböhmer 2023), can drive relocations of (energy-intensive) firms organized in global production networks (cf. Blažek and Lypianin 2024; Njøs et al. 2024).

Second, by synthesizing GPN literature (Kalvelage and Walker 2024; MacKinnon, Dawley, Pike, et al. 2019) and related research (e.g., Binz, Truffer, and Coenen 2016), we propose four mechanisms through which actors can influence competitive dynamics and mitigate risks in geographically uneven ways. From this perspective, emission reductions in GPNs can be understood as struggles among different actors with uneven capacities to align climate action with their economic interests, opening a new field of inquiry into power struggles and agency within global production networks (Coe et al. 2004). While some mechanisms, such as cost-capability optimization and asset creation have already been discussed in the GPN literature (Coe and Yeung 2015; Fu and Lim 2022; McGregor and Coe 2021), others are less explored and offer opportunities for dialogue to better understand the influence of actors on competitive dynamics and risks. In this regard, research on market creation/formation (Boon, Edler, and Robinson 2022; Dewald and Truffer 2011; Mazzucato 2016), lead markets (Beise 2001; Losacker and Liefner 2020), climate finance (Bracking and Leffel 2021), and derisking (Gabor 2021) proves insightful.

Third, the legitimacy of using the CARM mechanisms for climate action depends on the (envisaged) economic developments they propel. Drawing from literature on technology legitimation in emerging industries (Binz, Truffer, and Coenen 2016; Heiberg, Binz, and Truffer 2020; MacKinnon, Afewerki, and Karlsen 2022), we argue that the legitimacy of climate action depends on the extent to which local firms benefit from investments by global lead firms and price increases that the financing of these investments can imply for buyers.

The EU and the German state are willing and able to mobilize the CARM mechanisms for developmental purposes. Our findings align with that of other scholars who emphasize the agency of states in shaping competitive dynamics (Dewald and Truffer 2011; Kalvelage and Walker 2024; Mazzucato 2016; Uyarra et al. 2020). Given the materially conditioned cost-capability challenges of climate-friendly processes (Njøs et al. 2024), new markets for climate-friendly products are likely going to emerge in advanced economies. In these economies, governments may have greater leeway to create lead markets for global lead firms to invest in because local firms and specialized suppliers may benefit from these investments. In addition, these states may be able to shield lead markets from international competition (Lewis 2014; Magacho, Espagne, and Godin 2024). In this regard, the lead market concept seems well suited to understand the geographies of market development (Beise and Rennings 2005), complementing the GPN literature (Yeung 2022), and provides insights into the fragmentation of global markets resulting from climate action (Gong, Hassink, et al. 2022; Lewis 2014).

While acknowledging the agency of states in climate action (cf. Kalvelage and Walker 2024), we have also highlighted their limitations, even of powerful states like Germany. For example, fiscal constraints limit the ability of states to finance climate action (Gabor 2023), potentially leading them to adopt mandates that raise prices and shift the burden of the green premium to buyers (Clancy and Moschini 2018). This can undermine the legitimacy of climate action (De Almeida and Esposito 2023; Drews and van den Bergh 2016). Moreover, states find it easier to incentivize emission reductions in global production networks serving regional markets, where the risk of decoupling is less pronounced (cf. Dray and Doyme 2019; Ponssard and Walker 2008).

State policies might also be incoherent across scales and evolve dynamically over time, proving unable to de-risk investments (Steckel and Jakob 2018). These incoherences require further exploration from a state-theoretical perspective, which we did not provide in this paper. Although state theory has been incorporated into the GPN literature to some extent (Smith 2015), we suggest incorporating insights from research focused on the capacities of states to enact climate action against economic development imperatives, such as the green state literature (Hildingsson, Kronsell, and Khan 2019).

Empirically, our study offers insights into the cement industry, which, like the other most emission-intensive industrial sectors including steel, chemicals, aluminum, and glass, has received too little attention in GPN research. These emission-intensive sectors constitute the material basis of the manufacturing sectors that GPN literature has focused on, from semiconductors (Yeung 2022) to automotives (Pavlínek 2018). Therefore, they merit more attention, both in their own right and in regard to intersections with buyers, which play a powerful role in mitigating investment risks (Bridge and Bradshaw 2017). Given the pronounced climate action gap in emission-intensive industries (Bataille et al. 2018), examining the conditions under which recoupling processes succeed or fail could offer valuable insights for practitioners aiming to support emission reductions.

The GPN framework has enabled us to analyze why cement lead firms aim to turn their captured emissions into a resource for synthetic fuel production in Germany. The increasing costdeterioration of climate-damaging cement production and the emerging lead market for climate-friendly cement incentivize cement firms to undertake costly investments in carbon capture. To minimize cost increases for buyers, state institutions support these investments by facilitating the production of synthetic fuels. Since the lead firms lack the capabilities to produce synthetic fuels and are unwilling to take over the costs and risks of investments alone, they have formed strategic partnerships with other lead firms. The geographically uneven distribution of regional assets has incentivized lead firms with complementary capabilities to strategically couple with the cement plants in Northern Germany, whereas competing cement lead firms have strategically coupled in Southern Germany to prevent the cement firms in Northern Germany from developing capabilities alone. However, the lengthy negotiations between governments and firms across scales reflect the contested legitimacy of climate action and the difficulty of aligning it with economic development. In particular, looming price increases for flights and cement, the missing willingness of airlines to commit to long-term offtake agreements, and potentially cheaper imports of synthetic fuels from abroad undermine the legitimacy of climate action.

Nevertheless, the use of the CARM mechanisms shows that competitive dynamics of energy-intensive global production networks are increasingly driven by climate action (supporting the hypothesis of Coe and Gibson 2023). Moreover, the emergence of new actor networks and strategic couplings indicates that global production networks are already restructuring in response to climate action (validating the hypothesis of Blažek and Lypianin 2024).

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Manuscript II

Walker, B., Coulomb, F. The de-risking state in global production networks: Why and how the German state de-risks investments in synthetic aviation fuels. Unpublished manuscript, in peer review at Advances in Economic Geography. The article is intended to be licensed under the CC BY-NC-ND 4.0 license.

The de-risking state in global production networks: Why and how the German state de-risks investments in synthetic aviation fuels

Abstract

The literatures on global production networks (GPNs) and de-risking have not significantly intersected. We argue that integrating them offers new insights into why and how states mitigate private investment risks and the developmental implications. We propose an integrative framework using a strategic-relational perspective to analyze why states de-risk beyond financial market interests. Additionally, we advocate for a broad understanding of de-risking, including regulatory measures, and explore the territorial limitations of regulatory de-risking. We emphasize capability and reputation as key concepts to assess de-risking's developmental impacts. Through a qualitative case study, we apply this framework to examine the de-risking efforts of the German government and the EU in a GPN for synthetic aviation fuel in Germany and South Africa. Our findings show that renewable energy-poor states like Germany use de-risking to balance climate and industrial policy goals. However, while the German government and the EU employ regulatory de-risking, penalties for violating the regulations are too low, and firms can evade them due to the limited territorial reach of the state. Lastly, we highlight that de-risking aimed at building capability and reputation in climate-neutral production faces a trade-off: industrial policy requires limiting extraterritorial spillovers, while climate policy views them as beneficial.

Keywords: geography of risks, risk management, green hydrogen, energy transition

1. Introduction

In the global production networks (GPN) literature, debates on risks (Völlers et al. 2023) and the role of states (Horner 2017) have largely remained separate, with some exceptions (Kalvelage and Tups 2024; Kalvelage and Walker 2024). This research gap is significant for two reasons. First, the de-risking literature highlights that states increasingly use de-risking to govern firms, wherein de-risking refers to "state interventions to steer price signals and correct market failures that generate 'uninvestable' risk/return profiles" (Gabor 2023, 54). While GPN frameworks consider risk to explain firm behavior, they lack an understanding of how states influence risks (Neilson et al. 2018). Second, defossilization innovations often face techno-economic risks, which may create uninvestable risk/return profiles (Baker 2022; Christophers

2024). Therefore, integrating the de-risking perspective into GPN research could offer novel insights into the role of states in GPNs, especially in mitigating risks that hinder defossilization (cf. Coe and Gibson 2023).

Research about de-risking states explains why and how states employ de-risking, while criticizing the uneven development it can propel (Gabor 2023; Gabor and Sylla 2023). According to Gabor (2021), states often de-risk private investments in the financial sector's interest to expand. However, uneven (fiscal) capacities between states, particularly between the Global North and South, can exacerbate uneven development through de-risking (Gabor and Sylla 2023).

While the de-risking literature offers insights into state-capital and financing-cost-risk relations, we argue that the GPN literature can contribute in four ways. First, de-risking studies sometimes envision the state as a "a homogenous Leviathan aligned with, or subordinated to, (financial) capital" (Gabor 2023, 56) that "entrenches neocolonial patterns of unequal ecological exchange, enabling resource transfers both directly via commodities trade and via capital flows from the Global South to the Global North" (Gabor 2023, 58). In contrast, GPN research adopts a strategic-relational perspective, seeing states as multi-scalar entities comprised of multiple institutions, whose actions reflect underlying social forces (Dawley, MacKinnon, and Pollock 2019; Smith 2015). Hence, states are not unitary actors dominated by financial-sector interests but represent varying and sometimes competing interests.

Second, different authors have varied understandings of de-risking and have identified different methods states use (Gabor 2023; Klagge 2020; Schindler, Alami, and Jepson 2023; Valenzuela 2023). Building on a typology of state roles in GPNs (Horner 2017) we distinguish and relate different means of de-risking as a first step toward theorizing why states use and combine certain means of de-risking.

Third, while Gabor (2021; 2023) emphasizes the dominance of financial capital interests over the state as the reason for why states rely on certain means of de-risking, we focus on the economic competitiveness of states and potential price increases for buyers. Thereby, we highlight that the contemporary push for de-risking does not simply reflect a dominance of financial sector interests but the interests of a much wider variety of actors.

Fourth, the de-risking literature has critically discussed the distributional and developmental implications of de-risking, primarily focusing on financial costs and benefits (Gabor 2021), and, to some extent, ecological impacts (Gabor 2023; Gabor and Sylla 2023). We further suggest reputation and capability building as indicators for development (Billing and Bryson 2019; Coe and Yeung 2015, 181). Focusing on capability and reputation building allows us to explore de-risking efforts that have not received much attention, specifically those aimed at ensuring (Laplane and Mazzucato 2020) or preventing knowledge spillovers (Poitiers and Sekut 2024). Examining these efforts provides insights into the trade-offs between de-risking that supports industrial and climate policy goals.

The four contributions form the basis of our analytical framework, which we detail in the next section. We then apply this framework to analyze why and how the German national government and the EU de-risk investments in a GPN for synthetic aviation fuels, and what the developmental implications of these de-risking efforts regarding capability and reputation building are.

The analysis offers empirical insights into the synthetic aviation fuel (eSAF) industry, which has not received attention in the GPN literature to our knowledge, and – to a lesser extent – the aviation industry (Bowen Jr. and Leinbach 2006; Niewiadomski 2017). eSAF are produced by storing renewable electricity via electrolysis of water in green hydrogen. This hydrogen is then synthesized with renewable or circular carbon.[22]

Besides the empirical insights, we chose the case study because it illustrates key theoretical aspects of de-risking. The GPN is led by the South African multinational Sasol, a global leader and prospective exporter of eSAF technologies, and the German state de-risks investments in two coal mining regions in Germany and South Africa. Addressing critiques of de-risking as a driver of unequal (ecological) exchange and development (Gabor 2023; Gabor and Sylla 2023), the case highlights the diverse interests influencing de-risking efforts and the potential of de-risking as a policy tool for territorial cohesion and international development. The case also allows us to examine various means of de-risking and their territorial dimension, as the EU and the German state have used different means of de-risking within and beyond their territorial boundaries. Finally, the case exemplifies the trade-offs between industrial- and climate-policy goals in de-risking efforts focused on capability and reputation building: while the necessary capabilities and reputation to produce eSAF should diffuse globally from a climate-policy perspective, industrial policy seeks to prevent extra-territorial spillovers.

2. Analyzing de-risking from a GPN perspective

The next four sub-sections present the analytical framework (Table 11). To analyze why states de-risk private investments, we suggest the strategic-relational view of the state (2.1). To distinguish how states de-risk, we develop a typology of different means of de-risking (2.2), followed by a political-economic perspective that can explain why states often favor facilitative

[22] Renewable or circular carbon refers to carbon derived from plants that absorb CO_2 from the atmosphere during growth, or from direct air capture technologies, ensuring that the combustion of synthetic fuels does not contribute to a net increase in atmospheric CO_2 levels (Dahal et al. 2021; Schmid and Hahn 2021).

over regulatory means of de-risking (2.3). Last, we introduce capability and reputation building as indicators for assessing the developmental implications of de-risking (2.4).

2.1. A strategic-relational perspective on the de-risking state

The de-risking literature highlights diverse actors and interests supporting de-risking efforts by state institutions. Gabor (2021) and Gabor and Sylla (2023) emphasized the financial sector's interest to expand as the main reason why states de-risk private investments. Recently, Hunt and Tilsted (2024) argued that de-risking also reflects real-economy interests, such as those of (petro-)chemical firms. Schindler et al. (2023) found that states can develop strategic visions somewhat autonomous of financial capital interests, using de-risking to balance regional development. Similarly, Steckel and Jakob (2018) argued that effective de-risking requires building winning coalitions and compensating losers to avoid resistance against the economic change that de-risking should propel since such resistance implies political risks in the eyes of politicians and investors. Thus, the de-risking logic is sensitive to socio-political contestation and is not solely driven by financial capital interests.

In the GPN literature, Völlers et al. (2023, 14) have highlighted that risk perceptions are subjective and can emerge, among other things, within the "relational network ties between GPN actors" and the territorial contexts of GPNs. Whose risk perceptions come to matter in GPNs depends on underlying power relations (Völlers et al. 2023). To analyze whose risk perceptions drive de-risking efforts by state institutions, we adopt a strategic-relational view of the state (Jessop 2016). This perspective offers two key insights: First, it understands the state as a field of social struggle where various forces compete to influence different state institutions, in our case, to prioritize and mitigate the risks they perceive (Smith 2015). Consequently, different state institutions reflect different policy mandates, strategic (de-risking) objectives, and operating practices (Dawley, MacKinnon, and Pollock 2019).

Second, the strategic-relational perspective considers the structural limitations of states. "Structural constraints are those elements in a situation that cannot be altered by agent(s) in a given time period and vary according to the strategic location of agents in the overall social formation" (Jessop 2016, 95). For example, GPN research identifies regional assets – such as natural, industrial, and human resources – as key structural constraints (cf. Yeung, 2015).

Building on these insights, we argue that the inter-organizational relations between the GPN actors and the associated risk perceptions explain why states de-risk investments in defossilization innovations. On the one hand, defossilization innovations, especially in energy-intensive industries, are often still uncompetitive with established fossil fuel technologies, for example, because renewable energy carriers, like green hydrogen, are more expensive than fossil fuels (Bachorz et al. 2024). Hence, firms and their financiers face risks when they adopt defossilization innovations even when climate policies aim to improve the competitiveness of defossilization innovations because climate policies may lack credibility due to incoherences or missing enforcement mechanisms (Brunner, Flachsland, and Marschinski 2012; Rogge and Dütschke 2018). On the other hand, defossilization innovations can promise returns that are attractive enough to take risk – with or without the support of climate policies. Moreover, climate inaction may not be an option as – besides climate risks – climate activism can undermine the legitimacy of state institutions and the reputation of firms, creating political risks for the former and economic risks for the latter (Kalvelage and Walker 2024; King 2015; Ramelli, Ossola, and Rancan 2021).

The territorial contexts of GPNs present uneven opportunities and risks for the adoption of defossilization innovations. Hence, they can explain why different actors lobby the state to de-risk investments in defossilization innovations in different places. In more detail, we understand renewable energy and circular carbon sources as regional assets that constitute structural constraints to the de-risking efforts of renewable energy and circular carbon-poor states because of the geographical disparity of renewable energy and circular carbon sources, and because renewable energy and circular carbon are more costly to transport than fossil fuels. Therefore, the energy transition introduces an incentive for energy-intensive industries to relocate from renewable energy-poor to renewable energy-rich regions (so-called "renewables pull effect" Samadi, Fischer, and Lechtenböhmer 2023). This relocation could have knock-on effects for downstream industries, such as chemical or machinery production (IRENA 2022, 21; Verpoort et al. 2024). Hence, labor unions and other actors with an interest in the development of renewable energy-poor regions may associate risks with the transition (Wang and Lo 2021) and may lobby states to de-risk investments in defossilization innovations in renewable energy-poor regions despite the structural constraints imposed by the availability of renewable energy sources.

On the contrary, corporate and private buyers may lobby the state to de-risk investments in renewable energy-rich regions, where the production of energy-intensive products may be cheaper, thereby promising cheaper products. Hence, if renewable energy-poor states want to support defossilization, they may de-risk investments to defossilize energy-intensive industries in renewable energy-rich regions outside their territories, even if this support may increase the likelihood of industrial relocations. Although these de-risking efforts may not reverse unequal ecological exchange between renewable energy-poor states in the Global North and renewable energy-rich states in the Global South, they offer opportunities for creating and capturing value in renewable energy-rich states of the Global South (cf. Samadi, Fischer, and Lechtenböhmer 2023).

2.2. Different means of de-risking

Different authors emphasize different means of de-risking private investments. Some mention tax-credits, insurances, and guarantees, financial stability, liberalization, and privatization (Elsner et al. 2022; Gabor 2023). Others focus on spatial incentives like investments in public infrastructures and special economic zones (Schindler, Alami, and Jepson 2023). Additionally, state-owned enterprises can de-risk private investments by taking over costs and risks as producers, buyers, or infrastructure providers (Anguelov 2024; Valenzuela 2023). Lastly, states use regulations to de-risk investments. For instance, states use carbon pricing (Gabor 2023) and enforce mandates, purchase obligations or renewable energy quotas, requiring utilities to buy or sell a certain share of renewable electricity as part of their portfolio (Christophers 2024; Clancy and Moschini 2018; Klagge 2020). These measures encourage buyers to sign offtake agreements, which are crucial for securing a business case for producers, enabling them to get access to financing (Hunt and Tilsted 2024).

To distinguish and compare different means of de-risking as a first step toward theorizing why states employ certain means of de-risking and combine them in particular ways, we build on Horner's (2017) typology of state roles. Horner distinguishes the facilitator, regulator, producer, and buyer roles. Facilitation refers to supporting GPNs through measures like subsidies and networking. Regulation means controlling negative externalities of GPNs and redistributing the value they create. Additionally, states can take part in GPNs as a buyers or producers, often through state-owned enterprises (SOEs).

Building on Horner's typology, we distinguish between facilitative, regulatory, and entrepreneurial means of de-risking. Entrepreneurial de-risking involves government participation in GPNs as buyers or producers, either through public procurement or SOEs. Facilitative de-risking provides investment incentives, whereas regulatory de-risking creates disincentives, such as penalties and or pricing mechanisms, to discourage undesired investments. These disincentives raise the costs of undesired production or services, such as fossil fuel production, making them less competitive with alternatives like renewable energy. In this way, states can make certain alternatives more competitive, encouraging investment in them.

2.3. Political-economic constraints of de-risking

To advance the theorization of why states use and combine certain means of de-risking, we distinguish three political-economic constraints. First, while some scholar argue that even liberal European states have established SOEs or acquired shares in companies for de-risking purposes (Valenzuela 2023), GPN research suggests that SOEs are "hybrid assets" not universally available to all states (McGregor and Coe 2021). Therefore, the availability of SOEs can constrain the use of entrepreneurial means of de-risking. Second, as Gabor (2023) has demonstrated by comparing the European and US-American de-risking states, macrofinancial constraints influence de-risking strategies as they limit the resources states can allocate to facilitative efforts.

Third, while Gabor (2021; 2023) argues that de-risking states avoid regulatory means of de-risking because they are dominated by financial capital interests, we argue that a broader range of actors favors facilitative over regulatory means because regulation can lead to price increases and hinder territorial development. Whereas facilitative de-risking reduces costs, regulatory de-risking increases the costs of undesired production and services. However, climate-neutral production often remains more expensive, especially in energy-intensive industries. For example, eSAFs are currently at least four times more expensive than fossil jet fuels (Dahal et al. 2021). Hence, when states increase the costs of emission-intensive products through regulatory de-risking, purchase prices increase. Since (climate) regulations that increase living costs are unpopular (Drews and van den Bergh 2016), we argue that corporate and private buyers, in particular, tend to prefer facilitative over regulatory means of de-risking.

Moreover, state regulation usually only applies to the state's territory (Krisch 2022). If such regulations increase prices within the state's territory, they can create competitive disadvantages for local firms compared to other states without such regulations. Firms organized in GPNs, which by definition[23] span multiple countries, may relocate regulated parts of production to other jurisdictions and then export the commodities back (Li and Zhou 2017). In climate policy research, this circumvention of regulation is known as carbon leakage, "refering to companies moving emissions-intensive operations abroad to escape regulation" (Grubb et al. 2022, 755). Although studies often find low rates of carbon leakage, the "specter of carbon leakage" stifles regulation nevertheless, not only due to corporate but also labor-union lobbying (Grubb et al. 2022, 761).

In comparison, facilitative means of de-risking do not face the risk of carbon leakage and may even attract investments by global lead firms. Therefore, we argue that the territorial perspective can explain why actors with an interest in territorial development, such as labor unions, prefer facilitative over regulatory de-risking. In addition, different means of de-risking have varying territorial reaches and states can only use entrepreneurial and facilitative means beyond their borders (cf. Kalvelage and Walker 2024). For example, states might mobilize SOEs to exert influence beyond their borders (Lim 2018) or may use facilitative means, such as subsidies, to de-risk investments abroad (cf. Kalvelage and Tups 2024).

[23] A GPN is an „organizational arrangement, comprising interconnected economic and non-economic actors [such as states], coordinated by a global lead firm, and producing goods or services across multiple geographical locations for worldwide markets" (Coe & Yeung, 2015, pp. 1–2).

2.4. Developmental implications of de-risking: Focusing on capabilities and reputation

To analyze the developmental implications of de-risking, the literature uses several indicators. These include the distribution of costs, risks, and revenues between the public and private sectors (Mazzucato 2016; 2018), with a particular focus on the financial sector (Gabor 2021; Gabor and Sylla 2023). Other indicators focus on territorial development, e.g., in terms of unequal ecological exchange (Gabor 2023; Gabor and Sylla 2023) or regional development (Schindler, Alami, and Jepson 2023). Additionally, the importance of learning and capacity building within organizations and firms benefitting from de-risking is highlighted (Anguelov 2024), along with the spillover effects between these organizations and other stakeholders (Laplane and Mazzucato 2020; Waidelich, Krug, and Steffen 2024).

Building on the latter thoughts and GPN research (Billing and Bryson 2019; Coe and Yeung 2015), we propose integrating capability and reputation building into the de-risking literature as indicators of development. Capability and reputation building is particularly relevant in industrial sectors at early stages of their lifecycle and those characterized by capital-intensive investments, such as the synthetic fuel industry (Billing and Bryson 2019; Laplane and Mazzucato 2020).

In early stages of industrial lifecycles, technologies are often unreliable and costly, but their quality tends to increase and prices decrease as production scales up (so-called learning or experience curves, Samadi 2018). Different actors associate different risks with learning curves, reflecting the temporality and subjectiveness of risk perceptions (Barratt and Ellem 2019; Völlers et al. 2023). Adopting technologies undergoing a learning curve is risky for technology users because costs may decline and performance improve over time, making early adoption potentially expensive and inefficient compared to waiting for maturity. However, delaying adoption risks missing competitive advantages, such as gaining market share or technological leadership, which depend on timely engagement and mastery of the innovation (Sarkar and Zhang 2020). Nevertheless, technology users may defer their investment decisions, which creates economic risks for technology developers, as they may not be able to sell the technologies they develop and, hence, will not be able to create a return on investments in technology development. Hence, public institutions may de-risk R&D investments to prevent underinvestment by technology developers (Castrejon-Campos, Aye, and Hui 2022).

Reputational assets – positive judgments about the future performance of a company – are especially important in capital-intensive sectors, where the economic risks associated with failed investments are significant due to the scale of the investments (Billing and Bryson 2019). To attract investments in these sectors, we highlight two key reputational assets: heritage and innovativeness. Heritage is derived from a firm's historical record, including the reputation of production sites, products, and brands, as well as accumulated capabilities and proven technologies (Billing and Bryson 2019). It signifies the confidence of investors and buyers in a firm's capabilities and, hence, that investors and buyers associate little risks with a firm. In return, missing heritage can lock-out firms from doing business. Consequently, building heritage is critical for new firms, which states can support by financing relatively inexpensive, small-scale demonstration projects that showcase a firm's capabilities (Billing and Bryson 2019).

Heritage can create inertia and path dependencies as it is based on past success, which can lead firms to stick to established capabilities, even when adapting to new circumstances might be more beneficial (Billing and Bryson 2019). In contrast, a reputation for innovativeness – or even disruptiveness – is a reputational asset that firms derive from (expectations about) technological progress (Höflinger, Nagel, and Sandner 2018). States can foster this by de-risking R&D efforts.

New entrants often develop disruptive technologies more effectively (Obal 2013), posing economic risks to established (lead) firms with accumulated heritage, as innovations can lead to market shifts (Blume et al. 2020). To manage these disruptive threats, incumbent companies can collaborate with startups, leveraging the startups' innovative capabilities while providing their own heritage in return (Sandström, Magnusson, and Jörnmark 2009). More broadly, firms use different organizational strategies to share capabilities and reputation. Coe and Yeung (2015, 123–64) distinguish four organizational strategies that lead firms can employ, including intra-firm coordination, inter-firm control, inter-firm partnership, and extra-firm bargaining. Intra-firm coordination, i.e. in-house production, offers the highest level of control over capability and reputation spillovers. In contrast, inter-firm partnerships offer an opportunity to share capabilities, reputation, and risks (Coe and Yeung 2015, 16–17).

From the perspective of actors interested in the development of specific territories, sharing capability and reputation with strategic partners and extra-territorial company locations can lead to unwanted spillovers. To prevent such spillovers, states can implement various policies. For example, states might condition facilitative de-risking measures on firms' commitments to develop technologies in-house and prevent capability sharing with strategic partners, or restrict trade flows in strategic technologies to prevent reverse engineering (Poitiers and Sekut 2024). Such policies are becoming more common due to rising geo-economic competition and conflict (Poitiers and Sekut 2024). However, they may hinder international capability transfers crucial for more equitable development and defossilization. Therefore, Laplane and Mazzucato (2020) suggest that states should condition support on ensuring spillovers, which highlights a potential conflict between territorial development goals and climate policy objectives.

Summarizing our analytical framework, we argue that why and where states de-risk investments depends on the power relations underlying different state institutions. While states can theoretically use different means of de-risking, a range of actors will favor facilitative over regulatory de-risking, even though conflicts of interest may exist over where de-risking should take place. As a result, the developmental implications in terms of capability and reputation building depend on whether spillovers of capability and reputation are encouraged or prevented (Table 11).

Research Questions	Why and where states de-risk	How states de-risk	Why states use certain means of de-risking	What are the developmental implications of de-risking
Analytical Perspective	Strategic-relational perspective	Means of de-risking	Political-economic constraints of de-risking	Development
Analytical Categories	Diverse strategic interests	Facilitative (incentives for desired investments)	Availability of SOEs	Capability and reputation building
	Structural constraints: Regional assets	Regulatory (disincentives for undesired investments)	Macrofinancial constraints	Capability and reputation spillovers
		Entrepreneurial (use of SOEs and public procurement to de-risk investments as buyer or producer)	Price increases & territorial competitiveness	

Table 11: Overview of the analytical framework (the authors)

3. Methodology

We developed our analytical framework throughout a case study, which illustrates the theoretical arguments (see introduction). We gathered data on the case – Sasol's GPN and its activities in Germany and South Africa – between October 2021 and April 2023. We adopted a qualitative case study design to gain in-depth insights into an exploratory and contemporary research context. This approach should enable us to research the interactions between different variables (Yin 2018) – in our case, different actors and their interests, means of de-risking, their mutual interactions, and implications for the organization and developmental impact of GPNs.

Our analysis began with a review of policy documents (such as hydrogen strategies), corporate (climate) reports (from Sasol and its partners' websites and annual reports), and (digital) participation in green hydrogen conferences (e.g., the German National Hydrogen Assembly, the South Africa Green Hydrogen Summit, and webinars on eSAFs).

Additionally, we conducted 46 expert interviews in Germany (October 2021 until December 2022) and South Africa (February and March 2023). We selected interviewees based on their direct involvement in Sasol's GPN or their affiliation with organizations contributing to the eSAF industry in both countries, including policymakers, civil society organizations and researchers, or competitors of Sasol (see Table 12, Supplementary Material). Data on the German state's de-risking efforts in South Africa and the network's activities there were primarily gathered during the participant observation of a business delegation to South Africa in February 2023, organized by the economic development agency of the German Federated State of Brandenburg. All interviewees consented to the use of their organizational affiliations, provided that we ensured personal anonymity, which is why we use interview codes throughout the analysis (see Table 13, Supplementary Material).

The second author of this study conducted eight interviews about Sasol's commercial project in the German Federated State of Brandenburg (see 4.2), while the first author conducted the remaining interviews. Most interviewees in Germany were held digitally, with five conducted at industry conferences. In South Africa, all interviews were conducted in-person, except for one virtual interview held prior to the trip. The interviews lasted 45 minutes on average, were semi-structured, and focused on the risks of the eSAF industry, the German state's efforts to mitigate these risks, and the developmental implications of eSAF projects (see Table 14, Supplementary Material).

We recorded and transcribed all interviews except for two, which could not be recorded; for these we took detailed notes immediately after the interviews. We coded all materials, including the documents, transcripts, and notes, using Kuckartz's (2014) structured qualitative content analysis. We initially structured the content analysis using the four dimensions of the analytical framework as deductive categories (Table 11), and then supplemented these with additional inductive codes derived from the empirical material.

4. De-risking investments by Sasol's GPN

We first provide an overview of Sasol's current business operations, highlighting the risks and opportunities that the energy transition and eSAF production imply for the multinational. Afterwards, the four subsections use the analytical framework to explain why and how the German state de-risks investments by Sasol's GPN and analyze the developmental effects of these efforts.

Sasol is South Africa's second biggest firm by revenue and an integral part of its political economy (Mondliwa and Roberts 2021). The company consists of three business units: Sasol Advanced Chemicals, Sasol Energy, and Sasol ecoFT. The first two units generate around half of the external turnover. Sasol Advanced Chemicals operates internationally, producing and selling chemicals and advanced materials, such as catalysts. In contrast, Sasol Energy focuses on the production and sale of fossil fuels primarily in South Africa and Qatar (Sasol 2023).

Sasol Energy produces fuels using Sasol's proprietary Fischer-Tropsch technologies, which involve reactors and catalyzers for synthesizing aviation and other fuels from different feedstocks (Martinelli et al. 2020). Currently, Sasol Energy operates production sites in Sasolburg and Secunda (South Africa), where fuels are made from coal and methane, and one production site in Qatar, where fuels are made only from methane. Due to the energy-intensive nature of coal and gas-based fuel production, Sasol's operations in South Africa are extremely emission-intensive, with the Secunda plant even being the most emission-intensive industrial site globally (Stamm et al. 2023).

The emission-intensity of Sasol's operations and the sunk cost they represent increasingly pose political-economic risks for the company, as shareholders and stakeholders pressure to reduce emissions increases and markets shift toward climate-neutral products (Sasol 2024). To address these risks, Sasol has adopted a dual strategy.

First, Sasol Energy plans to gradually defossilize its existing synthetic fuel plants, beginning with the Secunda plant. Since Fischer-Tropsch technologies are feedstock-agnostic, Sasol can repurpose its facilities to produce eSAF from green hydrogen and renewable carbon (Rumizen 2021). Given Sasol's significance for regional development, the company is well-positioned to access these resources in South Africa. The gradual approach aims to develop new capabilities to reduce techno-economic risks related to technological challenges and transition costs (SA_Partner_1). Additionally, it seeks to ensure the legitimacy of the transition among workers and policymakers, who depend on Sasol's production plants[24] for work and regional economic development (SA_Partner_2).

Second, Sasol established a third business unit, Sasol ecoFT, in 2021. This unit licenses and sells Sasol's proprietary Fischer-Tropsch technologies. Notably, Sasol ecoFT offers Sasol's energy-efficient and industrially proven catalysts, which are manufactured in Johannesburg (Biofuels International 2011), are highly sought after by developers of Fischer-Tropsch reactors (see 4.1; Moodley et al. 2024). Sasol ecoFT also co-develops eSAF projects around the

[24] For example, the Secunda plant employs approximately 20.000 workers (Bischof-Niemz 2023).

world, like the Concrete Chemicals project in Germany (see 4.2), which will allow the company to enter international jet fuel markets as a producer and supplier of eSAF (GER_Partner_1).

Sasol ecoFT is well-positioned in the emerging eSAF market because Fischer-Tropsch technologies are currently the only certified method for eSAF production (Rumizen 2021). Worldwide, there are only eight synthetic fuel production sites that use Fischer-Tropsch technologies, three of which are run directly by Sasol and two have licensed Sasol's technologies (Martinelli et al. 2020). While these production sites run on fossil fuels today, Sasol has accumulated considerable heritage in the synthetic fuel market, which Sasol ecoFT can leverage in the eSAF market.

4.1. A strategic-relational perspective on the EU and the German state's de-risking efforts

The EU and the German state support Sasol's defossilization as they de-risk investments by Sasol's GPNs. The de-risking efforts reflect diverse strategic interests, including climate and industrial policy, as well as regional and international development goals. First, the de-risking efforts offer incentives to invest in two coal mining regions in Germany and South Africa (see 4.2). Supporting economic development in these areas aligns with the interests of regional and international development agencies:

"*The regional administrations cannot manage the structural change that the energy transition implies alone. We face structural change not only in our coal industry but our entire industrial sector*" (GER_Public_1).

"*[The towns of] Sasolburg and Secunda are literally named after Sasol [Secunda refers to the second synthetic fuel plant that Sasol developed in South Africa]. That should tell you enough about the importance of the [synthetic fuel] plants for the future of both towns*" (SA_Public_2).

Second, German eSAF producers and technology manufacturers, such as the startup Ineratec, are keen to cooperate with Sasol to benefit from its heritage and import technologies made by Sasol in South Africa (Moodley et al. 2024). Third, a conflict of interest exists between German labor unions and prospective eSAF buyers, i.e. the aviation industry. The labor union representing workers in the (petro-)chemical industry demands that the state prevents "green leakage" (IG BCE 2021, 46), which could result from the renewables pull, by creating the infrastructural conditions and regulatory incentives to import green hydrogen and produce synthetic fuels in the existing refineries in Germany (IG BCE 2020). In comparison, German airlines want to procure eSAF as economical as possible and show little concern about the future of the German refinery sector:

"*I simply cannot imagine that we will produce eSAF at scale in Germany. It simply does not make sense to ship green hydrogen to Germany instead of the finalized product. The state can* *of course subsidize eSAF plants in Germany but what will happen to them once subsidies run out?*" (GER_Buyer_2).

eSAF production in South Africa is expected to be cheaper than in Germany because repurposing Sasol's existing industrial assets in South Africa offers cost benefits over building new eSAF plants in Germany (GER_Competitor_1). Additionally, South Africa offers more economical renewable energy and carbon sources (SA_Civil_1, Chireshe et al. 2025). Therefore, German buyers are interested in the transition of Sasol's industrial assets in South Africa: "*South Africa is a really interesting place [for eSAF production]. It has the industrial capacities, the natural resources […] and of course, transitioning Sasol's fuel plants instead of developing new ones could save costs*" (GER_Buyer_1).

The German state's de-risking efforts reflect these competing interests between the German refinery sector, eSAF project and technology developers, and aviation industry buyers. The German state is working to facilitate the development of eSAF production capacities both in Germany and South Africa (see 4.2). This approach reflects a willingness to concede shares of fuel production to other countries with more favorable regional assets, while trying to maintain other shares within Germany despite less advantageous conditions. Simultaneously, the German state's de-risking efforts aim to foster a win-win scenario by incentivizing and strengthening Sasol's strategic partnerships with German firms (see 4.4). This finding suggests that de-risking does not necessarily entrench neocolonial patterns of unequal ecological exchange (cf. Gabor 2023; Gabor and Sylla 2023) but can potentially contribute to more equitable international development, particularly in the context of structural constraints imposed by the energy transition on renewable energy-poor states like Germany (cf. Samadi, Fischer, and Lechtenböhmer 2023; Verpoort et al. 2024).

4.2. De-risking Sasol's GPN by regulatory and facilitative means

Different German ministries facilitate different types of investments based on their policy mandates, reflecting different scopes and goals of de-risking. The Federal Ministry for Economic Affairs and Climate Action (BMWK) provides subsidies for the HyShift industrial demonstration project in Secunda, South Africa, and the commercial Concrete Chemicals project, located in Rüdersdorf, Germany. The HyShift project aims to demonstrate the techno-economic feasibility of defossilizing Sasol's existing synthetic fuel plants and build heritage to mitigate transition risks. Subsequently, the project plans to scale up eSAF production to commercial scale in Secunda. In contrast, the Concrete Chemicals project focuses on developing a new, commercial synthetic fuel plant in Germany (Interview_Public_1).

The Federal Ministry of Education and Research (BMBF) funds two research projects. The Care-O-Sene project focuses on developing human resources and enhancing the energy-efficiency and durability of Sasol's catalyzers to reduce eSAF production costs. In addition, the HySecunda project supports the HyShift project with R&D services (Figure 19).

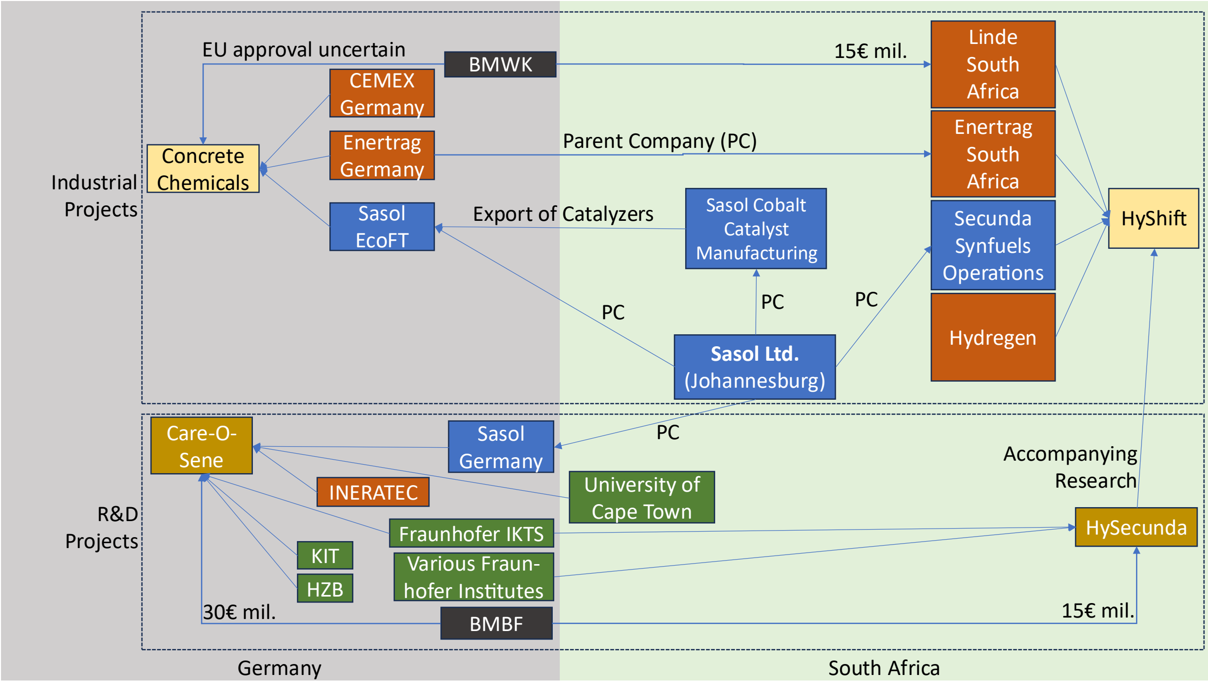

Figure 19: Overview of the German state's facilitative de-risking efforts. Color Code: light yellow = industrial projects, dark yellow = research projects, blue = Sasol parent company and subsidiaries, brown = corporate partners of Sasol, green = research institutes (Source: interviews, websites, document analyses)

The German state's regulatory de-risking efforts are ineffective so far because they lack reliable enforcement mechanisms. The EU and German regulations mandate increasing blends of eSAF in jet fuel at European airports (1.2% in 2030, 2% in 2032, 5% in 2035 and progressively reaching 35% in 2050; European Parliament 2023). The German government's blending mandate is slightly more ambitious to provide incentives for investments into eSAF production in Germany (0.5% in 2026, 1% in 2028, 2% in 2030; BMUV 2021). Despite these regulatory de-risking efforts, jet fuel suppliers and the aviation industry are reluctant to buy eSAF instead of fossil jet fuels. The primary reasons are the high costs associated with eSAF and the risks of entering into binding offtake agreements, which currently outweigh the penalties for not meeting regulatory targets. Both the EU and German regulations lack robust enforcement mechanisms. The EU does not have strong executive powers to penalize non-compliance, and the fines imposed by the German government are currently less costly than purchasing eSAF. This situation is expected to shift only around 2030, when the costs of eSAF are anticipated to decrease due to technological advancements and increased production experience (Richter et al. 2024, 19). However, from a de-risking perspective, such uncertain and dynamic policy implications present political and economic risks for firms and investors, as they will find it difficult to adopt long-term strategies (cf. Barratt and Ellem 2019).

4.3. Political-economic constraints of the German state and the EU's de-risking efforts

The German state faces three political-economic constraints that limit the means of de-risking it has at its disposal. First, the German government does not have SOEs available (project developers, aviation fuel suppliers, or airlines), which could otherwise de-risk investments in eSAF production as buyers or producers. In addition, funding a SOE for this purpose appears politically unfeasible in the contemporary German political economy. For example, the efforts of the Federal Minister of Economic Affairs and Climate Protection to create a SOE for hydrogen pipeline development failed to secure the necessary political backing (ZfK 2023).

Second, the territorial reach of regulation limits the EU's and the German state's agency to de-risk through regulatory means rather than facilitative ones. Specifically, mandating the use of eSAF instead of subsidizing it increases flight costs, potentially stifling market development in the aviation sector and related industries (Mueller, Winter, and Grote 2024). Additionally, the mandates could incentivize airlines and passengers to reroute flights to jurisdictions without such mandates. For instance, instead of a direct flight from Germany to Japan with the added cost of eSAF, travelers could opt for a split journey: a shorter leg from Europe with eSAF and a longer leg from a region without eSAF mandates (Pechstein 2024). These issues explain the minimal eSAF usage required of airlines by the mandates.

Third, the German national government and the EU face fiscal constraints that prevent them from implementing funding schemes with virtually unlimited financial resources, like the tax credits used by the US government:

"*In contrast to the USA, we always have to know how much money we are actually spending so that our budget is balanced. That means our programs have a fixed volume, otherwise we [the Ministry for Economic Affairs and Climate Protection] won't get them through the [parliamentary] budget committee. And that's why we need selection procedures, etc., because otherwise there's no way of knowing how many companies really want to invest or not*" (GER_Public_3).

Consequently, the government must set predetermined funding limits for industrial policy programs and typically run competitive selection processes. These competitions rank applicants based on various criteria, such as their location in regions undergoing structural economic change or their contributions to emission reductions (see, e.g., BMWi and BMVI 2021). Since the macrofinancial constraints necessitate the state to focus its facilitative de-risking efforts on specific firms, the government intends de-risking efforts to create spillovers in an attempt to maximize the effectiveness of public funds (see 4.4, Schmitz, Seidl, and Wuttke 2024).

4.4. Developmental implications of de-risking Sasol’s GPN

The German state’s facilitative de-risking efforts focus on capability and reputation building, evident in the funding allocated to R&D and industrial demonstration projects. This focus aligns with the EU’s industrial policy strategy (Kleimann et al. 2023) and the nascent stage of the eSAF industry. Accordingly, a representative of a German funding institution argued: “*Our funding is targeting very early, high risk investments, hence, it’s grant funding […] The private sector is moving towards commercial financing, but I think only around 2030, 2035 we will see commercial banks and institutional investors coming in*” (SA_Public_2). The absence of financial sector involvement at this stage underscores that the de-risking efforts in our case do not yet directly support financial sector interests (cf. Gabor 2021).

As a form of facilitative de-risking, the German state influences Sasol’s GPN by shaping its organizational strategies. It uses reputational assets as an eligibility criteria to allocate funding (GER_Public_2), thereby encouraging the formation of strategic partnerships among specialized producers. This approach leverages the reputational assets of different partners to mitigate perceived risks of projects failure. For instance, the HyShift consortium integrates Sasol’s heritage in synthetic fuel production with Linde’s expertise in hydrogen supply and Enertrag’s experience in renewable energy development. Additionally, including the South African, Black-owned project developer Hydregen adds political legitimacy to the project.

The German state also incentivizes the strategic partners to share heritage and innovativeness. Thereby, the German state aims to mitigate the risk that either firms that have accumulated heritage or firms that offer innovative solutions, disrupt each other’s business case. Sasol’s heritage offers competitive advantages because repurposing existing synthetic fuel plants is economically advantageous compared to building new plants, as it primarily requires investments in feedstock processing while leveraging existing infrastructure (GER_Buyer_3, SA_Partner_2). However, the large scale of Sasol’s current plants poses a challenge: their immense size makes it impractical to switch from fossil fuels to regional renewable resources (GER_Competitor_2). Transitioning these plants would necessitate developing green hydrogen pipelines and transporting renewable carbon from non-regional sources by truck (Bole-Rentel, Chireshe, and Reeler 2022; NCEDA 2023). In contrast, new eSAF plants can be sited closer to optimal renewable energy and carbon sources globally, and can be scaled according to the availability of these resources, reducing transport costs (Dieterich et al. 2020). As a result, the market may shift from legacy to new, purpose-built plants: “*I believe that existing plants have a competitive advantage for the time being [...]. However, as the capital costs of new plants fall, they will be able to produce more economically*” (GER_Competitor_2).

To protect Sasol from the disruptive threat posed by innovative, purpose-built eSAF plants, the German state facilitates collaborations between Sasol and the German startup Ineratec, which develops such plants. Ineratec offers modular Fischer-Tropsch reactors that can be scaled based on regional resource availability (Wassermann et al. 2022). The cooperation between Sasol and Ineratec in the Care-O-Sene project aims to foster mutual learning and help both firms to stay ahead of the learning curve of eSAF production (Sasol Germany 2023). Thereby, both firms remain aware of whether either existing synthetic fuel plants or purpose-built eSAF plants offer cheaper production costs, increasing their ability to mitigate risks associated with market shifts towards either approach to eSAF production.

These examples illustrate that the German government actively promotes capability and reputation sharing among strategic partners rather than restricting it. By funding individual firms and GPNs, the goal is to foster spillovers that help to de-risk the broader eSAF industry (Schmitz, Seidl, and Wuttke 2024). For instance, in the Care-O-Sene and HySecunda projects, non-profit research institutions are involved, which play a crucial role in training personnel and disseminating research findings (Fraunhofer IEE 2023).

While international spillovers are vital for climate policy, they pose challenges for industrial development. The IPCEI (Important Projects of Common European Interest) funding scheme, through which the German state subsidizes the Concrete Chemicals project, highlights that the German-European de-risking approach cannot prevent spillovers. The IPCEI scheme mandates that eligible companies must be registered in Germany (GER_Public_1). However, both Sasol ecoFT and Cemex (Mexiko), involved in the Concrete Chemicals project, are subsidiaries of Global South parent companies. These subsidiaries often design projects to facilitate capability transfers across borders:

"*One of [our] corporate principles […] is that we can replicate everything we do somewhere else and try to develop everything as modularly as possible, because we have a lot of locations worldwide*" (GER_Partner_1).

Hence, the German state lacks control over whether the capabilities gained by German subsidiaries is transferred to their parent companies abroad. In this sense, the missing restrictions on spillovers resolve the conflict between industrial and climate policy goals in favor of climate policies.

5. Conclusion

Considering the role of the state in mitigating risks offers novel insights for GPN research, particularly regarding the state's role within GPNs (Horner 2017). The de-risking literature highlights that states mitigate risks to govern firms (Gabor 2021; Klagge 2020; Steckel and

Jakob 2018). Furthermore, the de-risking perspective is especially useful to research the defossilization of GPNs (cf. Coe and Gibson 2023; Kalvelage and Tups 2024) because climate-neutral production can encounter techno-economic and political risks that result in high financing costs (Baker 2022; Christophers 2024).

By integrating the GPN and de-risking literatures, this paper aims to offer a more nuanced understanding of why states de-risk investments. We argue, first, that the strategic-relational approach to the state (Jessop 2016) better captures the diverse interests shaping de-risking efforts, rather than viewing de-risking as solely driven by financial-sector interests (Gabor 2021; 2023). Additionally, recognizing the structural limitations of state agency is important to avoid conceptualizing the state as a Leviathan (cf. Gabor 2023).

Second, building on a typology of the different state roles in GPNs (Horner 2017), we distinguish between facilitative, regulatory, and entrepreneurial means of de-risking. This categorization helps clarify the varied approaches to de-risking reported in the literature (Anguelov 2024; Christophers 2024; Gabor 2021; 2023; Klagge 2020; Valenzuela 2023). By doing so, we take a first step toward understanding why states adopt, avoid, or combine certain means of de-risking.

Third, we promote a political-economic perspective to investigate why states adopt, avoid, or combine certain means of de-risking. We argue that the territorial reach of state regulation often does not align with the global reach of GPNs (Krisch 2022). Consequently, regulatory de-risking, which raises the costs of undesired investments, can push firms to invest outside the state's jurisdiction (Grubb et al. 2022) and can undermine the legitimacy of climate policies in the eyes of corporate and private buyers (Drews and van den Bergh 2016). In contrast, facilitative means of de-risking do not raise costs and can be applied internationally (Kalvelage and Tups 2024). This perspective helps explain why states might prefer facilitative over regulatory means of de-risking.

Lastly, we suggest capability (Coe and Yeung 2015) and reputation (Billing and Bryson 2019) as conceptual perspectives to analyze the developmental impacts of de-risking in nascent industries (Samadi 2018). At early stages of industrial development, facilitative de-risking often focuses on R&D and demonstration projects (Billing and Bryson 2019; Mazzucato 2016; 2018). To assess the distributional implications of such de-risking measures, it is crucial to analyze how states promote or hinder capability and reputation sharing (Laplane and Mazzucato 2020), particularly by influencing the organizational strategies of GPNs (cf. Coe and Yeung 2015). While effective developmental states might control spillovers, particularly to other territories (cf. Gabor 2023), these spillovers are crucial for advancing international development and defossilization (Poitiers and Sekut 2024).

Focusing on the emerging GPN for eSAF led by the South African multinational Sasol, this study explores why and how the German state de-risks investments within this network and examines the developmental implications. The German state de-risks Sasol's GPN because Sasol provides unique industrial assets important for competitive eSAF production and plays a key role in defossilization from both climate-policy and international-development perspectives (Stamm et al. 2023). Additionally, Sasol's technology supply to German buyers and its reputational assets enhance trust and facilitate capability spillovers to innovative German startups. Furthermore, Sasol is well-positioned to leverage South Africa's renewable energy and biological carbon resources which are superior to Germany's (Chireshe et al. 2025).

Insofar as eSAF imports undermine market shares of German refineries in the emerging eSAF market, the German de-risking state is willing to cede parts of industrial production to other countries as a means to combat climate change (cf. Löschel et al. 2024; Verpoort et al. 2024). Simultaneously, de-risking Sasol's GPN aligns with the interests of German eSAF buyers and eSAF project and technology developers, creating a win-win scenario for these stakeholders. Hence, the structural constraints imposed by the energy transition create a negotiation space between energy-poor states in the Global North and energy-rich states in the Global South. Exploring this negotiation space, which holds potential for more equitable international development, warrants further research (Samadi, Fischer, and Lechtenböhmer 2023).

The German state de-risks Sasol's GPN by facilitative means, focusing on R&D and demonstration projects. The German state and the EU also engage in regulatory de-risking. However, the mandates for eSAF use are currently low, and penalties for non-compliance are insufficient, illustrating the challenges states face with regulatory de-risking (cf. Gabor 2023). The low percentages of eSAF use are not due to the state's alignment with financial capital interests (Gabor 2021; cf. 2023). Instead, we argue that regulatory means of de-risking increase the cost of flying, which is detrimental to the aviation industry and its customers. This could lead to efforts to circumvent regulations by relocating flights outside of Europe (Mueller, Winter, and Grote 2024). Thus, a diverse range of territorialized interests influences how states de-risk private investments.

Finally, our developmental perspective on reputation, capability building, and spillovers helps explain the German state's facilitative de-risking efforts. Given that eSAF production faces significant techno-economic risks – being unproven at an industrial scale and economically uncompetitive with fossil jet fuels – R&D initiatives are critical for reducing costs and enhancing technological reliability. Simultaneously, demonstration projects are needed to establish industrial heritage (cf. Billing and Bryson 2019). By fostering collaboration between Sasol and innovative German startups, the German government ensures both parties remain ahead of the learning curve.

The German state and the EU actively encourage mutual learning and even condition funding on spillovers (Schmitz, Seidl, and Wuttke 2024). This finding highlights the need for researchers to consider trade-offs between industrial, international development, and climate policy goals (Laplane and Mazzucato 2020; Poitiers and Sekut 2024).

Looking ahead, we argue that further integration of the de-risking and GPN literatures promises mutual insights in two areas: Firstly, the de-risking literature offers an understanding of the interrelationships between risks, costs, and financing, an area where GPN research is less developed (Yeung, 2016). This perspective can offer novel insights into the (private) financing of capital-intensive investments in new production facilities, such as commercial eSAF projects. These capital projects are places where global financial networks (GFN) and production networks meet. Thus, the de-risking perspective offers a pathway to deepen the connection between GFN and GPN research, emphasizing a crucial geographical aspect of GFNs. This aspect has often been overlooked as existing research has focused on financial centers and offshore jurisdictions (Coe, Lai, and Wójcik 2014).

Secondly, future research could delve into how geo-economic competition shapes the means that de-risking states employ. Our study highlights the limitations of (neoliberal) states like Germany, which lack SOEs to de-risk investments as buyers or producers. In comparison, states such as China mobilize SOEs to de-risk private investments (Kalvelage and Tups 2024), seemingly more effective in building synthetic fuel and green hydrogen production capacities than states without SOEs (Gong, Quitzow, and Boute 2023). This raises important questions about how liberal states will respond to this potential competitive disadvantage. Exploring whether the de-risking approach could push these states to establish new SOEs for de-risking purposes – an idea recently suggested by a German Minister (see 4.3) – could offer valuable insights into how de-risking might reinforce state capitalism (Schindler, Alami, and Jepson 2023).

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Supplementary Material

Date	Position	Organization
15.10.2021	Board Member	Klima Allianz
20.10.2021	Board Member	H2 Global Adivsory GmbH
04.05.2022	Account Manager	Deutsche Kreditbank
05.05.2022	Research Associate	Aireg
12.05.2022	Head of	CEMEX Germany
15.05.2022	Logistics Manager	AFS Services
18.05.2022	Senior Researcher	Sasol EcoFT
19.05.2022	Programme Coordinator	Agora Energiewende
23.05.2022	Sustainability Manager	DHL Logistics
26.05.2022	Head of	Schwenk Zement
26.05.2022	Team Leader	Enertrag Germany
30.06.2022	Team Leader	Umweltbank
05.07.2022	Consultant	Ministry of Economic Affairs, Labour and Energy of the State of Brandenburg
08.08.2022	Head of	Holcim Germany
09.08.2022	Working Group Leader	Helmholtz Hereon
10.08.2022	Department Leader	Flughafen BER
10.08.2022	Consultant	German Federal Ministry for Digitalization and Transport (BMDV)
14.08.2022	Business Developer	Open Grid Europe
29.09.2022	Project Developer	Enertrag Germany
29.09.2022	Deputy Managing Director of a Working Group	Association of German Mechanical and Plant Engineering (VDMA)
06.10.2022	Project Manager	Fraunhofer IEG
07.10.2022	Lead Manager	PtX Lab Lausitz
14.10.2022	Research Associate	Deutsches Institut für Luft und Raumfahrt (DLR)
02.11.2022	Project Developer	EDL Anlagenbau
22.11.2022	Senior Researcher	Fraunhofer UMSICHT
07.02.2023	Energy Analyst & Project Officer	WWF South Africa
07.02.2023	Project Coordinator	GreenCape
08.02.2023	Non-Executive Director	JustShare
08.02.2023	Professor	University of Cape Town
09.02.2023	Sector Lead	Freeport Saldanha
20.02.2023	Managing Director	move consulting
20.02.2023	Head of	Afrox South Africa
20.02.2023	Investment Lead	Development Bank of Southern Africa
21.02.2023	CEO	Ubuntu Green Hydrogen
22.02.2023	Head of	PARI (Public Affairs Research Institute)
23.02.2023	Senior Consultant	RebelGroup
23.02.2023	Senior Advisor	South African Wind Energy Association (SAWEA)

23.02.2023	Head of	GIZ
27.02.2023	Investment Officer	The Presidency of South Africa
27.02.2023	Team Lead	Industrial Development Corporation (IDC)
28.02.2023	Head of	Sasol Energy
28.02.2023	Project Developer	Enertrag South Africa
23.03.2023	Junior Sector Coordinator	KfW
29.02.2023	CEO	DFIC Consulting
29.02.2023	Programme Lead	Worldbank

Table 12: Overview of Interviewees (the authors)

Country/ Abbreviation	Strategic Partners	Lobby Organisations	Competitors	Potential Buyers	Public Institutions	Civil Society	Private Financiers	Research Organizations & Consultants
Germany/GER_	Partner_#5	Lobby_#1	Competitor_#3	Buyer_#3	Public_#4	Civil_#2	Financier_#2	Research_#4
South Africa/SA_	Partner_#3	Lobby_#2	Competitor_#1	Buyer_#0	Public_#8	Civil_#2	Financier_#0	Research_#5

Table 13: Overview of Interview Codes and Number of Interviews per Category (the authors)

Interview Stage	Objective
Introduction	Introduction of Research Objectives, Interviewer and Interviewee
National Context (Germany; South Africa) and international cooperation	Questions concerning development of national green hydrogen and eSAF industries, opportunities international cooperation/trade
Risks	Questions concerning risks of green hydrogen and eSAF markets in GER/SA
De-Risking	Questions concerning the German state's role in de-risking eSAF market in GER/SA
Development	Implications of de-risking and eSAF projects (including R&D projects) for development of GPN and regions where projects are located; regional/international conflicts of interest and sustainability aspects
End	Recommendations for future interview partners and open question about relevant issues not touched throughout interview

Table 14: Summary of Interview Structure

Appendix

Interviews

Interviews in Germany

Nr.	Date	Name of Organisation	Position	Actor Type	Interview medium	Duration in minutes
1	12.02.2021	Rheinischer Verkehrsverbund (RVR)	Division Manager	Municipal Utility	Video Call	58
2	22.09.2021	Stadtwerke Halle	Division Manager	Municipal Utility	In Person	132
3	14.10.2021	Verband Kommunaler Unternehmen (VKU)	Division Manager	Association	Video Call	52
4	15.10.2021	Klima Allianz	Managing Director	Civil Society	Video Call	44
5	20.10.2021	H2 Global Advisory GmbH	Managing Director	Private Company	Video Call	32
6	22.10.2021	Acatech	Project Lead	Academia	Video Call	54
7	28.10.2021	ISFH (Institut für Solarenergieforschung in Hameln (ISFH))	CEO	Academia	In Person	40
8	04.11.2021	Projektträger Jülich	Network Manager	Academia	Video Call	51
9	04.11.2021	GP Joule	Division Manager	Private Company	Telephone	60
10	09.11.2021	H2-Netzwerk Ruhr	Spokesman	Association	Video Call	56
11	10.11.2021	Energieagentur NRW	Network Manager	Public Agency	Video Call	49
12	26.11.2021	Arbeit & Umwelt (IG BCE Stiftung)	Managing Director	Labour Union	Telephone	72
13	06.12.2021	H2-Netzwerk Ruhr	Spokesman	Association	In Person	83
14	09.12.2021	Green Planet Energy	Division Manager	Cooperative	Video Call	56
15	18.02.2022	Regionalmanagement Mittelhessen	Division Manager	Economic Development Agency	Video Call	47
16	23.02.2022	Hamburg Invest	Senior Expert Hydrogen, Key Account Manager	Economic Development Agency	Video Call	61
17	23.02.2022	Enmacc GmbH	CEO	Private Company	Telephone	57
18	23.02.2022	EWE AG	Project Lead	Private Company	Video Call	48
19	24.02.2022	H2CLOUD GmbH	CEO	Private Company	Video Call	40
20	25.02.2022	IHK Schwerin	Division Manager	Association	Video Call	41

21	28.02.2022	Fraunhofer IKTS	CEO	Academia	Telephone	38
22	02.03.2022	e-mobil BW	Division Manager	Network	Video Call	
23	02.03.2022	ZINQ	CEO	Private Company	Video Call	62
24	03.03.2022	IHK Nord	Division Manager	Association	Video Call	55
25	07.03.2022	Wirtschaftsförderung Nürnberg	Division Manger	Economic Develop-ment Agency	Video Call	39
26	08.03.2022	terranets BW	Project Lead	Private Company	Video Call	51
27	09.03.2022	ITEL - Deutsches Lithi-uminstitut GmbH	CEO	Academia	Video Call	58
28	15.03.2022	H2.bayern	Division Manager	Association	Video Call	72
29	17.03.2022	Region Stuttgart GmbH	Division Manager	Economic Develop-ment Agency	Video Call	42
30	22.03.2022	Arbeitsgemeinschaft in-dustrieller Forschungsver-einigungen (AiF)	CEO	Association	Telephone	46
31	22.03.2022	Johannes-Rau-Forschungs-gemeinschaft	Managing Director	Academia	Telephone	38
32	23.03.2022	FZ Jülich	Managing Director	Academia	In Person	27
33	25.03.2022	bayernets GmbH	Project Developer	Private Company	In Person	39
34	29.03.2022	Müllverwertungsanlage Bonn GmbH	Division Manager	Public Uti-lity	In Person	47
35	30.03.2022	bayernhafen GmbH & Co. KG	Assistant Manager	Private Company	In Person	41
36	31.03.2022	EnBW	Manager Offshore	State-Owe-ned Enter-prise	In Person	23
37	31.03.2022	EnBW	Project Developer	State-Owe-ned Enter-prise	Written Communica-tion	-
38	12.04.2022	IG Metall	Representative	Labour Union	Video Call	52
39	02.05.2022	MAXIMATOR Hydrogen GmbH	CFO	Private Company	Telephone	26
40	04.05.2022	DKB	Account Manager	Specialized Bank	In Person	38
41	05.05.2022	Aireg	Research Associate	Association	In Person	49
42	05.05.2022	HH2E AG	CTO	Private Company	In Person	89
43	15.05.2022	AFS Services	Logistics Manager	Private Company	In Person	58
44	17.05.2022	Tree Energy Solutions (TES)	General Manager	Private Company	In Person	43
45	18.05.2022	Mittelsächsische Energie-genossenschaft	President	Coopera-tive	Video Call	52

46	19.05.2022	ZBT	Managing Director	Academia	Video Call	40
47	23.05.2022	DHL Logistics	Sustainability Manager	Private Company	Video Call	53
48	26.05.2022	Schwenk	Managing Director	Private Company	Video Call	47
49	01.06.2022	Energiegenossenschaft Niederbayern	Geschäftsführer	Cooperative	In Person	68
50	30.06.2022	Energieagentur Bayern	Mitarbeiter Bereich Energie	Public Agency	In Person	72
51	30.06.2022	Umweltbank	Team Lead	Bank	In Person	33
52	01.07.2022	Rießner Gase	Account Manager	Private Company	In Person	29
53	01.07.2022	HySON	Director	Academia	In Person	44
54	01.07.2022	Landkreis Wunsiedel	Climate Manager	Executive	In Person	52
55	05.07.2022	MWAE Land Brandenburg	Referent	Verwaltung	Telephone	49
56	20.07.2022	BEHALA mbH	Assistant Manager	Public Utility	Video Call	80
57	20.07.2022	TU Berlin	Postdoc	Academia	Video Call	121
58	20.07.2022	GASAG	Team Lead	Private Company	Video Call	37
59	07.08.2022	Hertie School	Research Associate	Academia	Written Communication	-
60	08.08.2022	Holcim	Division Manager	Private Company	Video Call	47
61	09.08.2022	VIK Verband der industriellen Energie- und Kraftwirtschaft	Referent	Association	Video Call	53
62	09.08.2022	Helmholtz Hereon	Division Manager	Academia	Telephone	19
63	10.08.2022	Ministerium für Energiewende, Landwirtschaft, Umwelt, Natur und Digitalisierung Schleswig-Holstein	Division Manager	Ministry	Written Communication	-
64	10.08.2022	TES Tree Energy Solutions	Head of Government and Regulatory Affairs	Private Company	Video Call	27
65	10.08.2022	BMDV	Advisor	Ministry	Video Call	59
66	10.08.2022	Flughafen BER	Advisor Climate Change Mitigation	Private Company	Video Call	49
67	11.08.2022	EEHH Cluster EE Hamburg	Managing Director	Association	Video Call	52
68	16.08.2022	BEE Bundesverband erneuerbare Energien	Team Lead	Association	Video Call	48
69	17.08.2022	Green Planet Energy	Advisor	Coopeative	Video Call	43
70	07.09.2022	50Hertz	Business Developer	Private Company	In Person	24
71	07.09.2022	Siemens Energy	Division Manager	Private Company	In Person	49
72	07.09.2022	Wasserstoffregion Uckermark-Barnim	Project Lead	Municipality	In Person	52
73	14.09.2022	Investitionsbank Schleswig-Holstein	Account Manager	Investment Bank	In Person	89

74	14.09.2022	BASF	Lead Transforma-tion Renewable Energy	Private Company	In Person	48
75	14.09.2022	Northvolt	Head of Strategy & Programm	Private Company	In Person	32
76	14.09.2022	elogen	Managing Director	Private Company	In Person	33
77	28.09.2022	H2 Giga/Fraunhofer IWES	Research Associate	Academia	In Person	45
78	28.09.2022	Lhyfe	Business Develo-per	Private Company	In Person	52
79	28.09.2022	Verband Deutscher Ma-schinen- und Anlagenbau (VDMA)	Projekt Manager	Association	In Person	64
80	28.09.2022	Apex	Head of Enginee-ring	Private Company	In Person	59
81	28.09.2022	Green H2 Systems	Sales & Business Development Ma-nager	Private Company	In Person	18
82	27.09.2022	H-Tec	Sales Manager	Private Company	In Person	32
83	27.09.2022	Norddeutsches Reallabor; Competence Center für er-neuerbare Energien und Energieeffizienz (CC4E)	Project Manager	Academia	In Person	38
84	27.09.2022	Kyros	Field Application Engineer	Private Company	In Person	27
85	27.09.2022	Fraunhofer IEE	Research Associate	Academia	In Person	55
86	29.09.2022	VDMA	Division Manager	Association	In Person	62
87	29.09.2022	Enertrag	Project Manager	Private Company	In Person	49
88	06.10.2022	TransHyDE	Managing Director	Academia	Written Communica-tion	-
89	06.10.2022	Fraunhofer IEG	Project Manager	Academia	Video Call	57
90	07.10.2022	PtX Lab Lausitz	Managing Director	Public Agency	Video Call	56
91	10.10.2022	Hüttentechnische Vereini-gung der Deutschen Glasin-dustrie e.V.	Division Manager	Association	In Person	61
92	14.10.2022	Deutsches Institut für Luft und Raumfahrt (DLR)	Research Associate	Academia	Telephone	56
93	02.11.2022	Horn	Division Manager	Private Company	In Person	50
94	02.11.2022	EDL Anlagenbau	Project Manager	Private Company	In Person	38
95	02.11.2022	CAC Chemieanlagenbau Chemnitz	Projektmanager	Private Company	In Person	27
96	04.11.2022	Deutsche Energieagentur	Division Manager	Public Agency	In Person	33
97	08.11.2022	Deutsche Industrie und Handelskammer	Division Manager	Association	Video Call	45

98	09.11.2022	Merkel Energies	Geschäftsführer	Private Company	In Person	52
99	09.11.2022	Scottish Development International	Divison Manager	Economic Development Agency	In Person	50
100	22.11.2022	Fraunhofer UMSICHT	Professor	Academia	Video Call	69
101	12.12.2022	FH Westküste	Professor	Adacemia	Telephone	72
102	15.12.2022	Stadtwerke Mainz	Division Manager	State-Owned Enterprise	In Person	133
103	04.01.2023	Hzwo e.V.	Managing Director	Association	Video Call	44
104	09.01.2023	Deutsches Institut für Luft und Raumfahrt (DLR)	Research Group Leader	Academia	Telephone	63
105	09.01.2023	Verband der Deutschen Verkehrsunternehmen	Managing Director	Association	Video Call	58
106	24.03.2023	Stadtwerke Düsseldorf	Division Manager	Municipal Utility	Telephone	34
107	26.05.2023	Kyros Hydrogen Solutions	Sales	Private Company	Telephone	54
108	01.06.2023	Lingl	Head of Technology Development	Private Company	Video Call	42
109	26.06.2023	Verein Deutscher Zementwerke	Division Manager	Association	Video Call	59
110	01.08.2023	EWE Netze	Division Manager	Private Company	Telephone	27
111	10.08.2023	Verein Deutscher Zementwerke	Division Manager	Association	Written Communication	-
112	08.09.2023	OGE	Senior Account Manager	Private Company	Telephone	53

Interviews in Namibia

Nr.	**Date**	**Organisation**	**Position**	**Actor Type**	**Medium**	**Duration in Minutes**
1	11.02.2023	Lüderitz Town Council	CEO, Strategic Executive Finance, Environmental Health Inspector	Executive	In Person	106
2	13.02.2023	Daures Green Hydrogen Village	Business Development Manager	Private Company	In Person	82
3	14.02.2023	Namibian Development and Investment Promotion Board	Head of; Green Hydrogen Commissioner; Ministerial Representatives; Financing Officer	Economic Development Agency	In Person	125
4	15.02.2023	Economic Association Namibia	Managing Director	Association	In Person	71

5	16.02.2023	Institute for Public Policy Research (IPPR)	Research Associate	Civil Society	Video Call	67
6	19.04.2023	SASSCAL	Managing Director	Public Agency	Video Call	43

Interviews in South Africa

Nr.	Date	Organisation	Position	Actor Type	Medium	Duration in Minutes
1	07.02.2023	WWF South Africa	Energy Analyst & Project Officer	Civil Society	In Person	59
2	08.02.2023	HYENA	CEO	Private Company	In Person	110
3	08.02.2023	University of Cape Town	Professor	Academia	Video Call	59
4	09.02.2023	Freeport Saldanha	Division Manager	Economic Development Agency	In Person	83
5	10.02.2023	Namaqua Engineering	CEO	Private Company	In Person	42
6	20.02.2023	move consulting	Senior Consultant	Private Company	In Person	34
7	20.02.2023	Afrox South Africa	Division Manager	Private Company	In Person	42
8	20.02.2023	Development Bank of Southern Africa	Investment Lead	Development Bank	Video Call	49
9	21.02.2023	Ubuntu Green Hydrogen	CEO	Private Company	In Person	45
10	22.02.2023	PARI (Public Affairs Research Institute)	Division Manager	Academia	In Person	70
11	23.02.2023	RebelGroup	Senior Consultant	Private Company	In Person	77
12	23.02.2023	South African Wind Energy Association (SAWEA)	Senior Consultant	Association	In Person	55
13	23.02.2023	GIZ	Divison Manager	Public Agency	In Person	30
14	27.02.2023	The Presidency of South Africa	Investment Officer	Government	In Person	74
15	27.02.2023	Industrial Development Corporation (IDC)	Team Lead	Economic Development Agency	In Person	82
16	28.02.2023	Sasol Energy	Division Manager	Private Company	In Person	46
17	28.02.2023	Enertrag South Africa	Project Developer	Private Company	Video Call	53
18	23.02.2023	KfW	Junior Sector Coordinator	Development Bank	In Person	48
19	27.03.2023	GreenCape	Project Coordinator	Civil Society	Video Call	43

20	03.04.2023	JustShare	Non-Executive Director	Civil Society	Video Call	49

Participant Observations

Nr.	Event Name	Organizer	Date
1	Nationale Wasserstoffkonferenz	BMVI & NOW GmbH	20.01.2021
2	Klimaschutz im Verkehr braucht reFuels	Ministerium für Verkehr Baden-Württemberg	11.02.2021
3	Bremer Donnerstag - „Wasserstoff im Hafen als Teil des Green Deal“ (März 2021)	swb	04.03.2021
4	European Green Deal & RED II – Impact on German Energy Policy and Industry	EEHH	21.03.2021
5	„Wasserstoff – zentraler Baustein für eine CO_2-neutrale Wirtschaft?“	Wirtschaftsbeirat Bayern	14.04.2021
6	The Potential for a German Danish Hydrogen Network	Gasunie & Energinet	25.05.2021
7	Online Live-Diskussion: Geesthacht - mit Wasserstoff in die Zukunft / DLR, Hereon & Stadt Geesthacht	Hereon Institut DLR Geesthacht	18.06.2021
8	Hydrogen Hub Aachen: Startschuss für das Wasserstoff-Netzwerk	Hydrogen Hub Aachen	28.06.2021
9	Hydrogen Potentials in the Ruhr Metropolis - New Energy for Change!	Metropole Ruhr	27.10.2021
10	DUH Großwärmepumpen	DUH	09.11.2021
11	FVEE Tagung	FVEE	10.11.2021
12	2. Lausitzer Fachkonferenz – Klimaneutrale Industrie	kei Cottbus	11.11.2021
13	Auf dem Weg zur H2 Roadmap- Wasserstoff Kompass Workshop	Wasserstoff Kompass	22.02.2022
14	Theen Great H2 Workshop	ThEEn	24.02.2022
15	H2-Meetup Region Hannover	Region Hannover Wirtschaftsförderung	03.03.2022
16	HyLunch: HyExpert Frankfurt Mainova	NOW GmbH	03.03.2022
17	H2UB Deep Dive #1: Startup-Meeting	H2UB	04.03.2022
18	Invest.RUHR - Innovationstransfer Wasserstoff	Metropole Ruhr	08.03.2022
19	6. Wasserstoff-Netzwerktreffen	IHK Schwaben (Bayerisch Schwaben)	08.03.2022
20	1. Netzwerktreffen "DurcH2atmen - Wasserstoffnetzwerk Lausitz"	Wasserstoffnetzwerk Lausitz / IHK Cottbus	09.03.2022
21	Abschlussworkshop des HYPOS-Forschungsprojekts H2 Großspeicher	HYPOS Netzwerk / INZIN Institut	10.03.2022
22	HyLunch Episode 11: HyExpert-Ergebnisse LK Osterholz (H2.N.O.N.)	Landkreis Osterholz / NOW GmbH	10.03.2022
23	Energiesysteme und Nachhaltigkeit	Energiecampus Nürnberg und nkubator Nürnberg	10.03.2022
24	Minori 3 Hydrogen Activities in Kobe	wokobe.eu	15.03.2022

25	Innovative Wasserstofftechnologien für die klimaneutrale Industriegesellschaft der Zukunft	IHK Oberfranken Bayreuth	16.03.2022
26	Geopolitics of the Energy Transformation: The Hydrogen Factor	IRENA	22.03.2022
27	"Wasserstoffregionen stellen sich vor – Förderaufruf HyLand (BMDV)“	Thüringer Energie- und GreenTech-Agentur GmbH (ThEGA), der Landesenergieagentur Sachsen-Anhalt GmbH (LENA) und der Sächsischen Energieagentur – SAENA GmbH	24.03.2022
28	Vollversammlunge Forschungsnetzwerk Wasserstoff	Acatech	31.03.2022
29	Alternative Kraftstoffe und Antriebe	Maritimes Cluster Norddeutschland	31.03.2022
30	Energiewende mit grünem Wasserstoff	Hydrogen Hub Aachen	04.04.2022
31	ChemSite meets Wasserstoffkoordination Emscher-Lippe (Lhyfe: Regionale Erzeugung von grünem Wasserstoff in industriellen Maßstäben)	ChemSite x Wasserstoffkoordination Emscher Lippe	06.04.2022
32	Tag der offnenen Tür Wasserstoffdorf Bitterfeld	DBI, MitNetz, Hochschule Leipzig	13.04.2022
33	Berliner Energietage	Pöschk GmbH	01.05.2022
34	Wunsiedler Wasserstofftage	Landkreis Wunsiedel	01.07.2022
35	Deutsche Wasserstoffvollversammlung	NOW GmbH	06.07.2022
36	Marktkonsultation	H2 Global	15.07.2022
37	Saubere-Fahrzeuge-Beschaffungs-Gesetz	EMEVO	21.07.2022
38	"Regenerative Kraftstoffe - unverzichtbare Maßnahme zur Reduktion der Treibhausgasemissionen."	VDI	27.09.2022
39	Netzwerktreffen Forschungsnetzwerk Wasserstoff	Forschungsnetze Energie	10.10.2022
40	Strukturwandel in der Lausitz: Wege zum Erfolg?	PtX Lab Lausitz	17.11.2022
41	Hydrogen Coffee VII	H2 Region Emsland	02.12.2022
42	Wirtschaftlichkeit von Wasserstoff- und Brennstoffzellentechnologien in der dezentralen Energieversorgung	Exportinitiative Umweltschutz NOW GmbH	07.12.2022
43	Berliner Energietage	Pöschk GmbH	03.05.2023
44	KEI Podium "Carbon Management"	KEI Berlin	28.09.2023
45	First IPCEi Conference	BMWK	06.12.2023

Analyzed Documents

EU

Complete analysis of all submissions to the consultation process:

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South Africa

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