Hydrogen (H_2) is rapidly gaining prominence in global climate strategies, especially for decarbonizing hard-to-abate sectors like heavy industry, freight transport, and aviation. Within this context, Northwestern Europe has positioned itself as a frontrunner, advancing an ambitious agenda centered on large-scale hydrogen imports. While policy and acade mic debates often frame hydrogen through technical and economic lenses, this dissertation reveals its deeply political character. Drawing on a socio-technical and constructivist approach, it examines hydrogen not as a neutral energy carrier but as a system shaped by historical legacies, infrastructures, actors, and power dynamics. Focusing on energy security, the dissertation explores how aspects of environmental sustainability, economic interests, national security strategies, and justice imperatives compete and intersect in shaping the hydrogen trade landscape. Ultimately, this dissertation argues that hydrogen occupies contested ground: will it prove to be a miracle—catalyzing a just and green transformation of carbon-intensive sectors and contributing to global justice—or a mirage, preserving the status quo beneath the veneer of a green transition?

GHENT UNIVERSITY

BE-HyFE
Belgian Hydrogen Fundamental Expertise

Marie Dejonghe

A MIRACLE OR MIRAGE?

2025

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Explaining the energy security implications of large-scale hydrogen imports into Northwestern Europe

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Supervisor: **Prof. dr. Thijs Van de Graaf**
Co-supervisor: **Prof. dr. ir. Ronnie Belmans**

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Abbreviations

ALK	Alkaline
APERC	Asia Pacific Energy Research Centre
BNEF	BloombergNEF
BRI	Belt and Road Initiative
CfD	Contract for difference
CC(U)S	Carbon capture (utilization) and storage
CH_3OH	Methanol
CH_4	Methane
CO_2	Carbon dioxide
CPI	Corruption Perceptions Index
CRM	Critical raw materials
DAC	Direct air capture
DRI	Direct reduced iron
ECDPM	European Centre for Development Policy Management
ECOWAS	Economic Community of West African States
ENTSOG	European Network of Transmission System Operators for Gas
EU	European Union
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
FID	Final investment decision
GEST	Global Energy System Transformation
GHG	Greenhouse gases
GVC	Global Value Chains
GW	Gigawatt
H_2	Hydrogen
IDOS	German Institute of Development and Sustainability
IEA	International Energy Agency
IPE	International Political Economy
IPCEI	Important Project of Common European Interest
IR	International Relations
IRA	Inflation Reduction Act
IRENA	International Renewable Energy Agency
LCA	Life-cycle assessment
LCR	Local content requirement
LNG	Liquified natural gas

LOHC	Liquid organic hydrogen carrier
MCA	Multi-criteria analysis
MENA	Middle East and Northern Africa
MLP	Multi-level-perspective
MoU	Memorandum of Understanding
Mt	Million tons
MWe	Megawatt electrical
MWh	Megawatt hours
NGHRI	Namibia Green Hydrogen Research Institute
NH_3	Ammonia
NASA	National Aeronautics and Space Administration
NO_x	Nitrogen oxide
NWE	Northwestern Europe
NZIA	Net Zero Industrial Act
PEM	Proton Exchange Membrane
PGM	Platinum Group Metals
PV	Photovoltaic
R&D	Research and Development
SGI	Sustainability and Governance Index
SMR	Steam methane reforming
SOE	State-owned enterprise
SOEC	Solid Oxide Electrolyzer
STS	Science and Technology Studies
TSO	Transmission System Operator
TWh	Terawatt hours
UN	United Nations
UNIDO	United Nations Industrial Development Organization
USSR	Union of Soviet Socialist Republics
WSC	Wall Street Consensus
WSI	Water stress index

Abstract - English

Hydrogen (H_2) has re-emerged as a key component in global climate neutrality strategies, particularly for 'hard-to-abate' sectors such as heavy industry, freight transport, and aviation. Within this context, Northwestern Europe (NWE)—a central player in the EU's hydrogen strategy—has prioritized large-scale hydrogen imports which places the region at the forefront of shaping emerging hydrogen trade regimes.

Existing policy and academic analyses emphasize technical and economic factors, such as cost competitiveness and technology readiness, while largely neglecting the political, historical, and societal forces that shape hydrogen import strategies. As a result, the emerging hydrogen trade regime is frequently seen as a technocratic and apolitical endeavor, obscuring its contested and deeply political nature. This dissertation addresses this analytical gap by asking: What are the energy security implications of large-scale hydrogen imports into Northwestern Europe?

Drawing on a socio-technical and constructivist framework, hydrogen is examined not as a neutral energy vector but as a system shaped by technologies, infrastructures, regulations, and actors. Within this framework, energy security is understood as a dynamic and multidimensional concept, encompassing national security, the economy, environmental sustainability, and justice. To further interrogate how these dimensions unfold in the context of hydrogen imports, this dissertation advances three explanatory logics—path dependency, actor-based dynamics, and geo-economic power struggles—that together illuminate the historical, institutional, and geopolitical forces shaping the evolving hydrogen trade landscape.

The findings showcase that all four dimensions play an important role in shaping the energy security implications of hydrogen imports in NWE. However, these dimensions do not always align, leading to trade-offs, and their relative importance has evolved over time. Early import strategies focused on environmental sustainability goals, while recent policies have increasingly highlighted national security and economic perspectives. In contrast, justice concerns continue to be largely overlooked, revealing a significant gap in current hydrogen import strategies. These changing priorities are the result of long-lasting path dependencies, fossil fuel incumbent's interests, and the intensifying geo-economic power relations.

The dissertation adds four broader reflections to the discussion on hydrogen imports. First, it argues that the narrative of large-scale hydrogen imports into NWE increasingly resembles a political mirage rather than a material reality. Second, it links this illusion to the outsized influence of industrial players, who impede critical scrutiny of the assumptions underpinning import strategies. Third, it contends that hydrogen is being strategically deployed as a "Trojan horse" to maintain fossil fuel dependencies while simulating climate progress. Fourth, it warns that the EU's obsession with hydrogen imports functions as a distraction from a more fundamental debate on the future orientation of its industrial base and the trade-offs such a transition entails.

In sum, this dissertation reveals that hydrogen's trajectory and energy security implications are deeply political, shaped by a dense web of actors, historical legacies, and geo-economic power struggles. Whether hydrogen becomes a lever for transformative change or a green façade for preserving the status quo will ultimately depend on whose interests are served and who gets to shape the outlook of a hydrogen future.

Abstract - Nederlands

Waterstof (H_2) wordt naar voren geschoven als een belangrijke pijler in de globale transitie naar klimaatneutraliteit. Waterstof heeft het potentieel om moeilijk te verduurzamen sectoren klimaatneutraal te maken, bijvoorbeeld de zware industrie, vrachtvervoer en luchtvaart. In deze context plant Noordwest-Europa (NWE)—een belangrijke regio in de waterstofstrategie van de Europese Unie—om op grootschalig niveau waterstof te importen. Bijgevolg bevindt NWE zich in een sleutelpositie in het vormgeven van de opkomende globale waterstofhandel.

De bestaande academische en beleidsanalyses richten zich voornamelijk op de techno-economische aspecten van waterstof, ze focussen bijvoorbeeld op de economische concurrentiekracht of de technologische haalbaarheid van deze technologie. De politieke, maatschappelijke en historische dynamieken die aan de basis liggen van de importstrategieën blijven in deze studies veelal onderbelicht. Hierdoor wordt de opkomende waterstofhandel vaak voorgesteld als technocratisch en apolitiek, wat de onderliggende machtsverhoudingen en spanningsvelden dreigt te maskeren. Dit proefschrift haakt in op dit hiaat door volgende centrale onderzoeksvraag te beantwoorden: Wat zijn de implicaties van grootschalig waterstof import voor de energiezekerheid in Noordwest-Europa?

Om deze onderzoeksvraag te beantwoorden hanteert dit proefschrift een sociaal-technisch en constructivistisch analytisch kader. Waterstof wordt hierin niet beschouwd als een neutrale energiedrager, maar als een sociaal-technisch systeem dat wordt gevormd door een configuratie van technologieën, infrastructuur, regelgeving en actoren. Verder wordt 'energiezekerheid' opgevat als een multidimensionaal en dynamisch concept, dat bestaat uit vier onderling verweven, dimensies: nationale veiligheid, economie, duurzaamheid en rechtvaardigheid. Daarnaast worden drie verklarende logica's geïntroduceerd: padafhankelijkheden, actoren, en geo-economische machtsverhoudingen. Gezamenlijk werpen deze logica's een licht op de historische, institutionele en geopolitieke krachten die de veranderende rol van waterstofimport bepalen.

De analyse toont aan dat alle vier de dimensies een rol spelen in het vormgeven van de energiezekerheid implicaties van waterstofimport in NWE. Deze dimensies zijn echter niet altijd op elkaar afgestemd, wat leidt tot dilemma's, en hun onderlinge verhoudingen zijn in de loop der tijd verschoven. Waar het prille beleid hoofdzakelijk werd gedreven door duurzaamheidsoverwegingen, leggen de recente strategieën de nadruk op nationale veiligheid en economische belangen. Daarentegen blijft de dimensie van rechtvaardigheid grotendeels onderbelicht, wat wijst op een lacune in het huidige beleid rond waterstofimports. Deze veranderende prioriteiten zijn het resultaat van langdurige padafhankelijkheden, de belangen van de bestaande fossiele brandstofbedrijven, en een toenemende geo-economische machtsstrijd.

Verder, voegt dit proefschrift vier bredere reflecties toe aan het debat rond waterstofimport. Ten eerste stelt het dat grootschalige waterstofimport in NWE steeds meer op een illusie lijkt dan op een materiële realiteit. Ten tweede wordt deze illusie in verband gebracht

met de disproportionele invloed van industriële belangen, die kritische reflectie over de onderliggende aannames van importstrategieën belemmeren. Ten derde betoogt het onderzoek dat waterstof strategisch wordt ingezet als een “Trojaans paard” om fossiele afhankelijkheid in stand te houden onder het mom van klimaatactie. Ten vierde waarschuwt het dat de Europese obsessie met waterstofimports afleidt van een fundamenteler politiek debat: de toekomst van de Europese industrie en de bijbehorende maatschappelijke keuzes die moeten worden gemaakt.

Kortom, dit proefschrift onthult dat het vormgeven van internationale waterstofhandel en de gevolgen voor energiezekerheid in NWE niet plaats vinden in een politiek vacuüm, maar midden in een complex web van actoren, historische erfenissen van fossiele brandstof infrastructuur en een geo-economische machtsstrijd. Of waterstof al dan niet zal fungeren als een katalysator voor een groene transformatie van het energiesysteem, zal uiteindelijk afhangen van wiens belangen domineren en wie zeggenschap krijgt over hoe de contouren van de toekomstige waterstofhandel er moeten uitzien.

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Tot aan de maan, en terug. Voor altijd. ♥

Marie Dejonghe
Gent, August 2025

“Le véritable voyage de découverte ne consiste pas à chercher de nouveaux paysages, mais à avoir de nouveaux yeux.”

Marcel Proust
À la recherche du temps perdu

Chapter 1. Introduction

Introduction

1.1 Introduction

Hydrogen (H_2) has re-emerged as a central pillar in the contemporary strive toward a climate neutral economy, frequently lauded as the 'Swiss Army Knife' of the energy transition. Its versatility—especially in so-called hard-to-abate sectors such as heavy industry, long-distance freight transport, and aviation—would position it as a catch-all solution to a range of decarbonization challenges. This resurgence of interest, often described as the 'hydrogen hype', has been driven by a mix of technological optimism, expansive policy advocacy, and a strong industrial push. Within this context, Europe has focused on hydrogen imports, as a strategic response to its geographic and infrastructural limitations in scaling domestic renewable electricity production as a basis for green hydrogen.

The current momentum around hydrogen cannot be disentangled from the broader global dynamics reshaping the European energy landscape. The Russian full-scale invasion of Ukraine in February 2022 marked a decisive rupture, laying bare Europe's acute dependence on (particularly Russian) natural gas imports and exposing critical vulnerabilities in its energy security architecture. In response, European policymakers are reconfiguring their energy strategies, by emphasizing industrial resilience, strategic autonomy, and the diversification of energy partnerships.

Despite these shifts, policy and much of the academic debate continue to frame hydrogen imports primarily through techno-economic lenses. Dominant analyses tend to focus on cost competitiveness and technology readiness, sidelining the fundamentally political nature of emerging hydrogen trade regimes. Such perspectives risk sanitizing what is, in fact, a deeply contested terrain—one marked by geopolitical asymmetries, strategic dependencies, and justice implications. By foregrounding technical feasibility over political complexity, these narratives may inadvertently reinforce the very dynamics of the existing energy system that a just energy transformation seeks to overcome.

This dissertation intervenes in this debate by offering a more critical and politically attuned analysis of hydrogen imports. It approaches hydrogen not as a neutral, technical fix, but as a socio-technical system shaped by power, interests, and contestation. By reframing hydrogen as a site of political struggle rather than a purely technological challenge, the study aims to deepen our understanding of large-scale hydrogen imports as a fundamentally political process.

Before turning to this analysis, a brief technical overview is necessary to outline the key characteristics and roles of hydrogen within the broader landscape of the clean energy transformation.

1.2 Hydrogen: a technical portrait

An important distinction should be made between hydrogen (H) as an atom and hydrogen (H_2) as a molecule. As a single atom, hydrogen is by far the most abundant chemical element in the universe, accounting for approximately 75% of its total mass. However, its molecular form (H_2), in which two hydrogen atoms are bonded without any other element involved, is comparatively scarce. On Earth, molecular hydrogen is seldom found in pure form; instead, it is predominantly found chemically bound within compounds such as water (H_2O) and hydrocarbons like methane (CH_4). Isolating pure hydrogen from these compounds necessitates considerable energy input, making it an energy-intensive process. It is this molecular form of hydrogen— H_2—that constitutes the focus of this dissertation.

Hydrogen production methods are often classified using a color-coded taxonomy —as exemplified in Box 1, each denoting a specific hydrogen production pathway (Incer-Valverde et al., 2023).

Box 1: Different 'shades' of hydrogen

Brown hydrogen (made from brown coal) and **black hydrogen** (made from black coal) is hydrogen produced via gasification of coal.

Grey hydrogen is hydrogen produced from natural gas through steam methane reforming of natural gas releasing a lot of CO_2.

Blue hydrogen is hydrogen produced through steam methane reforming of natural gas combined with carbon capture and utilization/storage.

Green hydrogen is hydrogen produced from the electrolysis of water powered by renewable electricity.

Turquoise hydrogen is hydrogen produced from pyrolysis of natural gas, with solid carbon as a by-product.

Pink hydrogen is hydrogen produced from the electrolysis of water powered by nuclear electricity.

Gold or white hydrogen is natural hydrogen that is formed through natural processes and can be found in the Earth's crust.

Currently, the dominant form of hydrogen production is grey hydrogen, accounting for approximately 99% of global supply. This method, which typically involves steam methane reforming without carbon capture, is highly carbon-intensive: its associated CO_2 emissions on a global scale are comparable to the combined annual emissions of France and Indonesia (IEA, 2024c).

In contrast, blue and green hydrogen represent cleaner alternatives with lower CO_2 emissions. Blue hydrogen is produced from fossil fuels, predominantly natural gas or coal, but incorporates carbon capture, utilization, and storage (CCUS) to mitigate the associated CO_2 emissions[1]. Green hydrogen, meanwhile, is produced through the electrolysis of water powered by renewable electricity. When carbon capture rates are sufficiently high and methane leakages sufficiently low, both blue and green hydrogen are categorized as low-carbon or clean hydrogen[2]. Additional, but less important, color-coded production methods are outlined in Box 1.

Hydrogen is primarily utilized as feedstock in heavy industrial applications, including crude oil refining, ammonia synthesis for fertilizer production, methanol production, and steel manufacturing. In 2023, global hydrogen demand reached 97 million tons (Mt), with nearly all consumption concentrated in these industrial sectors. Regionally, China emerged as the largest consumer, responsible for almost one-third of global demand—twice the consumption of the United States, the second-largest user. Europe accounted for approximately 8% of global consumption (IEA, 2024c).

Beyond traditional applications, hydrogen can also serve as a chemical 'energy carrier' or 'energy vector,' distinguishing it from primary 'energy sources' like crude oil or natural gas. In 2023, energy-related applications accounted for less than 1% of global hydrogen use (IEA, 2024c). Notably, hydrogen possesses a high specific energy, with one kilogram containing nearly four times the energy content of a kilogram of natural gas. In contrast, due to its extremely low volumetric density, approximately four times the volume of hydrogen is required to match the energy content of natural gas in terms of volume.

Box 2: Electrolyzers vs fuel cells

Electrolyzers are devices that use electricity to split water into hydrogen and oxygen with the following reaction: $2\ H_2O + 2\ e^- \rightarrow H_2 + 2\ OH^-$

Fuel cells are devices that electromechanically convert hydrogen into electricity through oxidation, in the following reaction: $2H_2 + O_2 \rightarrow 2H_2O$ + electricity + heat.

When used in combustion engines or fuel cells, hydrogen releases energy with water vapor as the sole by-product, making it a zero-carbon energy carrier[3]. There exist different types of electrolyzers and fuel cells. The key differences between electrolyzers and fuel cells are described in Box 2.

1 In addition to the carbon dioxide emissions generated during steam methane reforming, the production of blue hydrogen also carries significant risks of fugitive methane emissions—an often overlooked but critical issue, given that methane is a potent greenhouse gas with a global warming potential significantly higher than that of carbon dioxide (Howarth & Jacobson, 2021)

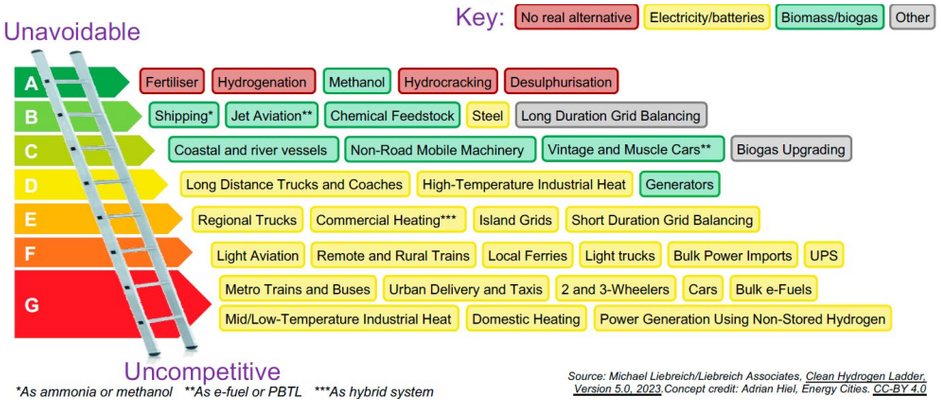
2 It is important to emphasize that hydrogen also affects global greenhouse gas emissions. Although hydrogen is not a greenhouse gas itself, its chemical interactions in the atmosphere can influence the concentrations of other greenhouse gases. As such, minimizing hydrogen leakage will be critical to achieving the anticipated climate benefits of a transition to a hydrogen-based economy (Sand et al., 2023).

3 Combusting hydrogen at high temperatures produces nitrogen oxide (NOx). The NOx that is emitted can be a significant source of air pollution.

As an energy carrier, hydrogen supports a range of emerging applications. It can be blended into natural gas networks for heating, used in fuel cell electric vehicles (FCEV), converted into synthetic fuels such as e-kerosene, or reconverted into electricity via fuel cells. This way, hydrogen is a key enabler of 'sector coupling', establishing links between hitherto separated energy systems in transportation, heating and electricity.

However, the use of hydrogen for energy applications remains very inefficient and energy-intensive compared to direct electrification. Many experts therefore argue that indiscriminate use of hydrogen will slow down the energy transition. To highlight this, Michael Liebreich (2023) developed the hydrogen ladder (see Figure 1), which ranks end-use applications based on their suitability for hydrogen. At the top are essential applications, such as fertilizer production and heavy industry, while lower tiers include sectors better served by more efficient alternatives, such as direct electrification via battery electric vehicles or heat pumps.

Figure 1: Hydrogen ladder based on Liebreich (2023)



1.3 Toward an international hydrogen market

While the majority of hydrogen is currently produced and consumed on-site, there is potential for hydrogen to develop into a globally traded energy commodity over time. Despite its relatively low energy density per unit volume—which renders it considerably more costly and technically challenging to transport compared to fossil fuels or electricity—various methods are emerging for enabling long-distance transport.

According to IRENA (2022a), pipelines represent the most cost-effective means of pure hydrogen transport over distances up to 4,000 kilometers. When existing natural gas pipelines are repurposed for hydrogen use, this cost-effective range can extend to approximately 8,000 kilometers. To contextualize these distances, a pipeline from Brussels to Sevilla would span roughly 2,000 kilometers, while a route between Algiers, Algeria, and Dakar, Senegal, would cover around 4,000 kilometers. For transport beyond these distances, maritime shipping of hydrogen becomes the more economically viable option.

At present, approximately 500 kilometers of dedicated hydrogen pipelines are operational in regions such as NWE, the United States, and Russia (IEA, 2024c), and the expansion of this network is anticipated. However, one potentially more expedient approach involves repurposing existing natural gas infrastructure to accommodate hydrogen transport. This strategy presents significant technical and economic challenges. Pure hydrogen can cause embrittlement and degradation of steel, necessitating a case-by-case assessment and costly retrofitting.

Maritime transport of hydrogen also involves substantial technical hurdles. To transport hydrogen in liquid form via tanker, it must be cooled to -253°C—a process that is markedly more energy-intensive than the liquefaction of natural gas, which requires cooling only to -160°C. Consequently, it is often more efficient to convert hydrogen into a carrier or derivative, such as methanol or ammonia (see Box 3), for long-distance shipping.

Box 3: Main hydrogen carriers and derivatives

Methanol: Hydrogen can be converted into methanol by combining it with CO_2 which can be both used from CCU or from direct air capture and can be used as a means of transporting hydrogen as a liquid without cooling. It is very similar to oil products and therefore similar infrastructure can be used.

Ammonia: Hydrogen can be converted into ammonia by combining it with nitrogen from the air. It has a higher volumetric energy density, which makes it possible to trade larger volumes of energy. Ammonia is already a globally traded commodity often used to produce fertilizers.

Liquid organic hydrogen carrier (LOHC): Hydrogen can be converted into a LOHC that can absorb and release hydrogen through chemical reactions. LOHCs are potentially cheap, safe, and easily manageable. Moreover, they allow for a long-term energy storage without boil-off or other hydrogen losses. However, the technology readiness level of LOHC is still low.

Synthetic or e-fuels: Hydrogen can be converted into synthetic or e-fuels by combining hydrogen with carbon dioxide. E-fuels are a synthetic version of fossil fuels. These come in different forms such as diesel, petrol, kerosene or LNG.

To date, international hydrogen trade has been limited to a handful of pilot shipments as shown in Table 1. However, IRENA (2022a) projects that by 2050, approximately one-third of green hydrogen production will be traded across borders. Their projection is normative, starting with the Paris Agreement's 1.5°C goal and outlining potential pathways to achieve this target. This projected share slightly exceeds the current global trade share of natural gas, which stands at around one-quarter. Of the hydrogen expected to be traded in 2050, about half is anticipated to be transported via pipelines, while the remaining half would be shipped over long distances, most likely in the form of hydrogen carriers. This projected trade structure could potentially mirror that of natural

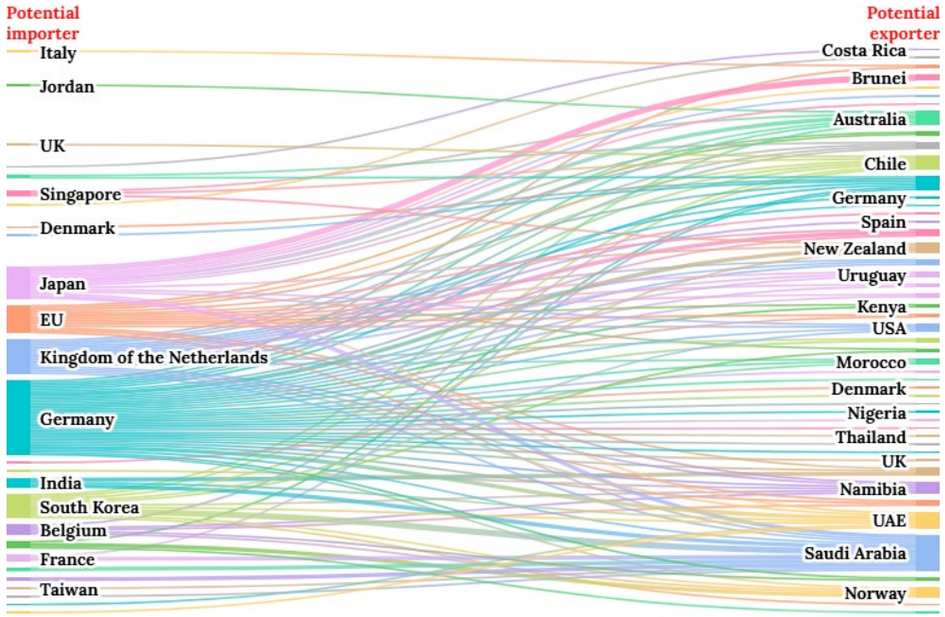
gas today, where roughly equal shares are transported through pipelines and as LNG. However, it remains to be seen whether this will materialize in the coming decades.

Table 1: Overview of hydrogen pilot shipments (2020–2024) based on news reports, government documents and official statements

Year	Exporter	Importer	Carrier
2020	Australia	Japan	Liquid brown hydrogen
	Brunei	Japan	Blue LOHC
	Saudi Arabia	Japan	Blue ammonia
2022	Brunei	Japan	Blue LOHC
	Saudi Arabia	South Korea	Blue ammonia
	United Arab Emirates	Germany	Blue ammonia
2023	Chile	United Kingdom	Blue synthetic gasoline
	Egypt	India	Green ammonia
	Saudi Arabia	Bulgaria	Blue ammonia
	Saudi Arabia	China	Blue ammonia
	Saudi Arabia	EU	Blue ammonia
	Saudi Arabia	India	Blue ammonia
	Saudi Arabia	Japan	Blue ammonia
	Saudi Arabia	South Korea	Blue ammonia
	Saudi Arabia	Taiwan	Blue ammonia
	The Netherlands	Germany	Green ammonia
2024	United Arab Emirates	Japan	Blue ammonia
	Norway	Sweden	Green ammonia
	Australia	Fiji	Liquid green hydrogen
	Australia	Indonesia	Liquid green hydrogen

Although international hydrogen trade remains in its early stages and is currently limited to pilot shipments, a variety of bilateral agreements have been established since 2018 to initiate the development of a global hydrogen market. These agreements vary widely in scope—from preliminary technical feasibility studies, such as those between Iceland and the Netherlands, to more advanced partnerships like the one between Belgium and Oman. Most of these arrangements take the form of memoranda of understanding (MoUs) or letters of intent, which generally carry limited legal obligations. Since 2018, over 130 bilateral agreements have been signed, reflecting the growing momentum of international hydrogen diplomacy as exemplified in Figure 2.

Figure 2: Overview of prospective bilateral hydrogen deals (2018–May 2025)



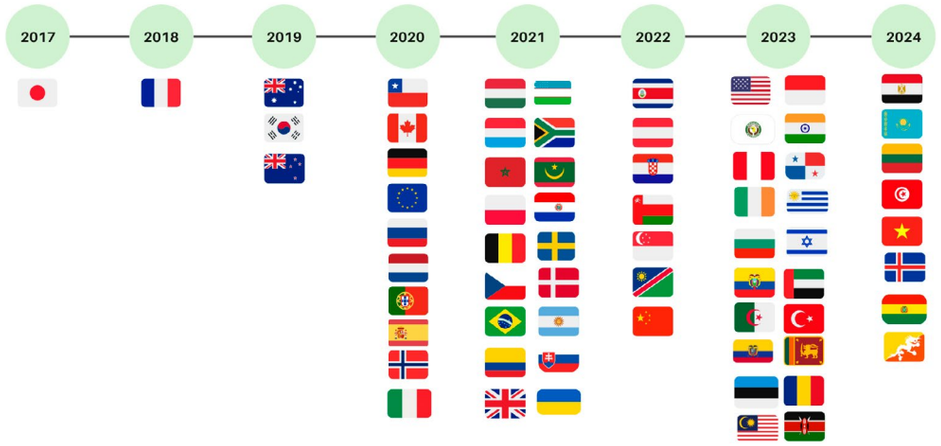
Source: author's own database based on news reports, government documents and official statements

1.4 Redrawing the geopolitical map

The global shift toward international hydrogen trade raises questions about energy security. Since 2017, at least 66 national governments—along with the EU and ECOWAS—have adopted dedicated hydrogen strategies, as illustrated in Figure 3. These strategies differ widely in scope but generally emphasize domestic hydrogen potential, clarify the country's ambition as an importer or exporter, and set out both short- and long-term policy measures to support hydrogen development.

Japan was the first country to introduce a national hydrogen strategy in 2017, which was updated in 2023 (METI, 2023). Its primary objective is to establish Japan as a 'hydrogen society' by promoting the use of hydrogen across key sectors such as transportation, power generation, and heavy industry. As an early mover, Japan has played a pioneering role in shaping the international hydrogen market, including facilitating the first hydrogen shipment from Australia—although the hydrogen involved was derived from unabated fossil fuels. In a similar vein, South Korea emerged as a key player, particularly through its ambition to become a global leader in hydrogen FCEV's.

Figure 3: Hydrogen strategies announced by country and year (2017–2025)



Source: author's own elaboration based on Corbeau & Nassif (2025)

In Europe, hydrogen plays a central role in the European Green Deal, which was introduced in 2019 (European Commission, 2020c). The EU's dedicated hydrogen strategy, launched in 2020, focuses on 'renewable hydrogen'[4]. In its first version, the hydrogen strategy foresaw 40 GW by 2030 installed capacity of electrolyzers in Europe, complemented with imports (European Commission, 2020a). However, following the Russian invasion of Ukraine, the strategy was updated with the introduction of the 'Hydrogen Accelerator' under the REPowerEU plan. This updated plan targets the production of 10 million tons (Mt) of green hydrogen domestically by 2030, with an equal volume to be imported (European Commission, 2022a). However, these targets have proven to be highly overestimated and unrealistic.

Meanwhile, the immense renewable energy potential in the Global South has sparked a wave of interest in large-scale green hydrogen production aimed at export. Countries including Mauritania, Namibia, Egypt, Morocco, South Africa, and Chile are pursuing ambitious projects to produce and export green hydrogen, particularly to energy-constrained regions in the Global North that lack sufficient renewable resources. In this case, hydrogen trade offers a unique opportunity for economic development, green industrialization, and value creation in the Global South, breaking historical cycles of underdevelopment.

At the same time, hydrogen is offering a strategic transition pathway for fossil fuel–dependent economies. Countries such as Saudi Arabia and Oman in the Middle East, as well as Australia, Norway, Canada, and Russia, are increasingly viewing hydrogen as a means to diversify their energy sectors. These countries can leverage existing energy infrastructure, including pipelines, ports, and storage facilities, to position themselves as future hydrogen exporters.

4 Renewable hydrogen corresponds with green hydrogen

In this shifting energy landscape, hydrogen has the potential not only to transform global energy systems but also to reshape geopolitical and economic power structures. Over the coming decades, countries like Morocco and Chile, traditionally energy importers, may become net energy exporters by capitalizing on their renewable resources. Meanwhile, established fossil fuel exporters, including Australia, Norway, and Saudi Arabia, could maintain their global influence by transitioning from oil and gas exports to hydrogen.

However, regions with limited renewable energy resources, such as Europe and Japan, are likely to remain heavily dependent on hydrogen imports. Specifically, in NWE, countries like Germany, the Netherlands, and Belgium are set to become major import hubs for hydrogen, projected to account for up to 75% of global hydrogen imports by 2030 (IEA, 2024d). This dependence on large-scale hydrogen imports raises significant energy security concerns, potentially mirroring the geopolitical vulnerabilities and injustices of the fossil fuel era, creating new and reinforcing existing dependencies and power structures.

1.5 Research question and approach

The establishment of large-scale hydrogen imports in NWE countries raises important and complex energy security concerns. While there are ample technical and economic analyses of hydrogen trade, there has been relatively little focus on the political, societal and historical dynamics involved. The emerging hydrogen industry does not merely introduce a large variety of energy carriers and hydrogen-related products—it reconfigures international dependencies, revives longstanding concerns around energy security, and raises new questions about justice, risk, and power in the energy transition.

Therefore, this dissertation seeks to address this critical gap by posing the following overarching research question:

What are the energy security implications of large-scale hydrogen imports into Northwestern Europe?

While the research question may seem primarily focused on mapping risks, the aim of this dissertation goes further. It is not just about identifying or listing energy security implications but about understanding the context under which these concerns emerge, and how they are framed and prioritized. The goal is to explain why certain risks are seen as pressing, while others receive less attention, and how historical experience, political priorities, and international dynamics influence these risks. What this dissertation ultimately seeks to explain is not just whether hydrogen imports pose energy security risks, but how these concerns take shape, how they are framed, and why they matter—in particular political, historical, and geopolitical contexts.

Focusing on NWE, the dissertation investigates how energy security debates around hydrogen are unfolding in a context where international hydrogen trade in various forms remains nascent and contested. It explores how past dependencies on fossil fuels inform current strategies; what role bilateral partnerships and global technological competition play in shaping national import strategies? And how questions of justice

and power are articulated—or omitted—within the context of North-South energy relations. Examining these issues at this formative stage is crucial—it helps to build a more informed and just approach to governing hydrogen trade.

These questions are explored through four academic articles[5], each addressing a different part of this broader puzzle. Together, they offer a multi-dimensional view and deeper understanding of the political dynamics behind hydrogen trade and its energy security implications. The articles are guided by four sub questions, as shown in Box 4.

Box 4: Central research question and sub-questions

What are the energy security implications of large-scale hydrogen imports into Northwestern Europe?

1.
What can past experiences with natural gas imports teach us about the energy security implications of future hydrogen imports?

2.
What kinds of energy security concerns are seen as most urgent in the context of bilateral hydrogen partnerships?

3.
How are questions of fairness and power addressed —or ignored—in North-South hydrogen trade?

4.
How does global technological competition influence national hydrogen strategies and the way energy security is framed?

To address these questions, the dissertation is grounded in and contributes to an expanding body of scholarship that reconceptualizes energy—not merely as a material input or infrastructure, but as a **socio-technical system** shaped by political, economic, and societal forces. Within this framework, hydrogen is not viewed as a neutral energy carrier but as an emergent arena in which competing visions, interests, and values are negotiated. The dissertation also draws on a **multidimensional understanding of energy security**, treating it not as a static or universally defined concept, but as a prism through which broader social concerns and geopolitical priorities are articulated and contested.

5 This dissertation includes three peer-reviewed journal articles and one peer-reviewed book chapter. For consistency, all four are referred to as 'articles' throughout the text.

Before proceeding, three clarifications are necessary to delineate the research approach in this dissertation. **First**, recent market and policy developments suggest that large-scale imports of pure hydrogen molecules are becoming less likely. Instead, attention is increasingly shifted to hydrogen carriers, derivatives, and even hydrogen-based end-products such as green steel or hydrogen-based fertilizer. Accordingly, this dissertation uses the term 'hydrogen' as an umbrella term to refer to all hydrogen-containing compounds unless specified otherwise.

Second, all references to hydrogen should be understood to refer to 'clean hydrogen'—that is, hydrogen produced via electrolysis powered by renewable energy sources or from natural gas with CCS technologies with high CO_2 capture rates and low methane leakage levels. Where distinctions are relevant, the conventional color-coded classification system as discussed in Box 1.

Third, it is important to acknowledge that, while writing this dissertation in 2025, a global hydrogen market is premature. International hydrogen trade is currently limited to a small number of pilot projects and demonstration shipments. As such, this dissertation does not aim to evaluate mature trade routes. Instead, it adopts an exploratory approach—seeking to anticipate potential trajectories, identify emerging dynamics, and analyze the risks and tensions that are already beginning to shape this early-stage trade landscape.

1.6 Outline of the dissertation

Besides this introduction, this dissertation contains five chapters, each building toward a comprehensive understanding of the energy security implications of hydrogen imports in NWE. **Chapter 2** presents a literature review, drawing on three distinct yet interconnected bodies of scholarship: (1) the evolving (geo)politics of energy, (2) theoretical lenses for studying energy, and (3) hydrogen as an emerging geopolitical factor in the energy transition. Together, these strands provide a robust conceptual foundation for understanding the energy security implications of hydrogen imports.

Chapter 3 introduces the analytical framework developed to examine the energy security dimensions of hydrogen imports in NWE which consists of two pillars: a conceptual pillar and an explanatory pillar. The conceptual framework is grounded in socio-technical regime theory and a multidimensional understanding of energy security. The explanatory framework integrates three complementary logics—path dependence, actor-based, and geo-economics—to enable a nuanced, systemic analysis of the political and structural dynamics at play.

Chapter 4 outlines the research design, detailing the geographic and thematic scope of the study, the data sources, and the data analysis approach. This chapter also discusses my positionality and reflects on the PhD trajectory. It concludes with an introduction to the individual research articles that form the empirical body of the dissertation.

Chapter 5 constitutes the main body of the dissertation and includes four academic articles. Each article explores different aspects of the energy security framework de-

veloped in Chapter 3. Table 2 provides a schematic overview of the main body of the dissertation, presenting the overarching research question, the guiding sub-question for each article, the publication status and the author details.[6] A more detailed introduction to each article is provided within Chapter 4.

Chapter 6 concludes the dissertation by synthesizing key findings from the four central articles, answering the central research questions, and reflecting on the broader implications of hydrogen imports using the analytical framework established in Chapter 3. The concluding chapter closes by outlining a future research agenda and offering policy recommendations based on the dissertation's insights.

Table 2: Schematic overview of the main body of the dissertation

Central research question	**What are the energy security implications of large-scale hydrogen imports into Northwestern Europe?**			
Title	From natural gas to hydrogen: Navigating import risks and dependencies in Northwest Europe	Risky business? Evaluating hydrogen partnerships established by Germany, the Netherlands, and Belgium	Green colonialism or green transformation? The equity implications of clean hydrogen trade	The Global Hydrogen Race: Competing strategies for hydrogen technology leadership
Guiding sub-question	What can past experiences with natural gas imports teach us about the energy security implications of future hydrogen imports?	What kinds of energy security concerns are seen as most urgent in the context of bilateral hydrogen partnerships?	How are questions of fairness and power addressed —or ignored— in North-South hydrogen trade?	How does global technological competition influence national hydrogen strategies and the way energy security is framed?
Status	Published in Energy Research and Social Science	Published in Sustainability	Published in Political Geography	Under review for Handbook of Hydrogen: Challenges and Opportunities in a Decarbonizing World
Co-authored	Thijs Van de Graaf Ronnie Belmans	Single-authored	Thijs Van de Graaf	Thijs Van de Graaf

6 In accordance with Article 6 of the Doctoral Regulations of the Faculty of Political and Social Sciences (FB, 10 November 2021), a detailed overview of my contributions to each co-authored article is provided in the Appendix

Chapter 2. Literature review

Literature review

To analyze the energy security implications of hydrogen imports into NWE, this dissertation draws upon three distinct but interconnected strands of literature. First, it builds on the scholarship on the changing geopolitics of energy, examining the shift from the geopolitics of oil and gas to the emerging politics of renewables. Second, it reviews the extensive theoretical discourse on energy security, exploring its conceptualization through a wide range of analytical frameworks. Finally, it engages with the emergent literature on hydrogen as a nascent geopolitical factor in energy politics. Together, these strands of scholarly debates offer a comprehensive foundation for analyzing the energy security implications of hydrogen imports in NWE.

2.1 The changing politics of energy

The politics of oil and gas

The origins of social science research on energy can be traced back to the 1980s, largely in response to the oil price shocks of the 1970s. For example, Deese (1979) illustrated the profound political, economic, and military consequences of disruptions in oil supply. Later on, the volatility of oil prices and their effects on the global economy became a subject of scholarly inquiry (Morse, 1986; Schlesinger, 1979). In general, research into the politics of energy often mirrored fluctuations in oil prices, with heightened interest during periods of price surges and diminished attention during price declines, particularly by the late 1990s (Hughes and Lipscy, 2013). At the turn of the century, however, a resurgence of social science research on energy issues took place (Van de Graaf et al., 2016), and much of the early literature, especially concerning the international dimensions of energy, was dismissed as “descriptive, atheoretical, and noncumulative” (Wilson, 1987, p. 128).

The bulk of the research on energy politics focuses on oil (Claes, 2018; Klare, 2004; Morse, 1986; Painter, 2014; Yergin, 1991). Ever since Winston Churchill’s decision in 1912 to run the British Royal Navy henceforth on (imported) oil instead of (domestic) coal, oil has occupied a prominent place on the political agenda worldwide (Yergin, 1991). The invention of the internal combustion engine and the mass production of Ford’s Model-T further cemented oil’s ubiquity (Maugeri, 2006). While oil traditionally dominated the study of energy politics, the 1973 Arab oil embargo led to the diversification of fuel sources, including natural gas (Victor et al., 2006). However, only in the 1980s natural gas became central to political discourses, particularly concerning Soviet gas exports to Western Europe (Högselius, 2013). Much of the subsequent research focused on Europe’s dependence on Russian natural gas imports (Correljé & van der Linde, 2006). The 2006 and 2009 gas crises, as well as the recent crisis in 2022, further underscored

gas's pivotal role in the study of energy politics (Bradshaw & Boersma, 2020; Grigas, 2017; Gustafson, 2020; Stern, 2006).

While oil and gas are central to the study of energy politics, coal and nuclear energy are two additional resources that merit discussion. In 2023, coal accounted for over a quarter of global primary energy consumption, highlighting its persisting significance in the global energy landscape (Our World in Data, 2024). However, less than 20% of global coal production is traded internationally, compared to oil, of which half of the total production is traded globally. As a result, coal markets are predominantly domestic in nature and less subject to international energy politics (Högselius, 2019). Nuclear energy, another significant energy carrier, plays a crucial role in the production of zero-carbon electricity. Unlike fossil fuels, nuclear energy requires —not only access to uranium for nuclear fission— but also the technical capacity for enrichment, the technological expertise to construct and operate reactors, creating complex political challenges surrounding its development (Siddi & Silvan, 2024)[7].

The debates in energy research are dominated by the classic paradigms of natural science and economics (Sovacool, 2014). Much of this scholarship adopts a techno-economic approach, often neglecting the societal, political, and cultural dimensions of energy use (Stern, 1986). Energy was frequently depoliticized, treated primarily as an object of policy rather than as an inherently political issue (Van Veelen et al., 2019). The last two decades, scholars begun to challenge this apolitical view of energy, arguing that energy challenges—such as securing access to energy supplies or managing the energy transition away from fossil fuels—should be understood as a social problem with technical components, rather than a simply technical issue (Mulvaney, 2020).

One of the central debates amongst academics of oil and gas politics concerns how energy resources and technologies can be used as instruments of foreign policy (see Table 3) — a practice often referred to as 'energy statecraft' (Van de Graaf & Sovacool, 2020). Due to the interconnected nature of energy trade relationships, intricate forms of energy interdependence often develop, occasionally allowing states to exploit this reliance for strategic gain—a strategy Farrell and Newman (2019, p. 43) describe as 'weaponized interdependence'. Consequently, countries might pursue war by other, often economic, means (Blackwill & Harris, 2016).

Högselius (2019) outlines five main ways countries can manipulate energy resources for foreign policy goals: manipulating energy flows, adjusting prices, and energy systems, managing ownership, and shaping public narratives. Both exporting and importing countries can use these strategies. A well-known example of export countries manipulating energy flows is the 1973 Arab oil embargo (Painter, 2014). In the context of natural gas, Russia has used its role as a major supplier to influence neighboring countries, often through more subtle tactics than full embargoes (Smith Stegen, 2011).

7 For a detailed discussion on the political economy of coal and nuclear energy see Jakob and Steckel (2022) for coal, and Brutschin and Jewell (2018) for nuclear energy.

Researchers have also studied disruptions in midstream part of the energy value chain, such as pipeline issues (Proedrou, 2023) or blockages at key maritime routes like the Strait of Hormuz (Barnes & Jaffe, 2006). This kind of energy manipulation is not limited to oil and gas—countries have also used resources like uranium and rare earth elements for strategic purposes (Högselius, 2019). Importing countries can influence energy flows too, often by imposing sanctions. A key example are the US oil sanctions on Iran, described by Van de Graaf (2013) as the "reversed" oil weapon. More recently, the EU has used similar tactics by sanctioning Russian energy after the invasion of Ukraine (Batzella, 2024).

Besides controlling energy flows, energy-exporting countries also often manipulate prices to gain political influence. A key example is Gazprom, Russia's state-owned gas company, which has been widely discussed for using gas prices as a political tool—a practice Stern (2015, p. 11) describes as "political" price setting. A recent example of this was the 2022 gas crisis, where Gazprom played a major role in pushing up gas prices across Europe (Milov, 2022).

A commonly used strategy by countries that rely on energy imports to reduce their risk from supply disruptions or price swings is diversification (Yergin, 2006). As Stringer (2008) explains, this can mean either using a mix of different energy sources or relying on a variety of energy suppliers. On the other hand, Vivoda (2009) argues that diversification alone is not a guaranteed solution. Its effectiveness depends on factors like strong political ties with other exporting countries, access to alternative energy resources and transport infrastructure, and having clear policies in place.

A third important part of energy statecraft is the strategic use of energy infrastructure. A clear example is the political controversy over the Nord Stream 2 gas pipeline (de Jong, 2023). However, energy infrastructure does not always lead to conflict. For instance, Willy Brandt's Ostpolitik showed how it can also promote cooperation (Högselius, 2013). Another well-known example is the building of East-West gas pipelines during the Cold War, which helped foster collaboration between opposing sides (Högselius et al., 2013).

As the global energy system transitions toward renewable sources, scholars anticipate that the practice of energy statecraft will evolve. The political dynamics of renewable energy have gained increasing scholarly attention, with research focusing on how state strategies might adapt to the changing energy landscape (Bazilian et al., 2017).

Table 3: Different tools of energy statecraft

Energy statecraft tool		Historical examples	Sources
Manipulating flows	**Export country**		
	Embargo's Flow disruptions	1973 Arab oil embargo Russia using gas supplies to influence neighbouring countries	Batzella, (2024); Högselius, (2019); Painter, (2014); Smith Stegen, (2011); Van de Graaf, (2013)
	Create bottlenecks: maritime choke-points & pipelines	Russia manipulating gas supplies through pipelines to Europe Control over maritime chokepoints (e.g. the Strait of Hormuz)	Barnes & Jaffe, (2006); Proedrou, (2023); Stringer, (2008); Yergin, (2006)
Manipulating prices	Adjust energy prices to influence political outcomes	Gazprom manipulating gas prices in Europe (e.g. 2022 gas crisis)	Milov, (2022); Stern, (2015)
Manipulating infrastructure	Build or invest in strategic energy infrastructure	Construction of Nord Stream 2 Cold War East-West pipelines	de Jong, (2023); Högselius, (2013); Stringer, (2008); Vivoda, (2009); Yergin, (2006)
	Build or invest in strategic energy infrastructure		
	Diversify suppliers		
	Diversify supplies		
	Sanctions	US oil sanctions on Iran EU sanctions on Russia post-Ukraine invasion	

The politics of the energy transition

In recent years, a fledgling stream of literature addresses the energy transition and its implications for global power dynamics (Hafner & Tagliapietra, 2020; Scholten, Bazilian, et al., 2020; Scholten, Criekemans, et al., 2020; Vakulchuk et al., 2020). Similar to traditional energy resources, the literature on the energy transition is predominantly driven by techno-economic and engineering studies (Scholten, 2018). The relatively limited research on the politics of renewable energy is influenced by interdisciplinary insights from various fields such as (political) geography (Bridge et al., 2013), climate politics (Dalby, 2013) or International Relations (IR) (Hafner & Tagliapietra, 2020).

Much of the research on the changing geopolitics of the energy transition is explorative, often presented as scenario mapping exercises (Bazilian et al., 2020). For example, the IRENA's (2019) report is an early attempt to fully understand the geopolitics of the energy transformation. It looks at how the rise of renewable energy and the decline of fossil fuels could affect global power relations, suggesting that this transition might change global dynamics in a way similar to the historical shift from coal to oil.

In a similar vein, Bazilian et al. (2020) present four potential scenarios for the energy transition. The first scenario, the 'Big Green Deal', envisions full cooperation among states, centered on concerted efforts to combat climate change and a wave of green globalization. The second scenario, 'Technology Breakthrough', perceives clean tech powers like the US and China as competing actors in a 'clean-tech cold war', where each block seeks to control materials essential to clean technologies and restrict access to these technologies by rival countries. This scenario could accelerate climate change mitigation efforts but also risks creating unequal access to technologies and escalating political tensions in fossil fuel-producing countries. The third scenario, 'Dirty Nationalism,' is driven by populist leaders advocating self-sufficiency, resulting in the simultaneous development of fossil fuels and renewables. The fourth scenario, 'Muddling On', predicts a business-as-usual trajectory, characterized by minimal international cooperation and a slow energy transition.

Overall, the politics of the energy transition is grounded in two primary streams of literature (Blondeel et al., 2021). The first stream focuses on the political implications of phasing out fossil fuels such as oil (Van de Graaf & Verbruggen, 2015) or natural gas (Proedrou, 2023). The second stream examines the role of renewables and other clean technologies (Vakulchuk et al., 2020). This dissertation delves deeper into the latter.

Over the past decade-and-a-half, renewable energy sources, especially wind and solar power, have experienced unprecedented growth. Projections indicate that global renewable electricity generation will exceed 17,000 TWh by 2030, representing an almost 90% increase from 2023 levels. By 2025, renewable-based electricity generation is expected to surpass coal-fired power generation, and by 2026, solar and wind power generation is forecasted to surpass nuclear power generation (IEA, 2024e). Compared to fossil fuels, the nature of renewables is fundamentally different as they are abundant. Moreover, they are not geographically dispersed in the same way as fossil fuels with both solar and wind energy being widely accessible around the world.

Given the relatively small share of renewables in the global energy mix[8] compared to fossil fuels, and the ongoing nature of the energy transition, much of the research on the politics of renewables remains speculative. It often focuses on projecting expectations and assumptions, rather than examining concrete case studies (Scholten, 2018). In other words, this emerging body of literature tends to adopt a broad, overarching perspective, rather than engaging in detailed analyses of specific countries or technologies. Furthermore, it remains largely dependent on the traditions, conceptual frameworks, and insights derived from the politics of oil and natural gas to understand the political dynamics of the energy transition.

For instance, one of the central debates in the politics of renewables revolves around the potential "peace dividend" that renewable energy could bring, compared to the fossil fuel era (IRENA, 2019, p. 55). While fossil fuels have long been a source of geopolitical conflict, many scholars point to the stabilizing potential of renewables. Månsson (2015), for example, argues that the abundance and geographical spread of renewable resources reduces the likelihood of interstate conflicts. Similarly, Overland et al. (2019, p. 9) suggest that "geopolitical drama" will stem from the decline of fossil fuels, rather than from the rise of renewables, and that the energy transition will lead to a more even distribution of geopolitical power.

However, some scholars caution that renewables might not be the panacea they appear to be. Raman (2013, p. 172) argues that renewable energy resources are becoming "fossilized," with the emerging renewable energy system mirroring the fossil fuel regime, and its accompanying geopolitical risks and tensions. Rothkopf (2009) echoes this concern, suggesting that a 'green world' might not necessarily be a safer world. Conflicts over water, minerals, and issues like green protectionism or trade wars could exacerbate geopolitical risks rather than mitigate them. In a similar vein, Braunstein et al. (2023) argue that renewables do not have a democratizing effect on states that deploy low-carbon energy systems and by extension, renewables cannot be assumed to bring peace.

This contentious debate extends into other discussions about the structure of the energy market. Some researchers believe that the decentralized nature of renewables will fundamentally reshape the energy market and make it more stable, potentially leading to more peace (Scholten & Bosman, 2016). Unlike the current fossil fuel system, which is oligopolistic with a few net-exporting countries dominating the market, renewable energy resources are more evenly distributed across the globe. This could create a more competitive market with a larger number of actors involved. Additionally, the decentralization of energy supplies could enable new business models, reduce energy poverty, promote local development, and empower communities (Scholten, 2018). However, some scholars argue that this decentralization might also lead to a more complex system with a broader and more diverse range of actors, and more potential causes of conflicts (Paltsev, 2016).

8 The majority of renewable energy in global primary energy consumption in 2023 comes from hydropower, followed by wind power, solar power, and biofuels (Our World in Data, 2024).

As renewable energy grows, the focus of energy politics shifts more toward electricity. Electricity becomes more important, leading to a more connected energy system where power producers and users are linked through regional—and possibly even global—grids (Scholten & Bosman, 2016). This interconnectedness could make more symmetric energy trade possible with electricity flowing in both directions (Overland, 2019). This would foster interdependence and make electricity less prone to conflict (Lilliestam & Ellenbeck, 2012). Some studies already explored the potential of electricity interconnection to promote energy cooperation, such as in the cases of Israel and Arab countries (Fischhendler et al., 2016) or between the EU and North Africa (Lilliestam & Ellenbeck, 2012). On the other hand, increased interconnection might also introduce risks, such as the potential use of electricity cut-offs as a foreign policy tool (Smith Stegen, 2018). Consequently, decentralization does not always reduce tensions, as geopolitical concerns can shift from energy inputs to the technologies themselves (O'Sullivan et al., 2017).

The discussion on cooperation and peace regarding renewables also intersects with concerns over new forms of dependency. Increasing attention is given to rare earth materials and so-called critical raw materials (Kalantzakos, 2020; Siddi, 2023). The rapid growth of electric vehicles (EVs), batteries, and solar photovoltaics has heightened concerns over minerals and metals essential to these clean technologies (Bazilian, 2018). Scholten, Criekemans et al., (2020) predict that competition for critical materials and technological expertise will intensify amongst countries vying for industrial leadership in clean technologies, with those controlling access to these resources becoming increasingly important. Moreover, countries will not only depend on raw materials but also the clean technologies themselves. Criekemans (2018) projects that to control these technologies and their supply chains will add a new layer to global power dynamics[9]. This shift underscores the growing importance of technological leadership and industrial capacity in shaping the politics of the energy transition. China, for instance, currently leads the clean energy race by producing and exporting solar pv panels and batteries, thereby strengthening its global influence (Van de Graaf, 2022). Table 4 organizes these debates surrounding renewable energy into themes of cooperation and competition, reflecting both the optimistic and cautious perspectives on the geopolitical implications of the energy transition.

While solar and wind energy often dominate scholarly discussions on the politics of the energy transition, other clean energy sources such as biofuels also play a significant role. For instance, in 2022, biofuels and waste contributed nearly 10% to global final energy consumption (IEA, 2022a). Biofuels—such as bioethanol and biodiesel used in the transport sector—are increasingly integrated into national decarbonization strategies. However, concerns persist about the environmental implications of bioenergy, its potential competition with food production (IRENA, 2019), and its exposure to similar supply risks as imported fossil fuels (Smith Stegen, 2018).

9 To reduce reliance on critical raw materials, recycling has emerged as a vital strategy for strengthening supply chain resilience.

Table 4: Renewables will bring more cooperation vs more competition

Theme	Cooperation	Competition	Sources
Decentralized energy market structure	More stable and distributed energy with increased energy access	Complex system with diverse actors heightening competition	Braunstein et al., (2023); Paltsev, (2016); Scholten, (2018); Scholten & Bosman, (2016)
Electricity & interconnected grids	Interdependence between supplier and off taker promoting energy cooperation	Energy cut-offs as a foreign policy via the electricity grid	Lilliestam & Ellenbeck, (2011); O'Sullivan et al., (2017); Overland et al., (2019); Scholten & Bosman, (2016); Smith Stegen, (2018)
Critical raw materials & technological	Circularity of CRM and technological innovation	Concentrated CRM supplies and technological know how	Criekemans, (2018); Kalantzakos, (2020); Scholten, Bazilian, et al., (2020); Scholten, Criekemans, et al., (2020); Siddi, (2023); Van de Graaf, (2022)

2.2 Different lenses to study energy

Scholars approach the politics of energy from various perspectives, or 'lenses', each offering unique insights. The following section explores the concept of 'energy security', a core pillar in energy politics research. Subsequently the different frameworks through which energy security can be understood are examined, including the geopolitical, economic, radical, and energy-system paradigms.

Energy security: a key pillar in global energy politics

Energy security is the most central concept in the study of energy politics. While the concept is widely used, it does lack a common and unified definition. Scholars frequently compare the concept to a 'Rorschach inkblot test' —its meaning shaped by the viewer's perspective (Sovacool, 2010). Its fluidity and malleability led to characterizations of energy security as a "slippery concept," one that can be defined across multiple dimensions, with its interpretation shifting according to country, region, timeframe, or energy source under consideration (Chester, 2010, p. 893). This definitional ambiguity is often attributed to the context-specific nature of energy security itself (Kruyt et al., 2009). Consequently, as Ciută, (2010, p. 138) argues, the term's ubiquity risks the "banalization" of the concept, potentially transforming it into an empty signifier rather than a concept that captures the complexity of its multiple dimensions.

Although a common definition of energy security is lacking, the traditional understanding is predominantly built around the concept of security of supply. For instance, the IEA (2014, p. 13), one of the most influential intergovernmental energy organizations, defines energy security as "the uninterrupted availability of energy sources at an affordable price". This market-centric definition is often reiterated in literature on energy security (Bielecki, 2002; Kruyt et al., 2009). Chester (2010) attributes this emphasis on market outcomes to the liberalization of energy markets, which treats energy security as a function of market performance.

Overall, research on energy security remains predominantly conceptual, all too often focusing on defining and identifying its characteristics rather than empirically testing these definitions. Much of literature is dedicated to introducing or adapting frameworks to conceptualize and understand energy security (Table 5). Over the past two decades, numerous frameworks have been developed for this purpose. One notable approach is the use of letter-coded systems to simplify the understanding of energy security. For example, the Asia Pacific Energy Research Centre (APERC) introduced the widely cited four 'A's' framework, which includes availability, affordability, accessibility, and acceptability (APERC, 2007). This 'alphabet' of energy security was expanded by other scholars ever since. Hughes (2009) proposed the four 'R's'— review (understanding the issue), reduce (lowering energy consumption), replace (diversifying energy sources), and restrict (limiting demand)—to capture different dimensions of energy security. Similarly, the US Department of Energy introduced a framework based on five 'S's': surety, survivability, supply, sufficiency, and sustainability (Kleber, 2009).

In addition to letter-coded frameworks, there are also various other approaches to energy security. von Hippel et al. (2011) expands the concept of energy security by introducing a conceptual framework comprising six dimensions: energy supply, economic, technological, environmental, socio-cultural and military security. Winzer (2012) developed a framework focusing on various energy security risks, such as technical, natural, and human risks. Additionally, he argues that besides assessing sources of risks, looking into the impact of the risks (scope and severity) is equally important to assess energy security.

Cherp and Jewell (2014) took a different approach by building on Baldwin's (1997) definition of international security to address energy security. Their conceptualization raises key questions, such as "security for whom?", "security for which values?", and "security from what threats?". They propose to define energy security as the "low vulnerability of vital energy systems," a perspective that helps to clarify what vital energy systems are and how these systems are either vulnerable or resilient to specific risks. Additionally, since 2010, the World Energy Council publishes the annual World Energy Trilemma Index, which expands the concept of energy security by incorporating two additional dimensions: energy equity, focusing on universal access to energy, and environmental sustainability, emphasizing the need to mitigate environmental degradation and combat climate change (WEC, 2024).

Several scholarly attempts were made to assess a country's energy security performance by introducing different sets of indicators and parameters to measure energy

security. Some of these indicators are qualitative. For example, as early as the late 1980s, Daniel Yergin (1988) identified diversification as a key indicator of energy security. Other studies employed quantitative indicators, such as the Herfindahl-Hirschman Index (Jun et al., 2009) or the Shannon-Wiener Index (Matsumoto et al., 2018). Some frameworks consolidate multiple factors into a single composite indicator (Kruyt et al., 2009) while others, such as Sovacool and Mukherjee (2011) offer a more extensive approach with over 320 indicators that researchers and policymakers can use to assess national energy security performance.

These indices are frequently applied to assess energy security across different countries and energy resources. Some studies focus on individual countries, such as the US (Greene, 2010) or China (Yao & Chang, 2014). Meanwhile, other research examines groups of countries or regions, such as Northeast Asia (Vivoda, 2010; von Hippel et al., 2011) or the EU (Matsumoto et al., 2018). A significant portion of the literature concentrates on specific energy resources. For instance, Cabalu (2010) specifically assesses energy security within the natural gas sector, while other studies focus on oil (Greene, 2010; Leiby, 2007). Overall, much of the research on gas security is catered for the EU, whereas studies on oil security predominantly focus on case studies from the US.

Table 5: Different definitions of energy security

Source	Definition
IEA (2014)	The availability of a stable energy supply at an affordable price
APERC (2007)	Four 'A's: Availability, Affordability, Accessibility, Acceptability
Hughes (2009)	Four 'R's: Review, Reduce, Replace, Restrict
Kleber (2009)	Four 'S's: Surety, Survivability, Supply, Sufficiency, Sustainability
Cherp & Jewell (2014)	Security for Whom? Which Values? From What Threats?
von Hippel et al. (2011)	Energy security consist of six dimensions: energy supply, economic, technological, environmental, socio-cultural, military security
Winzer (2012)	Energy security as technical, human and natural risks
World Energy Council (2010)	Energy trilemma: energy security, energy equity and environmental sustainability.

Finally, many perspectives exist to interpret energy security and how it can be achieved and whose responsibility it is. Many of these perspectives are rooted in longstanding intellectual traditions within the field of IR. The traditional framework in IR distinguishes between realism, liberalism, and Marxism (Gilpin, 1987): all of which have been applied to the study of energy issues. For instance, Kuzemko et al. (2015) identified four perspectives on energy security: political, economic, environmental, and technical. Similarly, Van de Graaf and Sovacool (2020) introduce an analytical framework that includes not only political, economic, and environmental perspectives but also an

egalitarian lens rooted in a (neo)Marxist approach to energy. Dannreuther (2017) refines this egalitarian approach as the radical perspective, incorporating colonial and North-South dynamics. Furthermore, he frames energy security as a value that can only be fully understood in relation to other competing values, such as economic prosperity, sustainability, and justice. The following section explores these frameworks, which are summarized in Table 6.

Table 6: Theoretical frameworks to study energy security

Kuzemko et al. (2015)	Van de Graaf & Sovocool (2020)	Dannreuther (2017)
Political Economics Environmental Technical	Neo-mercantilism Market liberalism Environmentalism Egalitarianism	Realism Liberalism Radicalism

Realist geopolitics and liberal economics

Research on energy politics is largely framed from a geopolitical perspective with a strong emphasis on national security. Klare (2004), for instance, argued that the US faces significant security threats due to its dependence on petroleum. The economic significance of oil and natural gas further elevated their importance, as they are central to national industries and overall national economic prosperity (Painter, 2014). Much of this stream of literature revolves around the concept of energy dependence which drives national interests and can lead to resource nationalism or even resource conflicts. In other words, energy security is considered of strategic national interests (Shaffer, 2009).

According to this paradigm, tensions arise between producers seeking to maximize profits and consumers looking for stable, low-cost supplies (Wilson, 2019). This geopolitical approach to energy politics aligns with realist ontological premises within IR theory (Stoddard, 2013). It highlights the scarcity of non-renewable energy resources as a security threat, particularly for energy-importing countries (Dannreuther, 2017). On the other hand, energy-exporting countries might view these resources as a powerful tool in their foreign policy toolbox (Klare, 2008). Much of the literature on resource-related conflict has focused on how resource windfalls empower belligerent states or actors, leading to violence (Victor, 2007). Accordingly, energy serves a dual role in international conflicts as it functions both as a tool which states can employ to wage war and as well as a potential cause of war itself. Moran and Russell (2008, p. 3) similarly argue that energy resources can become casus belli in their own right or can be used by governments as an alternative to military force, believing that wielding the "energy weapon" could obviate or substitute the use of conventional arms.

The dominant realist and geopolitical paradigm in energy politics has been increasingly challenged, particularly in the past two decades. Critics of the realist approach argue

that this paradigm frames energy security as a zero-sum game, wherein the security of one actor is seen as inherently linked to the insecurity of another (Goldthau & Witte, 2009). They contend that this perspective often overlooks the role of the international energy markets and their governance. Furthermore, these critiques suggest that geopolitical approaches tend to exaggerate the potential for conflict and associated risks, while underestimating the importance of international cooperation (Dannreuther, 2013). In response, they propose a new paradigm in which energy insecurity is seen as a consequence of market failures, which can be mitigated through collective action and effective governance (Goldthau, 2012). Accordingly, the primary function of energy policies should be to facilitate proper functioning of the market (Stoddard, 2013). By adopting a market governance approach to the study of energy security this framework introduces a broader array of actors, such as markets and institutions, that are often overlooked in traditional geopolitical analyses (Van De Graaf & Colgan, 2016). Correljé and van der Linde (2006, p. 533) categorized these two perspectives as two storylines: "Regions and Empires" and Markets and Institutions". They highlights that the two perspectives on international energy affairs reflect, albeit often implicitly, the long-standing discussion between realist and liberal schools in IR.

However, neither the realist nor liberalist approaches alone provide a sufficient framework for analyzing the complexities of international energy dynamics. Numerous efforts have been made to move beyond this dichotomy. Scholars have called for the incorporation of International Political Economy (IPE) as a more comprehensive analytical framework (Van de Graaf et al., 2016). For example, Stoddard (2013, p. 449) argues that energy affairs require "modes of analysis that directly seek to explicate the intersection of the interstate and capitalist economic spheres and that are thus able to develop understandings of the interactions of their respective political and economic logics". Similarly, Keating et al. (2012) advocate for greater engagement with IPE to explore the links between economics and politics, broaden the range of actors under study, address the transnational nature of energy, and consider the role of ideas in shaping energy politics.

Radical and critical approaches

Alternative perspectives have also emerged, offering critical and radical frameworks that challenge the moral and political legitimacy of the current energy system (Dannreuther, 2013). Many of these come from radical traditions, often rooted in Marxist theory. For instance, Huber (2009, p. 105) uses a Marxist approach to examine energy. He argues that instead of viewing energy simply as a set of 'resources,' we should understand it as a "social relation" that reflects broader systems of power and inequality.

In light of environmental and climate change challenges, there is also a growing body of literature foregrounding more critical perspectives on sustainability and environmental aspects of energy security. McDonald (2018, p. 155) introduces the concept of "ecological security" to orient energy security toward ecosystem resilience and the rights and needs of the most vulnerable across space (populations of developing worlds), time (future generations), and species (other living beings). While mainstream environmentalist scholars believe that environmental conservation does not require a fundamental

change in the economic and political structures, their radical counterparts perceive the capitalist economic structures as a major cause of environmental degradation, climate change and pollution (Kuzemko et al., 2015).

Another key concept within these approaches is 'energy justice', which envisions a world where the benefits and burdens of energy production and use are distributed equitably, and where principles of justice guide how individuals and communities are involved in energy decision-making (Sovacool & Dworkin, 2014, p. 13). Jenkins et al. (2016, p. 175) suggest that energy justice encompasses three key dimensions: distributional, recognition, and procedural justice. They call for a critical examination of how the benefits and harms are distributed, how victims are recognized, and how these issues are addressed. Heffron and McCauley (2017) expanded the so-called 'triumvirate of energy justice tenets' by adding the concept of restorative justice, which aims to repair the harm to people, society and/or nature.

Beyond the approaches already mentioned, other perspectives adopt a more critical lens in the study of energy. One such example is critical geopolitics, which emerges from political geography and questions the assumption that geopolitical analyses are neutral or objective. Drawing on constructivist theory, it argues that geopolitics is inherently ideological and shaped by competing discourses from both state and non-state actors (Dalby, 1991; Dodds, 2001). Nevertheless, the application of critical geopolitics to energy politics remains relatively sparse (Blondeel et al., 2021). Other critical approaches, such as feminist (Bell et al., 2020) and decolonial perspectives (Dunlap, 2023; Tornel, 2023a) are also emerging but still remain limited to this day.

Energy as a socio-technical system

Over time, there have been different calls from scholars studying energy politics to move beyond traditional technological and theoretical frameworks in order to better understand the complexities of energy, as well as the energy transition. For example, Kuzemko, et al. (2019) argue that the evolving energy landscape demands a more nuanced perspective. Rather than understanding energy purely as technical infrastructure, they advocate for viewing it as a socio-technical system—one that encompasses, material, political, and distributional dimensions. This systems-thinking approach broadens the lens on energy transitions, drawing attention to their societal, political, and justice-related implications. In a similar vein, Blondeel et al. (2021, p. 3) call for a more integrated approach to studying energy transitions—one that examines both the shift toward low-carbon energy (renewables) and the phase-out of high-carbon sources (fossil fuels) in parallel. They argue that existing literature often treats fossil fuel and renewable energy systems as distinct domains, thereby overlooking their interconnections. Instead, they propose viewing the transition as a comprehensive 'energy system transformation' that spans political, social, economic, and cultural dimensions. Building on these calls, Kuzemko et al. (2024, p. 1) introduce the Global Energy System Transformation (GEST) framework to analyze the politics of energy transitions. This approach highlights the inherently social character of energy systems, moving beyond the realist and neoclassical paradigms that have long dominated energy geopolitics. Instead, it adopts a constructivist lens, framing energy transitions as deeply transfor-

mative processes rather than merely technical shifts. The GEST framework underscores the societal and political dimensions of these transitions, challenging the prevailing focus on material and technological factors. It emphasizes that energy systems are socially constructed and often reproduce existing power relations.

These scholarly calls are often informed by and built upon established strands of literature, not necessarily focused on energy. For instance, Science and Technology Studies (STS) long explored the interconnections between science, technology, and society drawing on innovation studies and evolutionary economics (Sovacool et al., 2020). STS scholars argue that technologies create linkages between diverse societal elements, such as resource mobilization and social networks. They introduced the concept of 'socio-technical systems' to describe these technologies and highlight their social character (Geels & Schot, 2010). The energy sector, with its significant infrastructure investments, interdependence, and institutional actors, serves as an ideal example of a socio-technical system (Scholten, 2013; Sovacool, 2016).

Within STS, significant attention is given to sustainable transitions, which refer to the transformative changes in socio-technical systems, shifting them from unsustainable to more sustainable states (Johnstone & Newell, 2018). This body of work frequently explores low-carbon transitions as the dynamic interaction of multiple elements across different levels. Scholars in this field often draw on the influential Multi-Level Perspective (MLP) introduced by Frank Geels (2002) which explains transitions as unfolding across three levels: landscape, regime, and niche. In the context of the clean energy transition, the regime refers to the dominant fossil fuel-based energy system, while niches are spaces where radical clean energy innovations emerge. The landscape includes broader external factors, such as political events or cultural shifts, that influence the system from the outside. A key idea in transition studies is the tension between stability and change—something the MLP captures by examining how these three levels interact and shape each other over time (Köhler et al., 2019).

Nevertheless, the field of STS has faced criticism for placing too much emphasis on innovation while often neglecting the role of political power in shaping transitions (Shove & Walker, 2007). Similarly, the socio-technical transitions framework has been critiqued for its limited attention to issues of energy justice and broader justice-related concerns (Jenkins et al., 2018; Sareen & Haarstad, 2018).

Toward a just energy transformation

The justice dimensions of the energy transition are increasingly explored within the expanding literature on just transitions. This scholarship emphasizes that the shift to a low-carbon energy system must avoid reproducing the environmental and socio-economic injustices inherent in the existing energy system (Carley & Konisky, 2020). While past energy transitions were largely involuntary, the current transition is a complex, policy-driven process with specific time goals (García-García et al., 2020). This academic discourse increasingly recognizes that the shift from fossil fuels to low-carbon energy might create trade-offs between energy, development, and carbon growth (Newell & Mulvaney, 2013).

Analytically, the concept of the 'just transition' draws on three different fields of scholarly debate: energy, climate and environmental justice (McCauley & Heffron, 2018). Energy justice, as mentioned earlier, seeks to ensure equitable distribution of the benefits and burdens of energy resources (Chapman et al., 2018; Williams & Doyon, 2019). Climate justice focuses on the historically uneven impacts, vulnerabilities, adaptive capacities and responsibilities in the climate crisis (Sultana, 2022a). Both energy and climate justice are considered modern branches of environmental justice (Carley & Konisky, 2020).

Closely related to the just transition concept but not identical, is the burgeoning scholarship on 'green transformations' (Leach et al., 2015; Miller et al., 2013; Sovacool, 2016). This strand of literature re-engages with Karl Polanyi's (2002) concept of 'great transformations', referring to the social forces that organize and reorganize capitalism. The debate within green transformations centers on the idea that states should not merely adapt to the energy transition but should actively transform their societies (Hjerpe et al., 2017). Within this field, Newell (2019, p. 4) draws a key distinction between transformation and "trasformismo," a term coined by Antonio Gramsci (1971) that refers to shifts in socio-technical configurations that do not disrupt existing social relations or the distribution of political power. A true transformation would alter the global economy, reshaping everything from daily life to global economic governance (Paterson, 2020).

The transformative nature of the shift from fossil fuels to clean energy is increasingly being addressed in academic literature. Pearse (2020) argues that framing the energy transition as a transformation challenges the existing literature, which often focuses on fuel switching and technological innovation without considering power relations or the social and economic dimensions of energy. Further, IRENA (2019, p. 14) explicitly distinguishes between the shift from fossil fuels to renewables as an 'energy transition' and refers to its broader societal implications as an 'energy transformation'. Gielen et al. (2019) also suggest that while a technical change in fuels is possible, the success of the transformation depends on coordinated policies that address global concerns such as energy access, climate change, and national and local priorities. Moreover, while the energy transition is considered to be top down, green transformations are ought to be bottom-up (Stirling, 2014).

2.3 Hydrogen: a new geopolitical factor?

In the last decade, hydrogen garnered renewed attention as a potential alternative to fossil fuels and a means of decarbonizing hard-to-abate industrial sectors. While this increased interest might seem new, hydrogen experienced multiple cycles of enthusiasm, hype and disappointment over the decades resulting in waxing and waning of the attention for the technology (Bakker & Budde, 2012). The concept of hydrogen as an alternative energy carrier first emerged alongside the development of fuel cells in the 19th century (Andújar & Segura, 2009). Today's wave of interest in hydrogen has been driven by national governments and energy companies, who view it as a solution for post-COVID-19 recovery and as a tool to combat climate change. However, it remains uncertain whether this recent wave of hydrogen research will succeed and prove different from previous cycles of enthusiasm (Yap & McLellan, 2023).

Despite recurring cycles of attention and growing calls for a social science research agenda (Hanusch & Schad, 2021; Kalt & Tunn, 2022; Scott & Powells, 2020), much of the existing research on hydrogen and hydrogen technologies remains focused on technical and natural science perspectives. A significant body of work examines hydrogen production methods, with many studies exploring various production techniques and their associated emissions (Dincer & Acar, 2015; Kumar et al., 2021). These studies often take the form of life-cycle-assessments (LCA) (Cetinkaya et al., 2012) or delve into specific production methods such as water electrolysis (El-Shafie, 2023) steam methane reforming (Szablowski et al., 2025), or less common approaches like hydrogen production from biomass (Obiora et al., 2024) or pyrolysis of natural gas (Schneider et al., 2020). Another important area of research evolves around hydrogen transport, storage, and distribution (Faye et al., 2022). This research focuses on two primary storage methods: physical storage, which involves altering hydrogen's physical properties by increasing pressure or lowering temperature, and material-based storage, which requires the use of hydrogen carriers (Yang et al., 2023).

There is also a growing body of research on hydrogen's end-use applications. A large portion of this work concentrates on fuel cells, which received early attention as a promising technology (Andújar & Segura, 2009; Kumar Singla et al., 2021). Other studies explore hydrogen combustion for decarbonizing the power sector (Habib et al., 2024), power-to-X applications (Genovese et al., 2023), hydrogen's role in fossil-free steelmaking (Vogl et al., 2018), and ammonia synthesis (El-Shafie & Kambara, 2023). Additionally, economic analyses and LCAs that assess the full hydrogen value chain—covering costs and emissions—are becoming increasingly common (Demir & Dincer, 2018; Moritz et al., 2022; Valente et al., 2017).

While these studies are essential for understanding hydrogen technologies and potential adoption pathways, it is equally important for policymakers and investors to consider what energy markets and geopolitics might look like if clean hydrogen were widely traded. Recently, social scientists have increasingly focused on the political and societal opportunities and challenges of developing international hydrogen value chains. However, much of the research still takes the form of techno-economic scenarios regarding the future demand, supply, and trade routes for clean hydrogen. These reports are often commissioned by international organizations like the IEA (2021b, 2022b, 2023a) and IRENA (2022a) or by companies such as BNEF (2020) and the Hydrogen Council and McKinsey & Company (2022). These reports tend to be normative, starting with the Paris Agreement's 1.5°C goal and outlining potential pathways to achieve this target. In 2022, IRENA made a first attempt to provide a more comprehensive view of the potential political and societal implications of a hydrogen economy. As part of its "Geopolitics of the Energy Transformation" series, IRENA (2022a) published a report that approached the topic from a social science perspective, addressing the geopolitical ramifications, justice issues related to future hydrogen trade, and the role of industries and economic competitiveness.

Changing power shifts in the hydrogen economy

While there has been growing attention in recent years toward developing a social science research agenda on the hydrogen economy, it remains in its early and exploratory stages. Much of the existing work is still in its infancy, often taking the form of horizon scans and theoretical mappings, focusing on exploring potential implications departing from (normative) hypotheses. For example, Van de Graaf et al. (2020) highlight various challenges tied to hydrogen, including geo-economic competition, evolving coalitions, and the creation of new dependencies. In a similar vein, Van de Graaf (2020) emphasizes the importance of technological competition and industrial policies as key elements of hydrogen geopolitics. Other studies, such as those by Pepe et al. (2023), present scenario-based projections based on foresight methodology, outlining three possible pathways for the world by 2040: Hydrogen Realignment, Hydrogen (In) Dependence, and Hydrogen Imperialism. Likewise, Nuñez-Jimenez and De Blasio (2022) explore possible futures for a European hydrogen economy, forecasting that while the EU could become self-sufficient in hydrogen production, importing hydrogen might still be more cost-effective due to long-distance shipping advantages and diversification benefits. Similarly, Pflugmann and De Blasio (2020) predict that countries such as Australia and the US might emerge as hydrogen export leaders, while traditional energy exporters like Saudi Arabia could lose geopolitical influence due to limited hydrogen resource endowments. These shifts might give rise to new alliances and trade relations, reshaping the global energy order.

In terms of geography, social science research on hydrogen is heavily concentrated on Europe, focusing both on the EU as well as on individual member states—most notably Germany (Quitzow et al., 2024; Schlund et al., 2022). Quitzow and Zabanova's (2024) edited volume provides ten case studies on hydrogen policy development across Europe, exploring both policies on the EU-level as well as country-specific dynamics. Further, research on the role of hydrogen in EU policies is extensive. For instance, Jerzyniak and Herranz-Surrallés (2024) showcase how hydrogen might become a field of policy making where the EU can exert geo-economic power.

Nonetheless, case studies from outside Europe are rapidly emerging, including work on Australia or Japan and, by extent, countries in the Global South. For example, Kar et al. (2023) have looked deeper into the Australian hydrogen strategy. By using a SWOT-analysis they found that Australia's hydrogen strategy heavily relies on exports, which might be threatened by the competition of other exporter such as North America or the Middle East. In the case of Japan, Hancock and Ralph (2021) scrutinized the energy security and justice impacts of hydrogen exports from Australia to Japan. They observe both opportunities such as strengthening the existing strategic relationship between the countries, as well as risks in terms of increased emissions, given that the hydrogen is produced from unabated fossil fuels. Finally, there is an increasing strand of literature that delves deeper into hydrogen development in the Global South. For example, Müller et al. (2022) look into hydrogen projects in Morocco and Namibia to understand risks of injustices in those countries, building on energy justice literature, while Kalt et al. (2023) look into the justice aspects of hydrogen projects in South Africa.

The evolving geopolitical landscape surrounding hydrogen and the potential emergence of new actors in this domain spurred academic inquiry into the formation of hydrogen trade partnerships and their associated socio-political dimensions. Much of the existing literature on hydrogen partnerships has concentrated on techno-economic considerations, particularly the selection of partner countries. For instance, Moritz et al., (2022) identify potential partner countries for Germany based on the production costs of hydrogen and related commodities, such as ammonia and methanol. Their analysis suggests that importing green ammonia is possibly more cost-effective than domestic production, with Norway emerging as the most cost-competitive supplier. Similarly, Pflugmann and De Blasio (2020) assess prospective hydrogen partner countries by examining resource endowments, water availability, and infrastructure potential, while also addressing the broader geopolitical implications.

Increasing scholarly attention is directed toward incorporating socio-political factors in the analysis of hydrogen trade dynamics. Frontier Economics (2018), for example, introduced 'soft factors' such as political stability, development indicators, and energy governance into their evaluation framework. However, these factors remain classified as secondary considerations, while renewable energy and water availability—deemed 'hard factors'—continue to serve as primary filters in identifying suitable partner countries. Brauer et al. (2022) adopt a comparable methodological approach, employing a three-step process to assess potential hydrogen partner countries. First, they eliminate countries with limited renewable energy resources and inadequate infrastructure. This is followed by a detailed analysis of supply costs to determine cost-competitiveness. Finally, they develop a 'soft-factor index,' which evaluates countries based on political stability, macroeconomic conditions, technical expertise, and ease of doing business.

Further expanding the framework, Schulze et al. (2024) introduce additional indicators, creating a multidimensional model for assessing future trade partners. Their framework includes categories such as environmental and developmental factors, as well as innovation and cooperation. Although these categories overlap with earlier studies, some indicators are interpreted differently. For example, water availability, previously considered from an economic perspective, is reclassified as an environmental and developmental factor in Schulze et al.'s (2024) framework. This variation highlights that the categorization of indicators can shift depending on the energy security perspective employed.

Nunez et al. (2024) take a different approach by developing a quantitative Sustainability and Governance Index (SGI) to rank potential hydrogen partners for Germany. Their index prioritizes political and environmental factors, without incorporating cost dimensions. In addition to governance performance indicators, which largely overlap with those used by Brauer et al. (2022) and Frontier Economics (2018), Nunez et al. (2024) include criteria such as the political commitment to hydrogen (e.g., whether a country has adopted a hydrogen strategy) and the alignment of energy policies with those of Germany and the EU. Their analysis finds that many Global North countries rank highly, while China, Chile, and India also perform unexpectedly well. In contrast, some countries with which Germany has already established MoU's, such as Angola, score

lower on the SGI. Table 7 summarizes the indicators used in the selection of hydrogen partner countries, highlighting the varied focus of different scholars.

Table 7: Indicators of hydrogen partner country selection

Indicators	Authors
Economic	Brauer et al. (2022); Frontier Economics (2018); Moritz et al. (2022); Pflugmann and De Blasio (2020); Schulze et al. (2024)
Political	Brauer et al. (2022) ; Frontier Economics (2018) ; Nunez, et al. (2024) ; Schulze et al. (2024)
Environmental	Schulze et al. (2024)
Innovation	Schulze et al. (2024)

Despite differences in the categorization and prioritization of these indicators, this body of research coincides in underscoring the complexity inherent in selecting hydrogen trade partners. Each study highlights the trade-offs involved in choosing partner countries based on varying criteria (Brauer et al., 2022; Nunez et al., 2024; Schulze et al., 2024).

Hydrogen justice

In addition to the aforementioned geopolitical and security-focused literature, a small but growing body of critical scholarship is addressing concerns regarding the unequal distribution of the costs and benefits tied to the development of a hydrogen trade landscape. Scholars in this stream take a critical stance, particularly regarding the role of the EU and member states like Germany in advancing hydrogen projects and partnerships with the Global South. For instance, Claar (2022, p. 268) argues that the European Hydrogen Strategy "perpetuates colonialism". Similarly, Hamouchene and Sandwell (2023, p. 30) suggest that the hydrogen trade between Europe and Morocco exemplifies "green colonialism". Furthermore, Dagnachew et al. (2024, p. 1) assert that a "green hydrogen revolution in Africa remains elusive under current geopolitical realities".

This burgeoning critical scholarship draws heavily from well-established academic debates in areas such as energy justice, environmental justice, political ecology, critical IPE, and just transition studies. A substantial portion of this work engages with the concept of energy justice to expose potential injustices in the hydrogen trade. For example, Müller et al. (2022, p. 2) specifically coined the term 'hydrogen justice,' extending the energy justice framework by adding restorative, relational, and epistemological dimensions to assess potential injustices related to hydrogen development. They note that hydrogen injustices might arise from the interaction between international hydrogen governance and local conditions in hydrogen-producing countries. Dillman and Heinonen (2022) identify risks to justice across distributional, procedural, cosmopolitan, and recognitional dimensions, while proposing measures to mitigate these risks. Lindner (2022), examining 48 hydrogen partnerships, critiques their failure to incorporate an energy justice approach, with a predominant focus on techno-economic factors.

In addition, some scholars link hydrogen trade to the notion of 'green extractivism' a concept stemming from political ecology and the environmental justice literature. Tunn et al. (2024) in their study of 28 countries in the Global South, identify socio-ecological risks arising from export-oriented green hydrogen production. Their analysis reveals how such projects foster green extractivism, with profits and decision-making power concentrated in the Global North, perpetuating an uneven exchange. They argue that the dynamics of exclusion, externalization, and enclosure are present in the hydrogen sector. Galan and Lindner (2024, p. 4) similarly draw comparisons between the hydrogen sector and extractive industries such as mining, highlighting risks related to resource governance and the 'resource curse'.

Kalt et al. (2023, p. 305) employ (neo-)Gramscian hegemony theory to explore hydrogen projects in South Africa, using the concepts of "political project" and "political initiatives" to uncover four key political initiatives in the country's hydrogen sector: green extractivist, green developmentalist, fossilist, and socio-ecological. Adding an extra layer of complexity, Tunn et al. (2025) adopt a decolonial political ecology approach to examine the discourses and practices of coloniality embedded within the hydrogen sector. Müller (2024) goes beyond this, combining decolonial theory with transition literature to study hydrogen expansion in the Global South. Her work expands on the concept of 'coloniality' to offer a more nuanced understanding of 'energy colonialism,' integrating it with the MLP from STS literature.

Additionally, debates are emerging around the financial and political economic dimensions of hydrogen projects in the Global South. Gabor and Sylla (2023) observe that hydrogen projects are increasingly tied to the financialization of development aid, a new paradigm described by macro-economist Daniela Gabor (2021, p. 430) as the 'Wall Street Consensus' (WSC). The WSC postulates that public investments alone cannot meet sustainable development goals, and that institutional capital must be leveraged to attract private investors to advance public-interest projects like hydrogen. Governments are encouraged to 'derisk' investments using tools like green bonds or contracts for difference. However, Gabor and Sylla (2023) caution that such reliance on private investors could deepen the financial dependence of Global South countries on powerful Global North investors and exacerbate the risk of debt crises, particularly when loans are required to meet investor demands. They highlight hydrogen projects in Namibia as a case in point, warning that these initiatives could exacerbate financial inequalities. Similarly, Haag et al. (2024) caution that hydrogen projects in Namibia could risk deepening existing financial disparities, with potential long-term consequences for the country's economic stability.

Geo-economics of hydrogen industrial policy

Finally, the politics of renewable energy and the energy transition are increasingly intersecting with the politics of green industrial policy (Rodrik, 2014). Clean technologies and energy-intensive products like steel are becoming critical to industrial strategies and are gaining increased political importance (Scholten, 2018). Despite this, research on the intersection between energy politics and industrial policy remains underdeveloped. Consequently, Allan et al. (2021) call for greater integration of industrial policy

into climate and environmental research. Nevertheless, only a few studies so far do this. Crawford (2024, p. 114) explores the impact of the energy transition on European industries, predicting an 'industrial trilemma' that involves trade-offs between sustainability, security, and efficiency. Further building on this, Herranz-Surralles (2024) discusses how green industrial policy reflects the geopoliticizing framing of the energy transition.

While still sparse, there is an emerging body of literature looking into the geo-economic implications of hydrogen industrial policies. While industrial policy gained increased attention in policy circles, this shift yet needs to be fully reflected in academic scholarship, with most studies confined to reports and some initial investigations including those from think tanks. For instance, the IEA (2024b) highlights the interconnectedness between energy, trade, and industrial policy in its Energy Technology Perspectives and the importance of the manufacturing sector as a key pillar of the clean energy economy, including hydrogen-related technologies such as electrolyzers. They also project that the transition from energy products to energy technologies will alter existing trade relations from energy resources to energy products consequently strengthening energy resilience.

One of the first academic studies to address the politics of hydrogen and industrial policy was conducted by Eicke and De Blasio (2022) who examine how shifting industrial value chains might impact global markets and geopolitical dependencies. By evaluating existing industrial applications, economic relatedness, and resource endowment, they identify four categories of countries: frontrunners, upgraders, green hydrogen importers, and bystanders. They argue that countries like China and the US stand to benefit most from the hydrogen economy, while countries like Thailand and Mexico could capitalize on their existing industrial capacities and skilled labor forces to create value-added opportunities.

The geographical redistribution of energy-intensive industries is often considered a natural consequence of varying renewable energy conditions across the globe, a phenomenon dubbed the 'renewables pull' effect (Samadi et al., 2023). This effect could lead to regional shifts in industrial production, either through relocation or by redirecting investments. If such shifts involve the relocation of industries to take advantage of low-cost renewable energy, this is referred to as 'green relocation' (Verpoort et al., 2024).

While academic work on the renewables pull effect is still in its early stages, emerging research focuses on sectors like clean steelmaking and green ammonia production. Gielen et al. (2020) explore the potential relocation of the steel industry from fossil-fuel-based processes to hydrogen-based direct reduction iron (DRI) processes. They argue that countries rich in iron ore, such as Australia, could increase value-added production by leveraging renewable electricity alongside their iron ore reserves. Similarly, researchers from the European Centre for Development Policy Management (ECDPM) argue that North African countries, including Mauritania and Egypt, could seize opportunities to develop green steel industries, particularly as the EU works to decarbonize its steel sector. Their analysis, grounded in political economy, shows that while North African countries could benefit from investments and local economic growth, the EU might face challenges in terms of job security and high costs, complicating cooperation between

the two regions (Karkare & Medinilla, 2024). The green ammonia sector also exemplifies shifting industrial geographies. African countries like Egypt and Morocco, which are key exporters of fertilizer, could capitalize on renewable energy potential to develop green fertilizer industries. Both countries have set ambitious targets to become leaders in the green fertilizer market, further transforming the ammonia industry's global landscape (Medinilla & Dekeyser, 2024).

Finally, the changing industrial landscape is giving rise to new academic debates on the green industrialization in Global South countries. Unlike the critical scholars discussed earlier, these researchers take a more positive and pragmatic approach toward North-South hydrogen trade. For example, IRENA, along with the German development think tank IDOS and the UN Industrial Development Organization (UNIDO), developed a toolkit to help emerging economies leverage their resource wealth and stimulate industrial development (UNIDO et al., 2024). Other scholars argue that green industrial policies could reduce various social risks, such as labor and environmental issues, unemployment, gender wage gaps, and inequitable salaries. Akhtar et al. (2023) emphasize that domestic manufacturing of key hydrogen components can significantly mitigate these risks, increasingly legitimizing calls for green manufacturing and industrialization in the Global South.

2.4 Concluding remarks

The three aforementioned scholarly debates provide valuable insights into the potential energy security implications of hydrogen imports into NWE. From this literature, four overarching conclusions can be derived.

Firstly, the politics of energy remains predominantly focused on fossil fuels, and specifically on oil and natural gas. Much of the existing literature is informed by a geopolitical lens and studies how both exporting and importing countries historically utilized, and continue to leverage, their energy resources—or lack thereof—as strategic tools in foreign policy. The research on the politics of energy transitions, often coinciding with the politics of renewables, is, on the other hand, still relatively exploratory. Indeed, much of that literature continues to use the fossil fuel framework of competition and geopolitics as a lens to study the politics of renewables. Considering hydrogen's connection with both fossil fuels and renewables, studying the politics of hydrogen may bring these two streams of literature into conversation with each other, facilitating a broader perspective on the politics of energy.

Secondly, energy security, while central to energy politics, often functions as a Rorschach inkblot test—its meaning varies depending on the viewer's perspective (Sovacool, 2010). The literature on energy security tends to be highly conceptual and frequently lacks empirical embedding. It is dominated by studies on fossil fuels and focuses on industrialized countries with a high energy use. Furthermore, energy security is examined from a variety of theoretical lenses, each emphasizing different actors, values, and focal points. This multiplicity of definitions and conceptualizations reflects that 'energy security' is not a singular or fixed entity but rather a prism through which broader political, economic, and social issues are interpreted.

Thirdly, scholarly engagement with the politics of energy highlights the increasingly complex dimensions of energy resources, necessitating a more systemic approach to their study. Energy should not be viewed solely as a technical infrastructure but as a socio-technical system encompassing material, political, and distributional dimensions. This systems-thinking approach fosters a broader perspective on energy transitions, emphasizing their societal, political, and justice implications. It shifts the focus toward the transformative aspects of a clean energy system, rather than merely transitioning or replacing a fossil fuel based system.

Finally, although there is an abundance of studies examining the techno-economic aspects of establishing a hydrogen economy, the literature on its political and societal dimensions remains nascent. Nevertheless, the existing, albeit limited, literature on hydrogen politics diverges significantly from the broader scholarly discourse on energy transitions. While the latter is often exploratory and extrapolates insights from oil and gas sectors, the emerging literature on hydrogen politics is more focused, addressing specific issues such as partner country selection, risks of inequalities, and industrial policy. However, this burgeoning body of research is fragmented, drawing from diverse and often loosely connected scholarly debates.

Chapter 3. Analytical framework

Analytical framework

In this chapter, I present the analytical framework to examine and explain the energy security implications of hydrogen imports in NWE. The framework is built on two pillars: a conceptual pillar and an explanatory pillar.

The conceptual framework draws on two fundamental concepts: first, the notion of energy as a system, rooted in socio-technical systems theory; and second, the understanding of energy security as a multidimensional concept, comprising four core dimensions: national security, the economy, environmental sustainability, and justice.

The explanatory framework is built upon on three logics: a path dependence logic, which interprets the development of a hydrogen trade landscape as shaped by historical structures and legacies; an actor-based logic, which emphasizes the role of actors in either maintaining or altering these structures; and a geo-economic logic, which examines how global power struggles impact these dynamics. This explanatory framework serves as a heuristic device, wherein each logic contributes a distinct explanatory value for explaining and understanding the energy security implications of hydrogen imports in NWE.

3.1 Conceptual foundations

Hydrogen as a socio-technical system

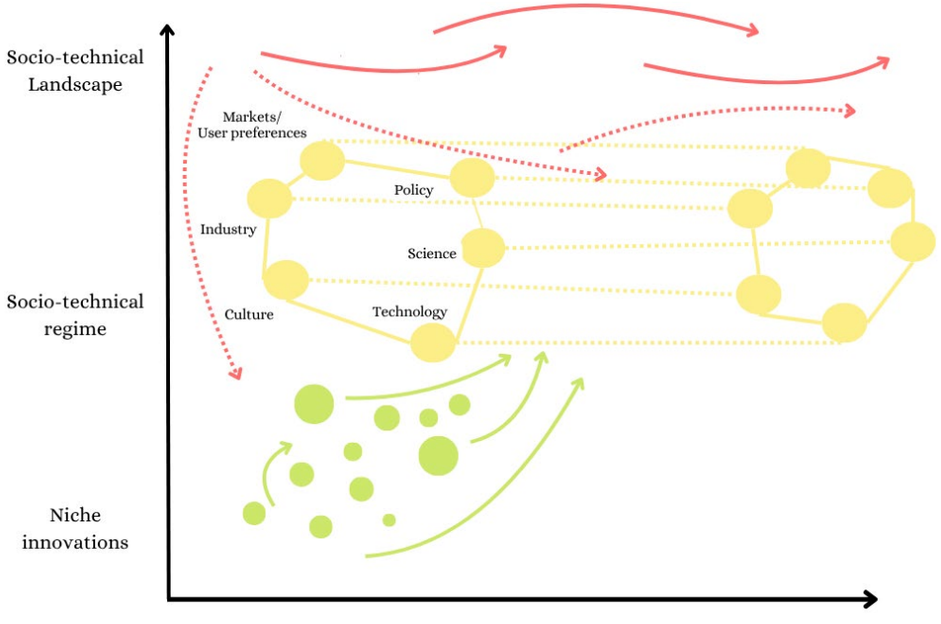
In this dissertation, I conceptualize hydrogen as a socio-technical energy system. The concept of socio-technical energy systems is grounded in STS, a field that explores the interplay between science, technology, and society. This approach is based on two key premises that I derived from the literature. First, technologies cannot be fully understood in isolation from their broader social contexts, as they continuously shape and are shaped by societal influences. Second, the energy security implications are inherently societal and multi-dimensional and, as such, necessitate a deep integration within a wider socio-technical framework.

An energy system can be defined as a configuration of technologies, services and infrastructures, regulations and actors (for example, producers, suppliers, policymakers and users) that fulfils a societal function such as energy provision. All these elements are aligned and fine-tuned to each other, and form an energy system (Schot et al., 2016). Consequently, energy systems are perceived to be “dynamically stable”: innovation still occurs but it is incremental and happens within the system (Grin et al., 2010, p. 21). Moreover, the energy system is perceived to be an open system, interconnected with other societal systems, such as food systems or mobility systems and are embedded within the broader societal context (Verbong & Loorbach, 2012).

The incumbent fossil fuel-based energy system is undergoing a profound transformation. The global urgency to address climate change highlights the necessity for a shift toward more sustainable patterns of production and consumption (Markard et al., 2012). This process is captured in the concept of sustainable transitions, which has become a central focus of Transition Studies over the past two decades. Energy transitions are conceptualized as prolonged shifts from one socio-technical system to another, ultimately resulting in the establishment of a new energy system (Schot et al., 2016). Sustainability transitions are "purposive" and driven by multiple factors, including concerns over GHG emissions, volatile fossil fuel prices, and energy import dependencies (Kern & Markard, 2016, p. 292).

In order to study the dynamics of such sustainable transitions, STS scholar Frank Geels (2002) introduced the multi-level perspective (MLP). According to the MLP, energy systems are viewed as 'regimes' that interact with the socio-technical landscape and niche innovations (Geels & Schot, 2007). The levels in the framework are viewed as heuristic, analytical concepts, and provide a means to focus on the interlinkages between a diversity of actors and institutions, who are connected to the socio-technical system through different roles (e.g. regulator, consumer, entrepreneur, activist), time and space as shown in Figure 4.

Figure 4: The Multi-level Perspective based on Geels (2002)



Socio-technical regimes refer to the incumbent socio-technical system (Geels, 2002). They are considered to be the dominant, stable set of structures, rules, and practices that guide the functioning of a particular socio-technical system (Grin et al., 2010). These regimes are made up of multiple interrelated components, including technology,

science, cultural norms, industries, policies, and market preferences. The core idea behind socio-technical regimes is that they are very resistant to change. This resistance can hinder the adoption of radical new technologies, such as clean hydrogen (Kuzemko et al., 2016). One of the primary challenges to the current transition to sustainable energy is the strong entrenchment of current energy production and consumption within fossil fuel-based socio-technical systems—a phenomenon known as carbon lock-in—which makes the adoption of clean technologies more difficult (Unruh, 2000).

Niches represent radical innovations that emerge and diffuse into the market and aim to replace the regime. These radical innovations, as Schot and Geels (2008) assert, do not function as mere technological fixes. Instead, they emerge within socio-technical niches, which are characterized by small, unstable, and precarious networks of entrepreneurs and innovators willing to take risks. These actors must exert significant effort to sustain and protect the niche, as the diffuse and underdeveloped nature of rules results in limited structuration, substantial uncertainty, and fluidity (Grin et al., 2010). Radical innovations are different from incremental innovations. The latter are in line with the prevailing technological paradigm, often improve the performance of existing technologies and reinforce the socio-technical system they align with (van den Bergh et al., 2006).

The active construction and protection of niches can be facilitated through *strategic niche management* interventions (Rip & Kemp, 1998), given that innovative technologies are typically disadvantaged and necessitate strategic support. Emerging clean technologies, despite their environmental and social benefits, face substantial barriers to development due to the complex and unfavorable selection pressures exerted by dominant fossil fuel regimes (Raven et al., 2016). To ensure the success of radical innovations, for example the uptake of clean hydrogen, dedicated policy interventions play a critical role. These may involve investments in R&D (van den Bergh & Oosterhuis, 2005), supply-side measures, such as tariffs and taxes, or demand-side initiatives, including public procurements (Smith & Raven, 2012). Consequently, this implies a more active role for national governments in promoting the establishment of new technologies (Hughes and Meckling, 2018). However, technological evolution is "uncertain, dynamic, systemic, and cumulative" (Foxon, 2011, p. 2260), with outcomes often unpredictable, so accordingly, policymakers should refrain from "picking winners" (Marechal & Lazaric, 2010, p. 111).

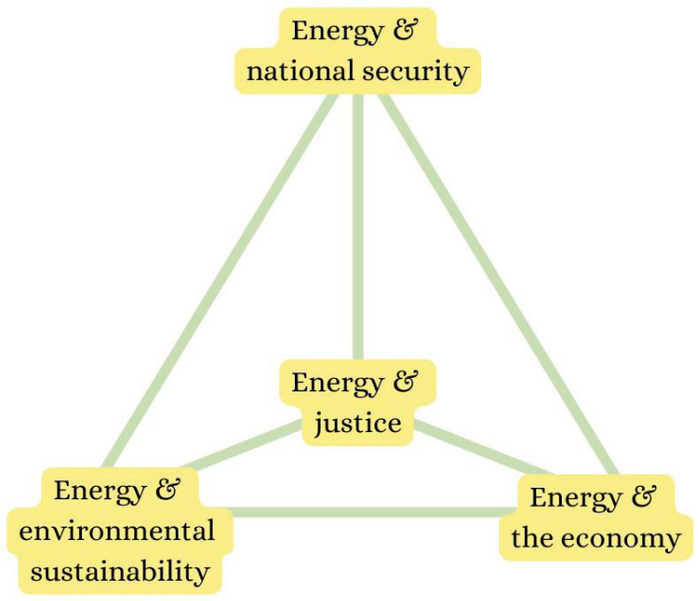
Finally, landscapes are external forces that exert pressure on regimes, creating opportunities for niche innovations (Geels, 2002). Any alteration in these landscape elements influences the prevailing socio-technical regime. Landscape pressures can be both unintentional and intentional. Unintentional pressures arise from unforeseen and unpredictable events (e.g., natural disasters or wars) that impact regimes, incidentally, functioning as exogenous shocks without a direct causal aim. Conversely, intentional pressures are strategically applied by stakeholders with the objective of disrupting or misaligning specific landscape factors in relation to the socio-technical regime (Morone et al., 2016).

Energy security as a prism

Having defined hydrogen as a socio-technical system, I now turn to the second key concept: energy security. The contemporary transition toward a clean energy system is characterized by a high degree of complexity and as a result, the understanding of what a secure energy system should look like is expanding. A secure energy system can be framed both as a strategic imperative (Klare, 2004) as well as a matter of public policy (Goldthau, 2012), despite these views being based on fundamentally different ontological assumptions. Moreover, normative and justice imperatives—particularly concerning who and what are considered valuable and worthy of protection—have become increasingly central to energy security discussions (Dyer & Trombetta, 2013).

These complexities underscore the critical need for conceptual clarity regarding the concept of energy security. Building further on the existing literature, I propose that energy security should not be viewed as a static concept. Instead, I consider it as a prism through which broader political, economic, and social issues are interpreted and contested (Van de Graaf & Sovacool, 2020). Indeed, the presence of multiple interpretations of energy security does not necessarily indicate the existence of entirely distinct conceptualizations. Rather, it suggests that energy security may manifest in various dimensions, as shown in Figure 5.

Figure 5: Energy security prism



Moreover, this multidimensional approach frames energy security as an inherently systemic concept, where security in one aspect of the energy system may not equate

to security in another, and vice versa. Consequently, this conceptual approach aligns with the socio-technical framework applied in this dissertation.

In what follows, I conceptualize energy security in the case of hydrogen as a multi-dimensional concept, viewed through a prism, with four core dimensions: hydrogen and national security, hydrogen and the economy, hydrogen and environmental sustainability, and hydrogen and justice. This constructivist framework is designed to capture the complexity and diversity inherent in various interpretations of energy security. These dimensions are not mutually exclusive and may intersect; sometimes they are complementing and at other times conflicting. I consider each of these dimensions equally important. An overview of The conceptualizations of the four dimensions can be found in Table 8.

Finally, it is important to note that the subsequent sections are concerned with the conceptualization of energy security through the development of a framework that delineates its core dimensions. The analytical task of linking these dimensions to relevant theoretical foundations will be undertaken in Chapter 4.

Hydrogen and national security

The first dimension in this framework sees hydrogen as a vital ingredient of national power and prosperity. States inevitably compete for access to hydrogen and are willing to, if necessary, contemplate to military action (Dannreuther, 2017). Often, the issue is not energy per se, but the geopolitical ambitions of energy-supplying states, whose increasing influence poses an inherent threat. Consequently, energy security policies often follow the true geopolitical power dynamics (Ciută, 2010). Given the importance of national security in securing energy resources, states are the central players within this perspective (Bradshaw, 2010).

This dimension of energy security is deeply rooted in the realist tradition of IR, which derives from the concept of anarchy, a condition in which no overarching sovereign authority exists to constrain the inherent drive for power and the natural human tendency toward aggression. Under this framework, the international system is defined by distrust, with the perpetual threat of conflict and war ever present (Dannreuther, 2013).

The main threat, according to this dimension of energy security is dependence, as it is considered to be a source of national vulnerability (Dannreuther, 2017). In the case of hydrogen, this dimension considers that hydrogen imports create dependencies that may weaken national sovereignty. Moreover, energy trade relations are frequently conceptualized as a zero-sum game, where protectionist policies are seen as essential to ensuring national security and economic prosperity. This is amplified by the idea of resource scarcity, which is a crucial concern within this dimension, particularly regarding non-renewable resources such as fossil fuels or critical minerals. As these resources become scarcer, competition intensifies, with states vying for control over the same finite supplies (Bridge, 2015). The scarce availability of clean hydrogen molecules and technologies may thus increase global competition.

According to this dimension, energy security is pursued through foreign policy or even military strategies (Proskuryakova, 2018). Control over energy resources—whether by buyers or sellers, —becomes a key instrument of strategic coercion, utilized to exert influence over others (Moran & Russell, 2008). For energy-producing states, the economic significance of energy transforms it into a powerful tool of foreign policy, wielded through either “energy diplomacy” or direct coercion via the “energy weapon” (Wilson, 2019, p. 115). Energy policy, in this context, has become a matter of military planning, with global competition for natural resources poised to redefine the nexus between security and trade relations (Ciută, 2010).

Hydrogen and the economy

The second dimension considers hydrogen and the economy. Based on this dimension hydrogen is conceptualized as a market commodity, rather than a matter of national security. The energy sector, according to this dimension, is subject to market forces and should be treated like any other commodity (Kilinç-Pala, 2021). From this perspective, perfectly competitive and comprehensive markets would theoretically yield an optimal level of energy security. As energy security is connected to the market, actors relevant in this dimension expand beyond the state, including companies, national and international institutions and civil society organizations (Dannreuther, 2017).

This dimension aligns closely with broader market liberalism and liberal institutionalist thought in IR (Dannreuther, 2017). It emphasizes confidence in market mechanisms and the potential for institutionalized international cooperation to create mutually beneficial outcomes for both economic actors and states (Stoddard, 2013). The underlying principle posits that competitive markets, in conjunction with independent regulation, represent the most efficient mechanism for delivering secure and reliable hydrogen supplies. The market, rather than governments or regulatory bodies, are typically better positioned to assess and respond to the varying levels of energy security. As a result, policy interventions and state involvement are only justified if they improve the function of the market (Valkenburg & Gracceva, 2016).

A key implication of this viewpoint is that energy security does not inherently equate to independence, in contrast to the perception of hydrogen as a matter of national security. In a globalized and liberalized energy market, pursuing independence would essentially amount to protectionism, thereby deviating from the broader principles of free trade and a liberalized market. Dependence on imports, rather than being a vulnerability, is conceptualized as an integral component of the global division of labour, fostering reciprocal benefits for both exporting and importing countries (Keppler, 2007).

Energy security can be enhanced through transparent policymaking and pluralism. In this regard, international cooperation and multilateral institutions are crucial in coordinating the energy sector internationally (Dannreuther, 2017). In competitive and open markets, issues of energy insecurity are addressed through price adjustments, where rising prices stimulate additional supply from marginal reserves. Affordability is crucial for consumers and therefore stabilizing prices ensures planning and investment security for energy producers (Van de Graaf & Sovacool, 2020). Consequently, governments should warrant a well-functioning hydrogen market to enhance innovations in hydrogen technologies and secure hydrogen flows.

Hydrogen and environmental sustainability

The third dimension of energy security, environmental sustainability, foregrounds environmental stewardship, emphasizing the preservation of ecosystems alongside the imperative to avoid exhausting non-renewable resources. This is to be achieved by a transition to renewable energy sources and other clean technologies. Central to this discourse is the concept of the ‘global commons,’ encompassing natural resources, the climate, and the environment — entities that transcend individual ownership and are collectively shared by humanity (Kuzemko et al., 2015).

This dimension draws on a long-standing tradition within environmental movements and activist circles that critiques human activity for its disruptive effect on the environment. Advocates within this tradition underscore the finite nature of planetary resources, and they highlight the intensified pressures of (population) growth, industrialization, and pollution, all of which are seen as placing an unsustainable stress on our planet Earth. Hence, proponents argue for a reorientation of human practices toward a more harmonious coexistence with the natural world (Kuzemko et al., 2015). Within this discourse, mainstream environmentalists maintain that ecological protection can be achieved within existing political and economic structures, while more radical environmentalists contend that the capitalist modes of production and consumption are fundamentally linked to ecological degradation (Van de Graaf & Sovacool, 2020).

A core risk within this dimension is the recognition of the profound environmental consequences of existing modes of energy production and consumption. The exacerbation of global warming using fossil fuels reinforces the urgency of decarbonization strategies aimed at reducing carbon emissions and progressing toward a carbon-neutral future. Transitioning to renewable energy is widely viewed as a key mechanism for mitigating the detrimental effects of climate change (Sovacool, 2010). According to this dimension, imports of hydrogen could enhance industrial decarbonization, however, this is only the case when hydrogen is produced in a sustainable way.

A more radical interpretation of the hydrogen and environmental sustainability dimension critiques the dominant paradigm of capitalist-driven economic growth as the principal threat to ecological balance. Advocates of this perspective argue for ‘degrowth,’ a planned and deliberate reduction in energy and resource throughput, as a necessary intervention to realign the economy with ecological limits, thereby fostering a truly sustainable energy system (Hickel, 2021).

Hydrogen and justice

The justice dimension represents a more critical aspect of energy security. From a justice-oriented perspective, energy security must address the spatial, temporal, social, and ethical factors implicated in the development of the energy system, spanning both energy production and consumption. The goal is to ensure that all individuals, regardless

of location, have access to safe, affordable, and sustainable energy (McCauley, 2018). An energy-just world is one in which both the benefits and burdens of energy production and consumption are shared equitably. It also involves fairness in the treatment of individuals and communities, particularly in their participation in energy-related decision-making processes (Sovacool & Dworkin, 2015).

In this context, the justice aspect of energy security is closely intertwined with the broader theoretical foundations of energy justice. Heffron and McCauley (2014) argue that addressing issues of energy justice along the energy supply chain has direct implications for energy security. Traditionally, the concept of energy justice rests upon three core tenets: distributional justice, which highlights the unequal allocation of environmental benefits and burdens, as well as the uneven assignment of responsibilities; recognition justice, which ensures that individuals are protected from physical harm and enjoy equal political rights; and procedural justice, which emphasizes equitable access to decision-making processes, ensuring non-discriminatory engagement with all stakeholders (Jenkins et al., 2016).

A key challenge, according to the dimension of justice, is the systemic inequality embedded in the global energy system, with significant portions of the global population lacking access to basic energy services (Mastor et al., 2018, p. 146). Energy poverty, in particular, can be understood as a security issue, functioning as a "threat multiplier" that exacerbates broader issues such as social unrest, political instability, migration, and economic poverty, further marginalizing already vulnerable groups. A second threat arises from the unequal distribution of benefits and burdens of the energy transition both in financial and physical terms (Jenkins et al., 2016). According to this perspective, hydrogen imports may reproduce in equalities and injustices in countries with high energy poverty and limited access to energy resources. In contrast, international hydrogen trade may also unlock an energy transformation toward a more equal and just energy system in the long term.

There are, however, tools available to mitigate or overcome potential energy justice risks. Inclusive and participatory decision-making is essential for addressing procedural justice concerns. Additionally, to address distributional challenges, energy access, as well as the associated benefits and burdens of energy systems, must be distributed equitably (Sovacool & Dworkin, 2014).

3.2 Explanatory framework

Socio-technical approaches to energy systems play a crucial role in advancing our understanding of the key components and dynamics involved in socio-technical and sustainable transitions. However, these approaches often downplay the "plural, messy, and contested character" of these processes (Bridge & Gailing, 2020, p. 1039). Moreover, contemporary conceptualizations of sustainable transitions tend to focus more on envisioning what a clean energy transition might look like, rather than adequately explaining the political mechanisms required to achieve these outcomes (Lawhon & Murphy, 2012).

Table 8: Four dimensions of energy security

Dimension	National security	Economy	Environmental sustainability	Justice
Central assumption	Competition over energy should be treated as a matter of national security.	Energy is subject to market forces. Perfectly competitive markets yield an optimal level of security.	Energy systems should protect the environment for future generation	Energy systems should consider fairness and equity in energy decisions and practices
Central actor(s)	The nation state	Multiple actors: Companies, national and international institutions, civil society organizations	The 'global commons': natural resources, climate and the environment	Marginalized communities and individuals
Theoretical tradition	(Economic) Realism (neo) Mercantilism Geopolitics	Liberal institutionalism Market liberalism	Environmental movements Environmental security	Energy justice Social justice
Perceived threats	Resource scarcity Import dependence	State-intervention Market failures	Environmental degradation Capitalism and economic growth	Energy deprivation Uneven distribution of benefits and burdens within the energy system
Proposed responses	Foreign policy Energy statecraft Energy diplomacy	Transparent market regulations Privatization and liberalization of the energy market	Decarbonization of the energy system Degrowth	Inclusive decision-making Improved access to energy Benefit sharing

As the future configurations of hydrogen imports will be influenced more by entrenched social and political dynamics than by technological advancements (Stirling, 2014), it is crucial to also construct an explanatory framework for understanding the energy security implications of hydrogen imports in NWE. This entails not only examining and listing the implications of hydrogen imports across the four dimensions of energy security but also critically addressing fundamental questions such as: What drives or constrains the development of international hydrogen trade? Whose interests shape the emerging hydrogen economy? And, as a result, which dimensions of energy security are then prioritized and for whom?

In the following sections, I present three explanatory logics that provide a nuanced understanding of the energy security implications of hydrogen imports into NWE within a broader socio-political and historical context. First, the path dependence logic suggests that the hydrogen economy will be heavily influenced by historical structures and policies. Second, the actor-based logic argues that the development of hydrogen trade will be shaped by both established and emerging actors in the energy sector. Third, the geo-economic logic posits that the evolution of the hydrogen economy depends on existing and evolving power dynamics.

These three logics are not mutually exclusive and often intersect. For instance, established actors may be driven by power maximization considerations, while power asymmetries can lead to path dependent outcomes. I do not consider any of these logics as inherently more significant than the others. An overview of the three logics is provided in Table 9.

Table 9: Explanatory framework

Logic	Key concepts	Theoretical foundations
Path dependence	Lock-in Increasing returns Policy feedback Exogenous shocks Critical junctures	Historical institutionalism Socio-technical regimes
Actor-based	Incumbent actors Veto-players Regulatory capture	International regime theory Regime complexity
Geo-economic	Weaponized interdependence Structural dependence Power asymmetries	Geopolitics Geo-economics Dependency theory

Path dependence logic

A primary logic for understanding the energy security implications of hydrogen imports into NWE is the path dependence logic, rooted in historical institutionalism. This perspective posits that the clean energy transition is not an isolated or ad hoc event,

but rather part of a broader, historically embedded process (Voß et al., 2009). Existing policy arrangements and institutions shape political processes, providing some actors with greater resources, influence, and access to policymakers than others (Thelen, 1999). Consequently, the notion that "history matters" (North, 1990, p. 100) is particularly salient when analyzing shifts in political dynamics, especially in the context of the evolving clean energy transition and the adoption of hydrogen technologies.

To fully grasp the changes brought about by the clean transition, historical institutionalists emphasize the role of institutions in shaping political behavior and the mechanisms through which institutional change occurs (Thelen, 1999). Institutions are broadly defined as "formal or informal procedures, routines, norms, and conventions embedded within the organizational structures of polity or political economy" (Hall & Taylor, 1996). This broad conceptualization allows the consideration that the emergence of a hydrogen economy represents a significant institutional transformation.

Once established, institutions exhibit a strong resistance to change, characterized by the concept of path dependence. Path dependence suggests that prior decisions in a particular direction set the course for continued movement in that direction, a process often driven by increasing returns. In such a process, the likelihood of further steps along the same trajectory grows as each move reinforces the relative advantages of current activities over potential alternatives. The 'cost' of moving toward another path are too high.

This phenomenon can be understood as a self-reinforcing or positive policy feedback mechanism (Pierson, 2000). Policy feedback theory captures the recursive relationship between actors and institutions, emphasizing how policies not only result from political action but also reshape the interests, strategies, and identities of those involved, thereby generating new political dynamics (Jordan & Matt, 2014). In the context of energy regimes, positive feedback loops are particularly significant, as they both stem from and reinforce the economic and political power of incumbent actors (Lockwood et al., 2017). These dynamics are driven by increasing returns, which arise from factors such as high initial investment costs, learning-by-doing, industrial interdependencies, and economies of scale—factors that contribute to the lock-in of socio-technical systems (Klitkou et al., 2015; Pierson, 2000). Accordingly, the development of hydrogen import infrastructures in NWE is likely to be shaped by existing institutional arrangements and established fossil fuel trade patterns.

However, institutional stability is not always a given. Traditionally, scholars have attributed radical institutional shifts to exogenous factors or shocks (Hogan, 2019). These shocks, such as economic crises, political turmoil, or conflicts, represent external, pivotal moments that affect society broadly and can result in 'critical junctures' (Mahoney, 2001, p. 11). Nevertheless, once political conflicts and realigned coalitions form new policy frameworks, these structures become once again entrenched or locked in through feedback mechanisms (Capoccia, 2016a). As a result, such a type of change is often seen as "crisis-driven" (Jochim & May, 2010, p. 316).

Yet, an overemphasis on exogenous shocks as the driver of institutional change can "obscure" the internal, or endogenous, sources of transformation (Mahoney & Thelen, 2010, p. 7). This path dependence logic may also fail to explain the factors leading up to critical junctures (Hall & Taylor, 1996) and tends to oversimplify the process of political changes in a deterministic way (Thelen, 1999), overlooking actor-based explanations of change. Moreover, the institutionalist approach is incomplete without consideration of relationships and interaction among institutions (Randall Henning & Pratt, 2023).

Actor-based logic

A second and complementary logic, the actor-based logic, emphasizes the complexity of actors that either drive or inhibit change. In the context of the energy transition, there exists a web of overlapping and non-hierarchical institutions governing specific issue areas—a dynamic captured by the concept of 'regime complexes' (Raustiala & Victor, 2004). According to this logic, significant policy changes emerge from struggles between incumbent coalitions and challengers, eventually leading to major defections and policy shifts. Unlike the path-dependence logic, this approach is characterized by high volatility and instability (Alter & Raustiala, 2017). As a result, institutions are here understood not as stable equilibria but as "arenas of conflict," where incumbents aim to slow down the progress while niche or peripheral actors push for acceleration (Capoccia, 2016a, p. 21).

Incumbent actors typically have a vested interest in preserving the status quo and will often act strategically to maintain their privileged position (Johnstone et al., 2017). Incumbents often enjoy greater access to resources, stronger alliances, and veto players in key positions (Lockwood et al., 2017). Veto players, defined as "individual or collective actors whose agreement is necessary for changes in the status quo" (Tsebelis, 2002) can hinder more ambitious goals related to renewables and clean innovations, which are considered to threaten some of the business models of dominant incumbent fossil fuel actors (Johnstone & Newell, 2018).

In contrast, peripheral or niche actors—often led by the "losers" of previous institutional conflicts (Capoccia, 2016b, p. 1101)—promote their causes by building coalitions, mobilizing resources (including financial resources and expertise), shaping the public opinion, and advocating in policy debates (Roberts and Geels 2019). Despite active engagement, alternative ideas and solutions proposed by bottom-up actors often remain peripheral, particularly when 'political opportunity structures' are closed. Such grassroots mobilization typically unfolds slowly and incrementally. However, acts of rule reinterpretation or non-compliance can disrupt the status quo, creating openings for policy entrepreneurs to influence and redirect policy trajectories (Roberts and Geels 2019). These entrepreneurs use "windows of opportunity" to reform initiatives, making this form of policy changes largely "coalition-driven" (Jochim & May, 2010, p. 316).

In light of the contemporary clean energy transition, there is an increasing recognition that the nation state will play an increasingly vital role in shaping the hydrogen economy. From protecting innovations, supporting research and technological advancement, to implementing industrial policies, regulation, and enforcement, the state's unique range

and depth of power will be essential in achieving a clean energy transition (Johnstone & Newell, 2018). In discussions surrounding the protection and fostering of sustainable niche developments, the state is frequently highlighted for its crucial role in providing regulatory frameworks that safeguard and cultivate emerging niches (Nill & Kemp, 2009).

Scholars, however, recognize that state decisions may be vulnerable to actions of regulatory capture (Dal Bo, 2006). Regulatory capture refers to a process in which a private actor exerts control over regulatory outcomes, which are then designed and operated primarily for the benefit of that actor, often to the detriment of society at large (Devaux, 2018). Thus, the risks of regulatory capture may result in the inequitable or inefficient allocation of gains and burdens over time or across different regions (Macatangay & Roeben, 2021). Consequently, the persistence of regime resistance or changes is not solely attributable to incumbent actors but is also rooted in the design of policy-making institutions, as certain institutional arrangements may be more susceptible to regulatory capture than others.

Geo-economic logic

The final logic, the geo-economic logic, provides a more power-laden framework for analyzing the development of hydrogen trade relations. This approach rests on the assumption that the evolution of hydrogen trade is significantly influenced by existing and shifting power dynamics.

This logic is state-centric and aligns with the traditional realist IR theory, which posits that states inherently seek power, resulting in intense competition among states under the premise that power is a zero-sum game. Historically, competition between major powers has driven imperialism, resource extraction, and colonization, with these powers consistently expanding their economic and commercial influence, often through military means (Lind, 2024).

In contemporary times, there has been an expansion from a primarily geopolitical and military focus on power toward an emphasis on geo-economics. Luttwak (1990, p. 21) introduced the concept of geo-economics to characterize the emerging post-Cold War order, predicting that economic factors would increasingly serve as both the primary causes and methods of conflict. Luttwak identified several novel policy instruments, or 'weapons of commerce,' such as import restrictions, export subsidies, and the financing of competitive technological projects and infrastructure as tools for states to advance their national interests. In this regard, geo-economics can be understood as the continuation of warfare "by other means" (Blackwill & Harris, 2016). Consequently, the development of international hydrogen trade could both provoke international conflicts and serve as a mechanism for exerting influence and maximizing state power.

The emphasis in the geo-economic logic lies on how asymmetries in hydrogen trade and dependency relations contribute to interstate rivalries and competition. According to this perspective, excessive reliance on foreign technologies diminishes both the autonomy and influence that characterize great powers. States can bolster their

technological sovereignty by enhancing self-sufficiency and diversifying partnerships to manage the diffusion of clean hydrogen technologies (Diesen, 2021).

However, the ability of states to maximize geo-economic power is not evenly distributed. The uneven distribution of power among states on the global stage can be understood through the framework of dependency theory (Dos Santos, 1970). This theory argues that disparities in power stem from the unequal control over valuable resources, which positions actors differently within the global system, thus shaping their capacity to influence and exercise power (Baumgartner et al., 1976). Central to this framework is the distinction between 'center' and 'periphery', where core countries are characterized by greater economic and political power, dominating global systems of production and trade, while peripheral countries remain structurally constrained and vulnerable (Tausch, 2019). The integration of peripheral economies into global markets occurs under conditions that overwhelmingly favor the core, or powerful countries, reinforcing and perpetuating global inequalities.

As a result, dependency theory reveals how the current global economic order limits the autonomy of weaker states, restricting their ability to pursue independent political and economic interests (Kvangraven, 2021). Accordingly, the development of the global hydrogen economy may reinforce the existing power asymmetries, where technologically advanced and industrialized may shape the future of hydrogen trade relations at the expense of the peripheral countries.

Chapter 4.
Research design & methods

Research design & methods

Before presenting the main body of this dissertation—the academic articles—I will first outline the research design and methods used. I begin by defining the thematic and geographic scope of the study. Subsequently, I expand on the data sources and methods of analysis. I then reflect on my positionality and discuss the overall research process and progress. Finally, I introduce the four articles part of this dissertation and their data collection and analysis methods and contextualize them within the dissertation, highlighting their theoretical and analytical position.

4.1 Scope

In this section, I define and delineate the thematic and geographical scope of my dissertation. I outline my conceptualization of the hydrogen ecosystem and provide a justification for the selected geographical focus, both for the dissertation as well as for each of the individual articles.

The hydrogen ecosystem

While this dissertation is centered on 'hydrogen', it is important to clarify that the scope extends well beyond the hydrogen molecule itself. Instead, the analysis encompasses the broader 'hydrogen ecosystem'—a multifaceted network of technologies, infrastructures, products, and policy frameworks. This includes various methods of hydrogen production, as well as hydrogen synthetic derivatives such as ammonia, methanol, methane, diesel, kerosine, liquid organic hydrogen carriers, and products like hydrogen-based fertilizer, DRI or steel. In other words, the term 'hydrogen' is used here as a shorthand for a wider set of clean hydrogen-derived compounds and applications.

Transportation methods for hydrogen and its derivatives are also integral to this ecosystem, given their strategic and political significance. In addition, the dissertation considers technologies across the hydrogen value chain—from upstream components like electrolyzers to downstream applications. Taken together, these elements form a complex and interconnected system. Accordingly, this approach gives this dissertation the possibility to treat hydrogen not as a singular energy carrier, but as a system embedded within broader industrial, socio-technical, political, and geopolitical dynamics (see Chapter 3).

Each article within the dissertation reflects this broad conception in different ways. Article 1 conceptualizes hydrogen through the lens of socio-technical regime theory, attending to the interplay between technical developments and the institutional and discursive forces shaping the hydrogen sector. Article 2 takes a pragmatic approach by analyzing hydrogen partnerships as they currently exist, often without clearly dis-

tinguishing between production methods or specific derivatives. Articles 3 and 4 adopt a more systemic perspective. Article 3 interrogates the hydrogen ecosystem through the lens of green colonialism and green transformation, while Article 4 explores the geopolitical implications of technological leadership in hydrogen-related technologies, including both upstream technologies like electrolyzers and downstream applications such as hydrogen-based fertilizers and green steel production.

Together, these contributions underscore the importance of analyzing hydrogen as an evolving and deeply interconnected ecosystem—one that traverses multiple domains and geographies, from local infrastructures to global political economies.

Geographical scope

The overall research question in this dissertation focuses on the energy security implications of hydrogen imports in NWE. The conceptualization of NWE is drawn from studies conducted by the IEA, specifically "Hydrogen in North Western Europe: A Vision Towards 2030" (IEA, 2021c) and "North West European Hydrogen Monitor" (2022c, 2024d). For this dissertation, NWE includes Belgium, Denmark, France, Germany, the Netherlands, Norway, and the United Kingdom. The selection of NWE as a geographic focus is based on three key criteria. First, the region accounts for about 55% of OECD Europe's total hydrogen demand, approximately 4.5 Mt per year, representing nearly 5% of global hydrogen demand in 2024. Second, NWE countries are expected to make up 75% of global hydrogen imports by 2030 (IEA, 2024d). Third, each of these countries has developed national hydrogen strategies and is actively formulating hydrogen policies (Corbeau & Nassif, 2025).

In Article 1, I conducted a case study on natural gas and hydrogen market developments in the aforementioned NWE countries. In Article 2, I narrow the analysis to Germany, the Netherlands, and Belgium, as these three countries are actively establishing import partnerships with third countries. Norway, Denmark, and the UK, are considered to be hydrogen exporting countries, and therefore excluded from the case selection, as was France, which aims for hydrogen self-reliance by solely relying on domestic hydrogen production.

In both Article 3 and Article 4, I expand the geographical scope as a consequence of the research design. In Article 3, I explore hydrogen trade between the Global North and the Global South employing a hermeneutic narrative literature review. Given that NWE is part of the Global North, I consider the findings relevant to NWE. In Article 4, I discuss NWE countries within the context of the EU as part of an interpretative case study. While Norway and the UK are not EU members, I argue that the findings and trends with regard to technological leadership and the geopolitical and geo-economic implications are applicable to them as well.

4.2 Data sources

This dissertation employs a combination of data sources, incorporating both existing and original data. This approach is deemed most suitable for the mixed-methods framework and the diverse methodologies applied across the various articles.

First, the research draws on existing primary quantitative data sourced from official institutional databases. Article 2 specifically relies on data from the World Bank and the United Nations, as well as datasets compiled by civil society organizations such as Transparency International and the Fund for Peace. In contrast, Articles 1 and 4 predominantly utilize publicly available databases from organizations such as the IEA, IRENA, EUROSTAT, BP, and CEDIGAZ.

Secondary data were also gathered from a variety of existing sources, including reports, national hydrogen strategies, policy documents, legislative texts, academic publications, policy papers, press articles (e.g., The Financial Times, Euractiv), and a broad range of peer-reviewed academic literature. Another secondary data source is a self-compiled hydrogen partnership database. The hydrogen partnership database, systematically compiled and continuously updated throughout the dissertation process, captures the global landscape of emerging hydrogen collaborations. The database is made publicly accessible via Zenodo.

Second, this dissertation draws upon one original data source: a series of semi-structured expert interviews. This data source significantly enhances the empirical foundation of the study, particularly considering the hydrogen market's early-stage and rapidly evolving nature. The interviews, conducted with key stakeholders actively shaping the hydrogen trade, yield rich, practice-oriented insights that are otherwise absent in the existing literature. In line with Ghent University's data management regulations, a data management plan has been devised to ensure the secure storage and ethical handling of interview data, which will be retained for five years following the dissertation's completion.

Below, a detailed account of the interview methodology is provided, as well as a discussion on the hydrogen partnership database as an important secondary data source.

Interviews

Interviews play a crucial role in this dissertation. I align with Mosley (2013, p. 2), who argues that "interviews are an important, and often essential, tool for making sense of political phenomena". In this dissertation, I conducted two types of interviews: expert interviews and elite interviews. While these interview types share similarities, they offer slightly different perspectives. In elite interviews, 'power,' 'status,' and 'perspectives' are central, whereas in expert interviews, the focus is on 'knowledge' and 'position' (Van Audenhove & Donders, 2019, p. 181). The purpose of conducting interviews is to gather specific types of knowledge. Scholars have categorized the knowledge researchers seek by conducting interviews in various ways. For example, Bogner et al. (2009) identify 'technical knowledge', 'process knowledge', and 'explanatory knowledge' which denotes

the normative positions experts take rather than purely factual stances. Kaiser (2024) adds 'context knowledge,' which encompasses the context, power dynamics, and interest structures influencing the resolution of societal conflicts.

Identifying or sampling potential interviewees can be done in several ways. Careful sampling helps minimize bias and challenges the homogeneity of expert knowledge (Van Audenhove & Donders, 2019). In this dissertation, I employed a non-probability sampling technique to select interviewees. Unlike probability sampling, non-probability sampling does not aim to create a representative sample of political actors for generalizing to a broader population. The first method of non-probability sampling I used is 'purposive sampling', which focuses on selecting key figures who participated in the processes under study. A considerable limitation of non-probability sampling is the role of subjective judgment in selecting the sample, as the researcher determines which individuals to include. On the other hand, it can provide detailed insights into highly specific events and processes and ensures that all important actors are included (Tansey, 2007). This is particularly helpful for receiving process, explanatory and context knowledge.

The second sampling technique utilized in this dissertation is 'snowball sampling'. Once an expert is identified, I asked them to suggest other experts in their field. To reduce bias, I requested that they provide names of individuals who both agree and disagree with their own perspectives. Alternatively, I asked for experts from related fields, such as economic, political, legal, or technical aspects of the topic under study. Given the rapidly evolving nature of the hydrogen market, I opted for this method, to ensure that all relevant actors were included.

This dissertation draws on a total of thirteen interviews, conducted in two distinct phases of the PhD. The first four interviews took place between March and April 2022, while the remaining nine were conducted between February and June 2024. These interviews were used in two separate articles within this dissertation, each with a distinct focus. The first four interviews were expert interviews, with participants selected based on their expertise and involvement in specific policy processes and developments. The goal of these interviews was to gain technical knowledge about the hydrogen and natural gas markets, understand the evolution, and provide context on various aspects of policy-making. The other nine interviews, conducted as part of Article 3, had a different focus. They were elite interviews aimed at gaining insights into the perspectives of elites from the Global South regarding the development of hydrogen trade with the Global North. A comparison between the two interviews can be found in Table 10.

Table 10: Differences between interviews for Article 1 vs Article 3

	Article 1	**Article 3**
Type of interview	Expert interview	Elite interview
Type of knowledge	Technical knowledge Process knowledge Context knowledge	Explanatory knowledge Context knowledge
Sampling tactics	Purposive sampling Snowball sampling	Purposive sampling
Structure	Semi-structured	Semi-structured
Place	Face-to-face	Face-to-face Online

Potential interviewees were initially contacted via email or phone, where they were introduced to the research topic, its objectives, and their potential role in the study. Upon request, guiding questions were provided in advance of the interview. Given that all interviews were granted anonymity they are referred to in a non-referable way, allowing them to speak openly and without reservation. Most interviews were recorded, and off-the-record comments were accommodated when requested. While the majority of interviews were conducted in English, some were held in Dutch or French. Most interviews took place face-to-face, with a few exceptions conducted online via Teams. A list of all interviews conducted can be found below in Table 11.

Table 11: Overview of interviews

No.	**Function**	**Place**	**Date**
1	Director of gas TSO	Brussels	30/03/2022
2	Former director of energy utility	Brussels	21/04/2022
3	Director of energy utility company	Gent	17/05/2022
4	Minister of State	Hasselt	19/05/2022
5	Ambassador	Brussels	20/02/2024
6	Head of Trade at Embassy	Brussels	20/02/2024
7	Ambassador	Brussels	28/02/2024
8	Head of Science & Technology at Embassy	Brussels	07/03/2024
9	Ambassador	Brussels	07/03/2024
10	Minister plenipotentiary	Brussels	23/04/2024
11	Diplomat	Brussels	17/04/2024
12	Representative of the government-owned H2 company	Online	29/04/2024
13	Head of Investment relations at national government	Online	18/06/2024

Hydrogen partnership database

Another important secondary data source utilized in this dissertation is a self-compiled hydrogen partnership database, developed during the course of this PhD research. The database draws on publicly accessible materials, including MoUs, corporate websites, and media reports. It is systematically organized by participating countries and their respective regions, the stated objectives of the partnership (e.g., trade, collaboration, investment, pilot shipment), the nature of the agreement (intergovernmental, public-private, or private), the commodity involved (where specified), the year of conclusion, and the current status of the partnership. Where relevant, additional actors beyond national governments are identified.

The database was initially constructed for use in Article 2, which examines existing hydrogen partnerships. It was subsequently expanded and employed in Articles 3 and 4. In Article 3, the database is used to highlight the prevailing North–South dynamic in prospective hydrogen trade, while in Article 4, it serves as empirical evidence of the potential hydrogen market and its derivative markets and intensifying global competition. The complete database has been made publicly available via Zenodo and was updated regularly.

4.3 Data analysis

This dissertation employs a multi-method approach to examine the energy security implications of hydrogen imports in NWE. I contend that a mixed-methods framework is particularly well-suited to address the central research question, given the theoretical variety and conceptual complexities underpinning this dissertation. Additionally, the methods were tailored to address distinct research questions in the individual papers, ensuring their suitability and avoiding methodological bias. This methodological triangulation enhances the ability to trace and analyze the different dimensions of the central research question. Moreover, I argue that the limitations of one method are often counterbalanced by the strengths of another, as suggested by Tzagkarakis and Kritas (2023).

Article 1 and Article 4 utilize interpretative case study methodologies, with the former adopting a comparative case study design and the latter focusing on a single case study. Article 3 also employs qualitative methods, specifically through a narrative literature review. Article 2 applies a multi-criteria analysis (MCA) that incorporates both qualitative and quantitative techniques. A more detailed discussion of these distinct methods is provided below.

Interpretative case study

A primary method of data analysis in this dissertation is an interpretative case study, which is used in two of the articles. According to Lijphart (1971), interpretative case studies apply theoretical frameworks to explain particular cases. These studies do not aim at generalizable conclusions but instead focus on detailed examination of specific cases, without adding to specific theories (Lijphart, 1971). In contrast, Eckstein (1975) argues that interpretative case studies can help to challenge or refine existing theories. They not only test whether theories fit particular cases but also suggest new theoretical insights in areas where theories might be insufficient or lacking. This approach positions interpretative case studies as more than passive applications of a specific theory; they actively contribute to theory development, especially when they expose mismatches between theory and empirical data.

Vennesson (2008, p. 226) defines a case as a “phenomenon or event that is empirically analyzed and conceptualized as part of a broader class of phenomena or events”. In this view, cases are not merely units of analysis or observations; rather, they are theoretical constructs shaped by the researcher’s theoretical perspective (Ragin & Becker, 1992). The delimitations of cases are therefore not predetermined or spatially defined but are the result of theoretical decisions made by the researcher (Vennesson, 2008). For example, in Article 1, the natural gas and hydrogen socio-technical regimes in NWE are treated as two distinct cases. The development of these markets is considered an ‘event’, and their theoretical framing is derived from socio-technical regime theory. Similarly, in Article 4, the development of the hydrogen industry is defined by the concept of technological leadership.

Interpretative case studies are idiographic in nature, as they aim to explain or to interpret a particular ‘case’ without aiming to generalize data. This idiographic approach[10] differs from ‘configurative-ideographic’ research (Eckstein, 1975) or ‘atheoretical’ research (Lijphart, 1971) that are often considered historical or inductive case studies that are rather descriptive. Interpretative case studies are explicitly structured by a well-developed framework that focuses on some theoretical specified aspects of reality and neglects others (Levy, 2008). In this dissertation I build on two rich theoretical frameworks. In Article 1, socio-technical regime theory is used to interpret the development of both the natural gas and hydrogen markets in NWE. Meanwhile, the concept of technological leadership, commonly applied in evolutionary economics and innovation studies, informs the analysis of hydrogen leadership strategies in different countries in Article 4.

Case studies offer several methodological strengths. By focusing on a small number of cases, researchers can conduct a more detailed and thorough examination compared to large-N research designs, which often sacrifice depth for breadth (Lijphart, 1971). Case studies provide higher validity in conceptual refinement as they enable a nuanced analysis of specific variables and processes, particularly when exploring complex causal relationships. This depth allows for longitudinal perspectives and an understanding of temporal dynamics within the case, which is a significant advantage over cross-sectional large-N studies. This advantage is particularly relevant for Article 1, as it covers the historical development of the natural gas market in NWE.

Furthermore, case studies are well-suited for identifying new variables and hypotheses, especially when combined with qualitative methods such as interviews (George

10 Idiographic research is different from nomothetic research which aims to derive to generalizable laws or conclusions.

& Bennett, 2005). This has also proven to be valuable for this dissertation considering that Article 1 also draws upon interviews to explain and understand the socio-technical regimes of natural gas and hydrogen.

Despite their strengths, case study research comes with several challenges. One risk is 'selective reconstruction,' where researchers may unintentionally reconstruct the case to fit their preferred theoretical framework, neglecting important evidence that contradicts the theory (Odell, 2001, p. 164). Additionally, 'case selection bias' is a major concern in case study research. If cases are poorly selected, researchers may overstate relationships between variables or draw inaccurate conclusions, particularly if they generalize findings beyond the specific cases analyzed (Bennett & Elman, 2006). To mitigate these risks, researchers can improve case selection by drawing on preliminary knowledge and existing theoretical insights. In this dissertation, for example, the selection of hydrogen as a case was informed by prior knowledge on the energy security challenges in NWE and socio-technical systems which helped enhance the analytical rigor of the study and improve the research design.

Another challenge in case study research is finding a balance between theoretical parsimony and explanatory richness. Case studies tend to prioritize explanatory richness, focusing on uncovering the conditions and mechanisms behind specific outcomes rather than seeking to generalize findings across a large number of cases (George & Bennett, 2005). This emphasis on explanation rather than generalization allows for a deeper understanding of the cases, but it may sacrifice theoretical simplicity. In this dissertation, I have sought to balance parsimony and richness by building on socio-technical regime theory, a well-established and rich theoretical framework, while maintaining a simplified analytical structure. For example, the framework used in the analysis of the natural gas and hydrogen markets is structured around three clear-cut dimensions—material, institutional, and discursive—drawn from socio-technical regime theory. In the fourth article, I similarly balanced richness and parsimony by using a straightforward operationalization of the technological leadership framework while drawing on a rich body of literature on evolutionary economics and innovation studies to feed into the analysis.

A final limitation of interpretative case studies is their lack of generalizability (Eckstein, 1975). However, this may be less relevant for this dissertation. Firstly, I do not aim to come to generalizable outcomes, as the primary objective of this dissertation is to explore the energy security implications of hydrogen imports in NWE and not to build a theory. However, to partially address this limitation, I employed a structured-focused comparison in the first article, analyzing two cases: the development of the natural gas market and the development of the hydrogen market in NWE. The standardized questions used in this comparison were based on the socio-technical regime theory analytical framework, focusing on the three dimensions of material, institutional, and discursive factors. The comparison was conducted using both the method of difference and the method of agreement, which allowed to identify both the differences and similarities between both cases, offering insights into the conditions under which specific outcomes in these markets occurred.

Multi-criteria analysis

In this dissertation, particularly in Article 2, a second method employed is a multi-criteria analysis (MCA). MCA is a method used to appraise or evaluate a plan by considering various dimensions of interest and the interaction between multiple, often conflicting, objectives and decision criteria (Dean, 2020). In Article 2, MCA was applied to evaluate the selection of potential partner countries, which are typically selected only on technological and economic factors. My approach expanded these factors by incorporating economic, socio-political, and sustainability dimensions.

The MCA does not represent a singular, fixed method; instead, it serves as an umbrella term encompassing a range of techniques and tools that integrate multiple objectives and decision criteria into the analysis of a problem. Scholars have attempted to classify and develop taxonomies for MCA methods. For example, Dean (2018) distinguishes between formal and simplified MCA approaches. Formal MCA methods are characterized by structured procedures, rigorous (though sometimes arbitrary) rules, and often advanced mathematical principles. In contrast, simplified MCA approaches involve less formal, and frequently more rough applications of the method. Given my background and the available resources, I employed a simplified MCA (Dean, 2020). Furthermore, the MCA applied in Article 2 did not assign weights to the different indicators, as all were considered equally important. Scoring was conducted using a binary method, in order to address the variety of each indicator, and the thresholds for dichotomization were theoretically determined.

This method presents certain limitations (Kujawski, 2003). First, MCA problems typically lack conclusive or unique solutions. However, I do not regard this as a disadvantage, as such an outcome itself provides valuable insights, reflecting the complexity of decision-making when selecting hydrogen partner countries. Second, preferences for specific criteria may be influenced by the values of other criteria. For example, in the socio-political dimension, indicators of fragile states may correlate with the Corruption Perceptions Index. To address this, an aggregated score was used for the socio-political indicators. Third, sensitivity analysis is critical for assessing how the scores affect the solution and for testing the robustness of results within an MCA model. To this end, I conducted a robustness check to ensure the stability and reliability of the categorization used.

Narrative literature review

A third method utilized in this dissertation is a narrative literature review, which provides a non-systematic summary and analysis of existing literature on a specific topic (Gregory & Denniss, 2018). The aim of such reviews is to deepen the understanding of a particular subject. In Article 3, a narrative literature review was employed to explore divergent perspectives on whether North-South hydrogen trade would exacerbate inequalities or catalyze economic transformation.

Unlike systematic literature reviews, which often seek the 'probabilistic truth' and aim to produce generalizable facts for prediction, narrative literature reviews deal with

the ‘plausible truth’ (Greenhalgh et al., 2018). This distinction is reflected in the review conducted in Article 3, which is grounded in the hermeneutic tradition. Hermeneutics sees literature reviews as an ongoing process of interpretation, where understanding grows and deepens over time. Instead of aiming for one final or ‘correct’ answer, it focuses on gradually developing deeper insight (Boell & Cecez-Kecmanovic, 2014). From this perspective, literature is not treated as an objective truth to be organized and combined into a single argument. Instead, it is seen as a collection of complex and varied meanings, each open to interpretation and shaped by different viewpoints. As a result, the purpose of such a literature review is not just to point out gaps or summarize existing knowledge, but to encourage critical thinking and deeper reflection (Smythe & Spence, 2012). Considering the emerging field of literature concerning North-South hydrogen trade and its implications, I opted for this methodology. The aim of Article 3 was not to come to a systematic overview of literature on hydrogen but rather to map the diverging views, understand their theoretical embedding and critically compare both.

Critics of the narrative literature review perceive it as secondary compared to systematic literature reviews (Greenhalgh et al., 2018). They emphasize that narrative literature review are often biased (Nevo & Slonim-Nevo, 2011, p. 1176). Additionally, a legitimate criticism of narrative reviews is that they may “cherry pick” evidence to bolster a particular perspective (Greenhalgh et al., 2018, p. 4). But this must be weighed against the counterargument that the narrative reviewer selects evidence judiciously and purposively with an eye on what is relevant for key policy questions instead of coming to generalizable outcomes. Considering the novelty of both streams of the literature discussed in Article 3, I deem such an approach not only relevant but also desirable.

4.4 Reflections on positionality and process

Before introducing the articles that are part of this dissertation, it is important to reflect on my positionality and its influence on both the research and the PhD journey. These factors have been pivotal in shaping the outcomes of this dissertation.

Reflections on positionality

In their seminal book chapter, Furlong and Marsh (2010, p. 184) argue that each social scientist’s approach to their subject is shaped by their ontological and epistemological positions, which act as “a skin and not a sweater”—they are intrinsic to the researcher and cannot be disposed of when one sees fit. In a similar vein, Holmes (2020) concurs that researchers are inherently part of the social world they are studying, and that this world has already been interpreted by existing social actors. Therefore, it is important to reflect on my ontological and epistemological position and how those have impacted this dissertation. I consider this reflection not as an apology for the potential absence of objectivity in this dissertation, rather I value subjectivity and underscore the significance of the “intertwined personal, interpersonal, methodological and contextual factors that bring research into being” (Olmos-Vega et al., 2023, p. 242).

Ontology deals with the nature of reality. There are two main types of ontologies. A realist ontology sees reality as independent of human perception, with one single observable truth. In contrast, a relativist ontology views reality as shaped by individual and collective experiences, with multiple valid interpretations. Researchers adopting this view often use qualitative methods to explore these interpretations (Pretorius, 2024). I subscribe to the relativist ontology and believe that reality is inseparable from how individuals interpret it, and accordingly, I cannot study them objectively — a phenomenon dubbed ‘double hermeneutics’ by Anthony Giddens (1982).

My epistemological position complements this ontological perspective, as I do not adhere to the belief in a singular, objective truth. Rather, the primary aim of my research is to explore the varied perspectives and realities of the actors engaged in shaping the development of hydrogen trade. I consider technological innovation and knowledge production as socially situated practices, inherently shaped by individuals operating within specific social, cultural, and material contexts. Consequently, I reject the idea that hydrogen technologies are neutral or that objective, universally applicable pathways for hydrogen trade can be established. Rather, I recognize that hydrogen trade will have economic, environmental, geopolitical and societal implications. I also believe that the development of hydrogen technologies reflects the interests of various actors—for example policymakers, industry players, or civil society organizations —each with potentially complementary or conflicting visions on how the hydrogen future should look like. Different pathways may create winners and losers, and the eventual structure of the hydrogen trade landscape will be shaped not just by technological innovation, but more so by the interplay of these actors’ interests.

Additionally, throughout the course of my PhD trajectory, I have also increasingly reflected on the role I play as a researcher in shaping and contributing to the development of the hydrogen economy. The methodologies I have employed, and the research questions posed in this dissertation reflect my active participation in this evolving field. I have increasingly reflected on whose ‘voices’ I engage with in formulating my research questions, and whose knowledge I prioritize. This reflection has also led me to consider how my own engagement with the subject may influence both the knowledge production about the hydrogen economy as well as the power structures that my work may reinforce or challenge. This is also reflected in the evolution of the articles, with an increased focus on systemic power structures and struggles in Article 3 and 4.

Finally, I believe that researchers, being part of the social world, inevitably bring moral judgments based on personal values to their work—a key debate in axiology (Pretorius, 2024). I acknowledge that my research is not value-free, but rather value-laden. I am personally committed to a socially just, inclusive and environmentally sustainable energy transformation. These values have shaped the way I formulated my research questions, selected theories, chosen methodologies, and interpreted results. I recognize that another researcher, with different values or perspectives, might reach different conclusions. However, I do not view this as inherently good or bad; rather, it is a natural outcome of the ontological and epistemological positions that have shaped myself as researcher and, by extension, my work.

Process of the PhD

The journey of this PhD has been one of serendipity—characterized by the unexpected discovery of valuable insights along the way. At the outset, the research question, design, and case studies were not fully defined, which led this dissertation to take a 'non-traditional' form. Rather than a monograph, it consists of a collection of three scientific articles and a book chapter, all examining different aspects of the energy security implications of hydrogen imports in NWE.

This approach is partly the result of the changing political landscape. When I began my PhD in November 2021, the context surrounding hydrogen was markedly different from when I finalized it during the first half of 2025. At the start, there was a notable hydrogen 'hype,' with countries unveiling hydrogen strategies and forming international partnerships at a rapid pace. Just a few months into my research, Russia brutally invaded Ukraine, further accelerating hydrogen-related policy developments in Europe as the region sought to reduce its reliance on Russian natural gas. This geopolitical shift motivated me to write both Article 1, which draws lessons from natural gas imports for hydrogen imports, and Article 2, which assesses the energy security implications of new hydrogen partnerships considering the renewed attention to energy dependencies.

As my PhD progressed, my perspective on hydrogen also evolved, and I became more aware of the potential uneven distribution effects of hydrogen and how hydrogen trade may perpetuate existing inequalities in relation to the Global South. The increased critical policy and academic attention to the concept of 'hydrogen justice' prompted me to explore this issue further, culminating in the development of Article 3. Meanwhile, the growing focus on industrial policy influenced by the publication of landmark policy instruments such as the US Inflation Reduction Act (IRA) and the EU's Net-Zero Industrial Act (NZIA), and the declining optimism on large-scale hydrogen imports, led to the writing of Article 4, which focuses on technological leadership.

My research was also further shaped by the conducted interviews and attending and participating in a lot of hydrogen related events. During my PhD, I was part of an interdisciplinary consortium, BE-HyFE, funded by the Energy Transition Fund of the Federal Public Service of Economics in Belgium. Although my work was financially supported by them, the research was carried out with full academic independence. As part of this project, I participated in various hydrogen-related activities. In Table 12 an overview is given of the events I attended, including their locations, dates, and the specific roles I took on.

Table 12: Hydrogen events & researcher's roles

Event	Place	Date	Role
Meeting Cabinet of Minister Van der Straeten	Online	22/02/2022	Observer
Helicopter view on the green hydrogen opportunity	Ostend	20/02/2022	Observer
Hydrogen Week 1	Antwerp	9-15/05/2022	Participant
Poster presentation Hydrogen research event	Antwerp	12/05/2022	Presenter
Presentation update Belgium federal hydrogen strategy	Antwerp	18/10/2022	Observer
Hydrogen platform event	Ghent	18/11/2022	Participant
Presentation about geopolitics of Hydrogen at Virya	Eigen-brakel	2/02/2023	Presenter
Site visit Van Hool & Cummins	Lier	12/05/2023	Observer
Conference Belgian Hydrogen Council	Brussels	16/10/2023	Observer
Hydrogen Platform event	Ghent	24/10/2023	Participant
Presentation Klimaatneutrale Haven ABC Engines	Ghent	28/11/2023	Presenter
H2 Colloquium as part of the Belgian Presidency of the Council of the EU	Liège	16/02/2024	Observer
Energy Fest	Ghent	27/02/2024	Participant
Hydrogen Week 2- EPHyC Conference	Ghent	18-22/03/2024	Co-organizer
Paper presentation FPS Economy	Brussels	29/03/2024	Presenter
Presentation Belgian Hydrogen Council	Online	31/05/2024	Presenter
Research stay Florence School of Regulation	Florence	June 2024	Participant
Dag van de Wetenschap	Ghent	24/11/2024	Participant
Site visit Bekaert	Kortrijk	27/11/2024	Observer
Site visit ABC Engines	Ghent	14/03/2025	Observer

The insights gained during these hydrogen-related events were primarily used to provide context and fill in the gaps in my understanding of the development of hydrogen policies and identifying the main and ongoing debates in the discourses of both policy makers and industrial actors. While I acknowledge that my perspective is not entirely free from bias, I balanced this through data triangulation, combining my observations with the interviews, other primary data resources and a comprehensive review of the literature.

In sum, my PhD journey evolved organically and was affected by different factors such as external (geo)political events like the Russian invasion of Ukraine or the shifting discourse on hydrogen—from a focus on climate and energy to one centered on industrial policy. These developments raised pivotal questions that directed the course of my research. In this regard, I resonate with Alexander Wendt's, (1999, p. 40) assertion that "science should be question-driven, rather than method-driven." Such a question-driven research approach necessitates the adoption of interpretive methods, which have therefore played a central role in shaping the direction and analytical framework used in this dissertation.

I consider the dynamic nature of this PhD trajectory as a strength rather than a weakness. The uncertainty about the PhD's trajectory allowed me to remain open to new actors and topics, which ultimately enriched my understanding of the energy security implications of hydrogen imports into NWE.

4.5 Introduction to the articles

The following sections introduce the four articles that form the main body of this dissertation. Each article is structured around a distinct research question (see Box 4) and is grounded in its own theoretical and empirical approach. Collectively, they contribute to addressing the overarching research question of the dissertation.

While energy security is conceptualized in this dissertation across four interrelated dimensions, the articles are not organized according to these categories. Such a division would risk oversimplifying the complex and overlapping ways in which these dimensions manifest in practice. Instead, each article explores how specific cases and dynamics bring to light the contested and multifaceted nature of energy security. In doing so, they reveal how these dimensions intersect, reinforce one another, or, at times, come into tension.

By using the guiding sub-questions as points of departure, the articles allow different dimensions of energy security to emerge organically from the data, rather than being a priori determined. In some cases, a single dimension becomes especially salient; in others, multiple dimensions intersect and interact. Viewed collectively, the four articles offer a broad and integrated perspective on energy security. In the remainder of this section, I present each article in more detail. For each one, I will describe its theoretical approach and concepts, data sources, methods, and main contributions. A summary overview of the articles—covering theory, data sources and methods—is provided in Table 13.

In **Article 1**, titled "From natural gas to hydrogen: Navigating import risks and dependencies in Northwest Europe" co-authored by Thijs Van de Graaf, Ronnie Belmans, and myself, we explore whether future hydrogen imports will effectively address the EU's security of supply concerns or merely perpetuate existing vulnerabilities. To investigate this, we analyzed the ongoing development of the hydrogen market in NWE, drawing parallels with the historical development of the natural gas market in NWE.

Our analysis is grounded in socio-technical regime theory, specifically the framework introduced by van der Vleuten and Högselius (2012). Their framework, rooted in STS and systemic conceptualizations of energy, views socio-technical regimes as shaped by material, institutional, and discursive factors. The stability and evolution of energy regimes are understood as outcomes of the dynamic interaction between these dimensions. Additionally, van der Vleuten and Högselius (2012) emphasize the transnational nature of energy systems, which frequently transcend national borders, making their framework particularly suitable for analyzing both natural gas and hydrogen markets.

In terms of data collection, we conducted a comprehensive review of primary and secondary sources. Between March and May 2022, we carried out four semi-structured interviews with experts in infrastructure, market organization, and policymaking. These interviews were supplemented by extensive desk research, drawing on official documents, industry reports, and data. Our analytical approach involved a structured-focused comparison based on the socio-technical regime theory framework, focusing on the material, institutional, and discursive dimensions. The geographical focus in this article on NWE stems from the region's significant consumption of both natural gas and hydrogen.

This article contributes to the literature in two key ways. First, it sits at the intersection of fossil fuel and renewable energy politics, incorporating insights from the study of natural gas politics while identifying crucial differences informed by the politics of renewable energy. Second, it broadens the emerging body of hydrogen scholarship by examining the establishment of a hydrogen market through the lens of socio-technical regime theory highlighting material, institutional, and discursive factors, and embedding these insights within broader debates on energy politics and socio-technical systems.

In **Article 2** titled "Risky Business? Evaluating hydrogen partnerships established by Germany, The Netherlands, and Belgium", I undertake a post-hoc analysis of the economic, political, and sustainability risks associated with hydrogen partnerships already established between Germany, the Netherlands, Belgium, and third countries.

The theoretical approach is grounded in the burgeoning field of 'hydrogen diplomacy,' wherein I identify key indicators to assess the energy security implications of these partnerships. To date, much of the research and policy discourse surrounding hydrogen partnerships is dominated by technical considerations, with limited attention given to the socio-political dimensions of bilateral hydrogen trade agreements. Therefore, the analysis considers factors such as economic, technological, political, and sustainability dimensions to assess the broader implications of these partnerships.

The empirical foundation of this article draws on a diverse array of data sources, including databases from the World Bank, the United Nations, and datasets compiled by civil society organizations such as Transparency International and the Fund for Peace. To map the established hydrogen partnerships, I further relied on my own hydrogen partnership database, encompassing all relevant bilateral hydrogen deals involving Germany, the Netherlands, and Belgium. For data analysis, a content analysis of 15

extant studies was conducted, identifying salient indicators. Additionally, it employed a multi-criteria analysis to evaluate the partnerships based on these indicators.

This article makes two key contributions to the literature. First, rather than applying pre-defined criteria to select potential hydrogen import countries, it offers a post-hoc evaluative review of existing agreements. Second, it adopts a comprehensive understanding of energy security, integrating economic, political, and sustainability dimensions, and critically addressing both political, environmental sustainability and justice considerations.

In **Article 3** titled “Green colonialism or green transformation? The equity implications of clean hydrogen trade”, Thijs van de Graaf, and I critically examine the mechanisms underpinning two competing paradigms in the emerging North-South hydrogen trade: ‘green colonialism’ and ‘green transformation’. Rather than treating these frameworks as mutually exclusive, we transcend binary interpretations by connecting and unpacking these competing mechanisms.

Theoretically, our analysis engages with two key conceptual debates: ‘green colonialism’ and ‘green transformation’. We identify three risks associated with green colonialism: domination, accumulation, and appropriation. In contrast, we identify three responses for promoting green transformation: ensuring a voice, obtaining a stake, and fostering autonomy. By juxtaposing these perspectives, we advance beyond simplistic dichotomies to emphasize tensions, contradictions, and opportunities embedded in the evolving clean hydrogen landscape.

Methodologically, we draw on nine semi-structured elite interviews to foreground perspectives from the Global South—voices that have been underrepresented in scholarly discussions to date. Additionally, we conducted a narrative literature review of academic literature and policy reports on clean hydrogen trade to further deepen our analysis.

This article contributes to the existing literature by bringing together these two perspectives and facilitating a conversation between them. By moving beyond binary evaluations, we shed light on the tensions and opportunities within the clean hydrogen sector. Additionally, we provide a comprehensive framework for analyzing how economies in the Global South can navigate the dual pressures of economic opportunity and extractive dependency in emerging energy and commodity markets, extending the discussion beyond hydrogen.

In **Article 4**, titled “The Global Hydrogen Race: Competing strategies for hydrogen technology leadership,” Thijs Van de Graaf and I investigate the emerging competition for technological leadership within the hydrogen value chain. Our analysis focuses on three strategically significant technologies—electrolyzers, green steel, and hydrogen-based fertilizers—and examines how various countries are positioning themselves to lead in these domains. In doing so, we explore the broader implications of this competition for global power dynamics and geopolitical influence.
Theoretically, the article engages with literature from innovation studies, evolutionary economics, and historical analyses of industrial revolutions. We refine the concept of

‘technological leadership’ by disaggregating it into three interrelated dimensions: innovation, manufacturing, and deployment. These dimensions include indicators such as investment flows, patent activity, equipment manufacturing, resource endowments, and developing downstream industries.

Empirically, the article presents a case study that maps patterns of technological leadership within the global hydrogen value chain. This analysis draws on a wide range of secondary data, including reports from the IEA, the World Bank, IRENA.

This research contributes to a growing body of scholarship that shifts the focus of energy geopolitics from control over natural resources—as was characteristic of the fossil fuel era—toward leadership in energy technologies. By foregrounding the strategic importance of technologies, the article highlights how states increasingly view innovation and industrial capacity as critical sources of geopolitical power in the clean energy transition. While the framework in this article is developed with respect to hydrogen technologies, the framework should lend itself to analyzing leadership in other areas as well.

Table 13: Schematic overview of the articles

	Article 1	**Article 2**	**Article 3**		**Article 4**
RQ in article	Will future hydrogen imports effectively address the EU's historical security of supply concerns, or will they merely perpetuate existing vulnerabilities?	What are the economic, political, and sustainability risks related to the established hydrogen partnerships?	Does North-South hydrogen trade offer a transformative opportunity for the Global South, or does it simply reproduce existing colonial patterns?		What are the opportunities for technological leadership across the hydrogen value chain?
Theoretical foundations	Socio-technical regime theory	Energy diplomacy	Green colonialism & Green transformation		Technological leadership
Theoretical concepts	Material Institutional Discursive	Economics Socio-political Sustainability	Domination Accumulation Appropriation	Ensuring a voice Obtaining a stake Fostering autonomy	Innovation Manufacturing Deployment
Data sources	Interviews Document analysis	Public databases Hydrogen partnership database	Interviews Document analysis		Secondary data Document analysis
Data analysis	Interpretative case study Structured, focused comparison	Multi-criteria analysis	Narrative literature review		Interpretative case study

Chapter 5. Academic articles

Article 1.
From natural gas to hydrogen: Navigating import risks and dependencies in Northwest Europe

Marie Dejonghe, Thijs Van de Graaf and Ronnie Belmans

Abstract

Energy security has become a key driver of the European Union's (EU) hydrogen ambitions, especially in the wake of Russia's invasion of Ukraine and its weaponization of gas exports. At the same time, the EU's Hydrogen Strategy relies heavily on imports, which should meet half of the bloc's demand by 2030. This raises a crucial question: Will future hydrogen imports effectively address the EU's historical security of supply concerns, or will they merely perpetuate existing vulnerabilities? To answer that question, this study analyses the history of natural gas trade in Northwestern Europe, using an analytical framework rooted in socio-technical regime theory. The underlying assumption is that, while the future of hydrogen trade is uncertain, its development may echo that of natural gas, given their physical similarities. Our findings reveal that the development of hydrogen markets is more policy-driven and could follow a different trajectory than natural gas, with seaborne (derivative) shipments preceding pipeline trade. The hydrogen market has significant potential to be less unified and concentrated than natural gas markets, reducing the risk of supply disruptions. However, the exact energy security consequences of hydrogen imports depend on choices made today, which will likely establish enduring path dependencies. Therefore, rather than automatically favoring the most cost-effective import pathway, policymakers should prioritize demand reduction (via efficiency and conservation), diversification (across suppliers, routes, and carriers) and resilience to shocks (facilitated by storage and emergency contingency planning).

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1. Introduction

The European Union (EU) has set ambitious goals for clean hydrogen[11]. Its 2020 Hydrogen Strategy emphasized the importance of hydrogen to support the European Green Deal and its central goal of achieving climate neutrality by 2050 (European Commission, 2020a). The REPowerEU package, proposed in the wake of Russia's invasion of Ukraine, highlighted the potential of hydrogen to achieve energy security and phase out the EU's dependence on Russian fossil fuels. The quantities of renewable hydrogen that the EU aims for are difficult to produce at home. Therefore, the EU's strategy relies on imports of hydrogen or derivatives. More specifically, REPowerEU sets targets of 10 million tons (Mt) of domestic renewable hydrogen production and 10 Mt of renewable hydrogen imports by 2030. The European Commission estimates that renewable hydrogen could reduce the EU's gas demand by approximately 27 billion cubic meters by 2030 (European Commission, 2022b)—that is, around 17% of total Russian volumes imported in 2021.

Given the importance of energy security as a driver of the EU's hydrogen policies, it is crucial to manage any new security of supply risks that may emerge with hydrogen imports. This study argues that the natural gas market can provide valuable insights into the development and potential risks of hydrogen import flows, for two reasons. First, there are important similarities between natural gas and hydrogen in terms of their physical properties and (potential) market structures and regulations. As the Hydrogen Council and McKinsey put it: "The evolution of the global gas and liquefied natural gas (LNG) market may have parallels with the prospective global market for hydrogen" (Hydrogen Council & McKinsey & Company, 2022). Analyzing the historical development of the gas market can thus provide valuable insights into the spatial and temporal sequencing of future hydrogen trade relations and dependencies.

Second, the 2022 gas crisis, triggered by a sharp reduction of Russian pipeline exports to the EU, raises the question of why so many countries have engaged in cross-border energy infrastructure relations that put them in such a vulnerable position. Many countries are now grappling with the challenge of securing energy and other resources in a time of increasing global competition and the urgent need to reduce greenhouse gas emissions. Bringing clean hydrogen to scale will require new transnational energy links and infrastructure. Policymakers looking to shape future clean hydrogen markets can learn from the risks and pitfalls of the 2022 gas crisis and the decisions and conditions that have enabled it.

The focus of this article is twofold: (1) examine the key features of the natural gas market and how they have evolved over time and across space, and (2) explore how a prospective hydrogen market may develop based on these features. In other words, we aim to identify whether and how natural gas trade can serve as a model for hydrogen trade. Our analysis is not a modeling exercise but a theory-guided, qualitative analysis,

11 The European Commission considers only renewable hydrogen or hydrogen produced through biogas reforming as "clean" hydrogen. "Renewable" hydrogen refers to renewable hydrogen as hydrogen produced trough electrolysis of water powered by renewable electricity.

drawing on a large body of literature on socio-technical regimes and regime change. This analytical framework is further elaborated in section 2.

2. Literature review and analytical framework

2.1 Hydrogen trade and geopolitics

There is a burgeoning literature on hydrogen and its potential role in the energy transition. While the consensus is that hydrogen is a key ingredient in reaching net zero emissions, there is still a lot of uncertainty regarding how quickly clean hydrogen value chains can scale, the extent to which hydrogen could become an internationally traded commodity, and the broader energy security challenges that such trade would entail.

These questions have predominantly been addressed by developing scenarios on the future of clean hydrogen demand, supply, and trade routes (BNEF, 2020; Hydrogen Council & McKinsey & Company, 2021, 2022; IEA, 2019, 2021b, 2022b; IRENA, 2022c). Often, these scenarios are normative, in the sense that they start from the Paris climate goal of 1.5°C and then lay out hydrogen pathways to achieve that goal.

In recent years, several studies have begun to analyze the broader (geo)political ramifications of hydrogen trade (Hausemann et al., 2021; IRENA, 2022a; Lebrouhi et al., 2022; Van de Graaf, 2020; Van de Graaf et al., 2020). However, these studies are often explorative, taking the form of thought exercises or horizon scans. Some have relied on various indices to try and position countries in the future landscape of hydrogen geopolitics (Eicke & De Blasio, 2022; Pflugmann & De Blasio, 2020), including patent filings (Moreno-Brieva et al., 2023), while others are based on expert surveys (IRENA, 2022a). Still others have mapped key stakeholders and their discourse around hydrogen (Belova et al., 2023).

While most studies assume that the EU will become an importer of hydrogen, Nuñez-Jimenez and De Blasio (2022) argue that the EU has the potential to achieve hydrogen independence with domestic production. However, they also highlight the advantages of importing hydrogen from neighboring countries to enhance cost efficiency, as well as the benefits of long-distance imports in diversifying hydrogen supplies for geopolitical aspirations and bolstering energy security in the EU.

In this paper, we take a different approach to sketch a possible pathway for the development of international hydrogen trade, and to examine the potential geopolitical consequences. Rather than developing scenarios or drawing inferences from various indices or expert opinions, we draw lessons for setting up hydrogen import value chains by looking at the historical development of natural gas import value chains. To that end, we draw on socio-technical regime theory.

2.2 Socio-technical regime theory

Socio-technical regime theory, as developed by scholars such as Grin et al. (2010), emphasize the interplay between social and technical factors in the development and

evolution of energy systems. This framework allows for a nuanced analysis of the ways in which social and political factors shape the development of energy technologies and infrastructures, and how these technologies and infrastructures in turn shape social and political processes (Geels and Schot, 2010).

Socio-technical regime theory has been applied to case studies of different energy technologies, including the electricity sector (van der Vleuten & Högselius, 2012; Verbong & Geels, 2007), renewable energy (Essletzbichler, 2012) and natural gas (van der Vleuten & Högselius, 2012). In a recent study, hydrogen has been conceived as a socio-technical regime as well (Griffiths et al., 2021). In their study, Griffiths et al. (2021) consider not only the technical aspects of the hydrogen energy system (e.g., hydrogen production) but the institutional aspects as well (e.g. policy drivers, governments, end-user preference).

One of the central ideas of socio-technical regime theory is the concept of a 'regime,' which refers to a set of shared beliefs, norms, and practices that govern a particular technological system (Geels, 2002, 2004). This concept is based on the idea that technological systems are not simply neutral tools, but embedded in broader social, political, and economic contexts that shape their development and use (Geels, 2002, 2005).

A key argument of socio-technical regime theory is that technological change is not a linear, one-way process, but is instead influenced by a complex web of social, political, and economic factors (Geels, 2002). These factors can either promote or hinder the adoption and diffusion of new technologies and can even lead to the emergence of competing technologies or 'path dependencies' that lock in certain technologies over others (Geels, 2002, 2005; Unruh, 2000; Verbong and Geels, 2007).

Another important concept in socio-technical regime theory is the idea of 'actor networks,' which refers to the various individuals, organizations, and institutions involved in the development, adoption, and use of a particular technology (Geels and Schot 2010; Sovacool and Hess, 2017). Actors may include researchers, policymakers, industry representatives, interest groups, investors and consumers, among others. Socio-technical regime theory argues that these actor networks play a crucial role in shaping the direction and trajectory of technological change (Fuenfschilling & Binz, 2018).

2.3 Analytical framework

For the purposes of our analysis, we rely on the analytical framework developed by van der Vleuten and Högselius (2012). Their framework is based on socio-technical regime theory but proposes several amendments to it. In particular, they call for a 'transnational' perspective on regime dynamics. This perspective focuses on the ways in which energy systems, and their associated technologies and infrastructures are shaped by global forces and transnational connections. The approach allows for a deeper understanding of the global context in which energy systems develop and evolve, and the ways in which they are interconnected across borders.

The central gist of their argument is that energy regimes are underpinned by at least three interlocking factors (see Table 14): institutional (actors and organizations), ma-

terial (technological infrastructure), and discursive (guiding ideas and expectations) dimensions. The growth, stability and change of energy systems results from the constituent evolution of these three dimensions, which are not a priori ranked in terms of importance (Verbong et al. 2002; van der Vleuten & Högselius, 2012).

The institutional dimension covers concepts like path dependence, actor constellations, and governance arrangements. It requires an analysis of what van der Vleuten and Högselius (2012) call 'antecedents': incumbent energy technology regimes that could influence the development of an industry or sector. Analyzing the institutional dimension also directs attention to the ways in which different stakeholders, such as governments, industry organizations, and civil society groups, have shaped the development of the natural gas industry, and the specific agreements they have forged to steer (transnational) energy exchanges.

The material dimension, in turn, addresses the technological infrastructure associated with natural gas and hydrogen trade. A focus on this dimension can help to explain the ways in which the availability and cost of transport infrastructure can influence the feasibility and economic viability of importing hydrogen or natural gas. It could also help to explain the concentration of production and trade within the hydrogen and natural gas industries, and the ways in which this concentration can create vulnerabilities and risks for importing countries (van der Vleuten & Högselius, 2012).

The discursive dimension, finally, considers the guiding ideas and expectations of energy regimes (van der Vleuten & Högselius, 2012). It is related to the concept of 'interpretative flexibility', which refers to the ways in which different stakeholders interpret and use technology in different ways (Bijker, 2009; Pinch & Bijker, 1984). This concept can help to explain the ways in which hydrogen and natural gas are used in different sectors, and the ways in which these end-use sectors can influence the demand for hydrogen and natural gas. It can also shed light on how the public perception of natural gas and hydrogen has evolved over time, notably in response to focusing events and changes in the broader landscape as previously examined by Belova et al. (2023).

Table 14: Analytical framework based on van der Vleuten & Högselius (2012)

Dimension	Features
Institutional	Antecedents: Incumbent energy technology regime Governance: actors, organizations and agreements
Material	Transport infrastructure Diversification of trade
Discursive	Discursive embedding

3. Methods and approach

3.1 Grounds for the comparative analysis

Our analysis is based on the assumption that the development of hydrogen markets will resemble that of natural gas due to similarities in their physical properties. Both hydrogen and natural gas are gaseous substances that can be transported via pipelines or, if liquefied, via ships. When natural gas is liquefied, it is referred to as LNG. Similarly, hydrogen can be liquefied through cooling, or converted into derivatives such as ammonia or methanol, which are relatively easy to store and transport. Moreover, both hydrogen and natural gas can be used as feedstock and fuel.

There are differences between the two gases as well. Firstly, hydrogen has a higher gravimetric energy density than natural gas, measuring 142 MJ and 55 MJ per kilogram, respectively, but it has a lower volumetric energy density, respectively 12.7 MJ and 40.6 MJ per cubic meter. Consequently, almost four times the volume of hydrogen is required to have the same energy content as natural gas[12]. Additionally, hydrogen liquefies at a temperature of minus 253°C, while natural gas liquefies at minus 162°C. Therefore, the process of liquefying hydrogen is more energy-intensive (The Engineering Toolbox, 2008).

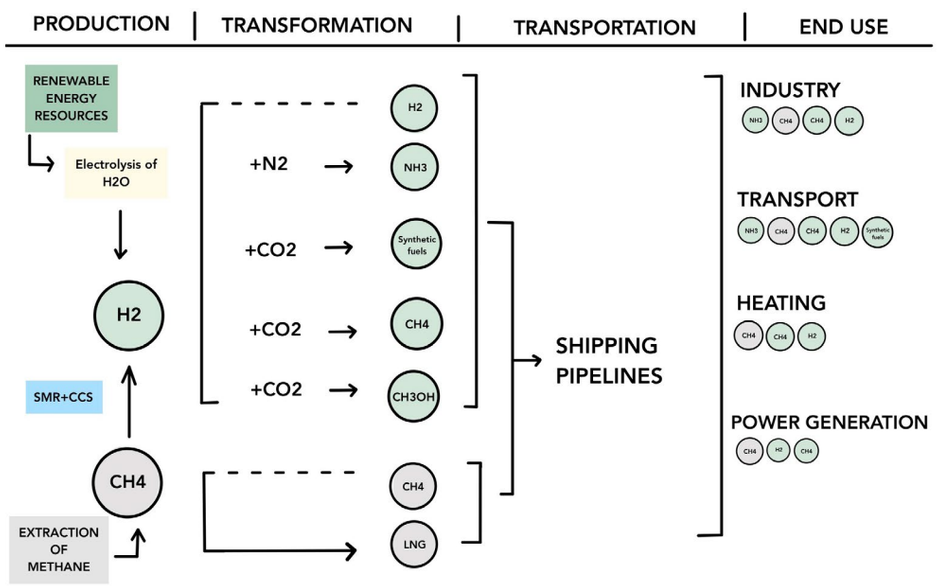
Secondly, natural gas is a fossil fuel extracted from natural gas fields, whereas hydrogen is not an energy source itself but rather an energy carrier that needs to be produced since it rarely occurs in its pure form (IRENA, 2022a). Hydrogen can be produced through various methods. 'Green' hydrogen is produced by electrolyzing water using renewable electricity, primarily from wind and solar energy. Hydrogen can also be derived from natural gas through steam methane reforming (SMR). When the CO_2 emitted during this process is not captured, the resulting hydrogen is referred to as 'grey' hydrogen. However, if the CO_2 is captured and stored or utilized (CCUS), the hydrogen is called 'blue' hydrogen. Other production methods exist, leading to different colors of hydrogen. Nonetheless, 'green' and 'blue' hydrogen are the most commonly discussed production methods within the context of carbon neutrality. Today, the majority of hydrogen produced is 'grey'.

In addition to similarities and differences, there are also overlaps in the value chains of hydrogen and natural gas (see Figure 6). As mentioned earlier, hydrogen could be produced from natural gas through SMR (or through methane pyrolysis, a process that yields 'turquoise' hydrogen). Conversely, synthetic methane could be produced from hydrogen through the Sabatier process, where hydrogen reacts with a CO_2 molecule obtained either from the air directly or from natural gas power plants and industrial processes (Benz, 2021). Furthermore, hydrogen can be blended with natural gas. There are ongoing projects exploring hydrogen blending with natural gas up to 20% in terms of volume (equivalent to 6% of energy density) (IEA, 2022b). However, the practice of blending hydrogen is contested on efficiency, economic and safety grounds. Additionally, the usefulness of blending hydrogen with natural gas is still a topic of debate (Fils & Deutsch, 2021). In sum, both gases and their value chains are interrelated and

12 These conversions are all at higher heating value.

cannot be considered in isolation from each other (Hollenhorst, 2023). Moreover, despite the differences between the two molecules, we consider these distinctions to be secondary to the systematic similarities between hydrogen and natural gas in terms of market structure.

Figure 6: Interrelatedness of hydrogen and natural gas value chains[13]



3.2 Data collection and case selection

To understand the socio-technical regimes of natural gas and hydrogen, we thoroughly examined a wide range of primary and secondary data. Between March 2022 and May 2022, we conducted four semi-structured interviews. The selection of interviewees was based on their expertise in three domains: infrastructure, market organization, and policy making. As the interviewees were granted anonymity, their insights are referred to in a non-attributable way. The interviews were complemented by extensive desk research of official documents, reports, and industrial data.

Our analysis constitutes a case study (Odell, 2001) of the natural gas and hydrogen regimes in NWE[14] , a major industrial region that accounts for almost half of Europe's natural gas consumption and around 60% of its hydrogen demand (BP, 2022). Most of the hydrogen consumed was produced on-site, although the NWE region also hosts the world's largest transnational hydrogen pipeline network, operated by Air Liquide.

13 There are other pathways to produce carbon neutral or low carbon hydrogen, in this figure we only included so-called 'green' and 'blue' hydrogen. H2= hydrogen, CH4= methane, NH3= ammonia, CH3OH = methanol, LNG= liquified natural gas.

14 In this paper we consider following countries as part of Northwestern Europe: Belgium, the Netherlands, Germany, Norway, Denmark, UK and France

The primary consumption of hydrogen in NWE is in the industrial sector, as the Antwerp-Rotterdam-Rhine-Ruhr area alone accounts for around 40% of Europe's chemicals production. Due to its highly industrialized nature, this region is considered a key hub for future hydrogen import demand, alongside North-East Asia (IEA, 2021c).

4. Analysis: From natural gas imports to hydrogen imports in Northwest Europe

In this section, we conduct our analysis of natural gas and hydrogen trade regimes along the three dimensions of our analytical framework: the institutional, material and discursive dimensions. For each feature, we trace the historical development of natural gas imports in NWE and contemplate about the lessons for the structure and consequences of the hydrogen trade relationships that might develop in the future (see Table 15).

Table 15: Key features of the natural gas market compared to prospective hydrogen trade

Features	Natural gas	Hydrogen
Antecedents	Town gas with small infrastructure network	Fossil fuel-based hydrogen with small infrastructure network
Governance	Long-term contracts Take-or-pay clauses Oil indexed prices Consortia	Long-term contracts Auctions Joint procurements Certification
Transport infrastructure	Pipeline trade, later seaborne trade	Seaborne trade, later pipeline trade
Diversification	Concentric circles: geography and diversification	Bilateral agreements with mostly non-regional actors
Discursive embedding	Debate on import dependencies came only after the first imports were already set up	Debates on imports or domestic production Debates on consumption Debates on hydrogen 'color'

4.1 Institutional make-up

Antecedents

The start of natural gas imports in NWE did not take place in a vacuum. Before the 1960s, gas consumption in NWE predominantly comprised coal gas, made from (local) coal supplies. Initially, coal gas was simply a byproduct of the process to produce coke for steelmaking but, later, dedicated coal gas factories were built (De Clercq, 1975). Coal gas was mostly consumed in the vicinity of these factories, often located in

cities, which is why it came to be known as ‘town gas’. Distribution occurred through relatively small pipeline networks centered around these gas factories (Eandis, 2013).

The development of the modern natural gas industry in NWE started with the discovery of the Groningen field in 1959. Parallel to serving the domestic market in the Netherlands, large volumes of Dutch gas were soon exported to West-Germany (1963), followed by Belgium (1966), France and Luxembourg (1967) (Messner et al., 1986; Nies, 2011). In 1971, contracts were also signed with Italy and Switzerland. Until the 1970s, the Netherlands were the only supplier of internationally traded pipeline gas in Western Europe, rendering importers in Belgium, Germany and France almost fully dependent on Dutch gas supplies (Correljé et al., 2003).

In the 1950s, significant gas reserves were found in North Africa and the USSR, yet importing their natural gas to Europe posed unique political challenges. Suspicions stemming from past colonial exploitation complicated price negotiations for Saharan gas. Nonetheless, in 1964, limited quantities of Algerian LNG began arriving in the UK and France, followed by Libyan LNG deliveries to Spain and Italy in 1969. Concerns of the Soviet Union wielding natural gas as a political or economic weapon initially deterred Western European countries from engaging in Soviet gas imports. Still, in 1968, the Austrian company ÖMV became the first Western European firm to import natural gas imports from the Soviet Union, with ENI from Italy following suit. It was only in the early 1970s that Western Germany concluded a contract to start importing Russian natural gas as part of Willy Brandt’s Ostpolitik (Gustafson, 2020; Högselius, 2013; Högselius et al., 2013). Overall, the impetus for importing natural gas into new was mostly driven by the interests of energy companies such as Ruhrgas, Gas de France, ÖMV, ENI, and Distrigas (Gustafson, 2020).

Initially, imported natural gas was blended with town gas. However, the town gas network quickly underwent a comprehensive transformation to accommodate natural gas. In Belgium, for example, both the consumption of town gas and the network to transport natural gas were fully replaced in as little as five years (De Clercq, 1975; Eandis, 2013). Contemporary parallels to hydrogen may be drawn. Just as natural gas was once blended with town gas, hydrogen can be blended into the natural gas grid, piggybacking on the existing infrastructure. Hydrogen blending trial projects are being carried out in various NWE countries, including Denmark (Gas Infrastructure Europe, 2021) and the UK (HyNTS, 2022) up until blends of 25% and 30% respectively. Nevertheless, the European Commission adopts a more cautious approach to hydrogen blending within the natural gas transmission grid (European Commission, 2022b).

In conclusion, mirroring the historical context of town gas, today’s global hydrogen supply sees approximately 85% produced and consumed on site (IEA, 2021b), with a relatively modest pipeline network of 2000 kilometers transporting fossil-based hydrogen in Europe (Ludwig et al., 2021). The characteristics of the current local hydrogen market bear striking similarities to the gas market landscape in NWE during the 1950s. Much like town gas served as a precursor, today’s hydrogen demand and infrastructure could provide an antecedent that facilitates hydrogen imports.

Governance

The first volumes of natural gas that were imported into NWE were secured via long-term contracts with take-or-pay clauses. The price of natural gas was linked to the price of other petroleum products in the destination country, so gas prices could differ depending on the customer country. Therefore, destination clauses were put into place to exclude gas-to-gas competition. Later, the natural gas price became indexed to the price of crude oil (Melling, 2010). These intricate natural gas supply contracts were forged within large consortia, often involving state-owned energy companies from various NWE countries, such as Ruhrgas, Distrigas, and Gas de France. This collaborative approach was instrumental in bolstering their collective bargaining power toward natural gas suppliers (Conoco Phillips, 2017; Gustafson, 2020; Matlary, 1985).

However, by the turn of the century, NWE gas markets underwent some structural changes, including liberalization (European Community, 1998), the growth of LNG trade, the emergence of spot markets and gas pricing hubs (Melling, 2010), and the end of negotiations in large consortia (Conoco Phillips, 2017; HyNTS, 2022). Long-term contracts lost ground to spot market procurements and oil-indexed long-term contracts were gradually replaced with spot market indexed long-term contracts (Finon and Locatelli, 2002; Interview #1). From the 2010s until mid-2021, oil-indexed long-term contracts often carried higher prices than their spot market indexed counterparts, leading to a wave of contract renegotiations. These renegotiated contracts have subsequently incurred negative consequences, exacerbated by Russia’s war in Ukraine, resulting in soaring natural gas prices (ACER, 2022).

Looking ahead, the future hydrogen market may potentially adopt a model reminiscent of the initial natural gas trade, based on bilateral long-term contracts. Such long-term contracts serve as efficient tools to secure volumes for importers and mitigate investment risks for producing countries. However, it is important to note that these contracts can also lock countries into import dependencies (IEA, 2022b; Nuñez-Jimenez & De Blasio, 2022; Roberts et al., 2021). Initiatives such as the German H2Global initiative have emerged to serve as auction platforms for the conclusion of such contracts (H2Global, 2022). Additionally, endeavors like the Energy Platform introduced through the REPowerEU plan (European Commission, 2022b), and the European Hydrogen Bank (European Commission, 2023a), present opportunities for joint hydrogen procurements, reminiscent of the consortia arrangements seen in the early years of natural gas trade. The key distinction, of course, is that joint procurement would now be politically steered and managed at the EU level.

A concrete example of how a similarly governed hydrogen market might evolve is the revision of the Gas Directive of 2009 to cover low-carbon and renewable gases such as biomethane or renewable hydrogen (European Commission, 2021a). One proposed revision involves the introduction of a European Network of Transmission System Operators for Hydrogen, similar to the European Network of Transmission System Operators for Gas (ENTSOG). As the current hydrogen transport network in NWE is owned by the French company Air Liquide, this raises questions as to whether the current national natural gas transmission network operators (TSOs) should repurpose their networks

or if Air Liquide, with its existing experience in handling hydrogen transport, should expand its network.

Finally, an important difference between the governance of natural gas and hydrogen pertains to the carbon intensity of hydrogen. Hydrogen's carbon intensity can vary significantly depending on its production and transportation methods, a characteristic that may implicitly or explicitly influence international hydrogen trading flows and prices. No direct analogy exists in the governance of natural gas, although major jurisdictions have adopted specific and often distinct quality and composition standards for imported natural gas and LNG (Mokhatab et al., 2014). Since 2019, a number of so-called 'carbon-neutral LNG' cargoes have been sold, although this kind of trade currently lacks transparency and, hence, credibility (Cahill, 2022).

4.2 Material dimension

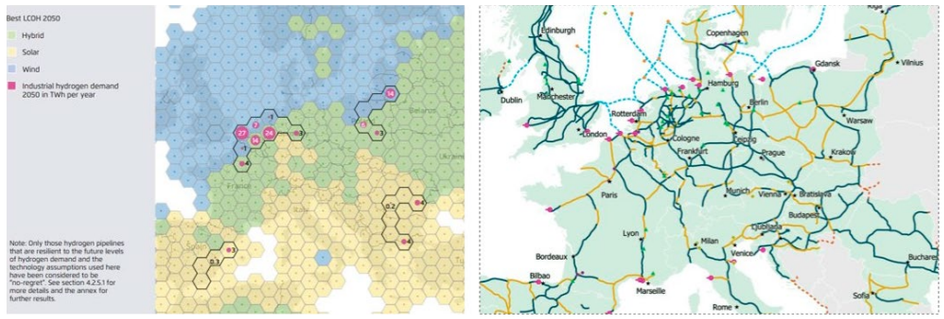
Transport infrastructure

Hydrogen and natural gas have similar transport methods: pipelines and shipping[15]. The first cross-border natural gas pipelines in NWE were built in 1960, while LNG terminals were built a bit later, for example in the UK and France in 1964 and Belgium in 1978. The choice for LNG versus shipping was driven by the technical, political and economic considerations. In the case of Dutch gas, geographic proximity, bulk volumes and political trust led to the construction of a high-pressure gas pipeline network in NWE. Soviet gas exports to Western Europe were an extension of pipelines branching out to the different COMECON countries. In the case of Saharan gas, LNG was used first because it required smaller initial investments, and it was more flexible than submarine pipelines. It was only later, in 1983, that a first gas pipeline would connect Algeria to Italy, the Transmed pipeline (Hayes, 2004; Interview #3; Musso, 2016).

Germany, the largest natural gas importer in NWE, notably refrained from building any LNG terminals until recently, although it did consider doing so. During the early 1970s, for example, Western Germany started talks with Algeria to import LNG via a planned LNG terminal in Wilhelmshaven. However, in 1972, these talks were suspended, along with the plans to build an LNG terminal in Germany. This was the result of escalating political frictions that emerged on the eve of the oil crisis and Algeria pushing for higher LNG prices (Atz, 1982; Gustafson, 2020; Högselius, 2013). At that time, imports from Algeria were perceived as less reliable than natural gas imports from the Soviet Union (Stern & Rogers, 2017). Furthermore, in the case of Germany, piped (Russian) natural gas was cheaper than Algerian LNG, and the construction of an LNG terminal to receive Algerian LNG was very costly compared to pipelines from Russia (Högselius, 2013). In the end, LNG terminals were never built until the gas crisis of 2022.

Several gas TSOs advocate for repurposing parts of the existing natural gas network for hydrogen transport (European Hydrogen Backbone 2022), akin to the adjustments made to domestic town gas pipelines for accommodating natural gas. However, this comparison holds only partly. Repurposing natural gas pipelines to hydrogen is technically challenging, due to the risk of steel embrittlement, necessitating a case-by-case approach (IRENA, 2022c). Nonetheless, gas TSOs have proposed new hydrogen pipeline projects, including 'H2Med' from Barcelona to Marseille (Carreño, 2022) and the 'SouthH2 Corridor', connecting North Africa via Italy to Austria and Germany (Thomas, 2023). They see these lines as precursors to a pan-European hydrogen network, dubbed the 'Hydrogen Backbone'. In contrast, Agora Energiewende and AFYR Management Consulting (2021) have put forward a 'no-regret' vision for hydrogen infrastructure that includes only four hydrogen corridors in Europe, with a corridor centered in NWE anticipated to harbor the largest clean hydrogen demand in Europe (see Figure 7).

Figure 7: 'No-regret vision' VS pan-European hydrogen network



Source: Agora Energiewende and AFYR Management Consulting (2021) & European Hydrogen Backbone (2022)

Hydrogen can also be transported via shipping, either in liquid form or as a derivative. Several pilot projects are already underway. In 2021, the first shipment of liquid hydrogen was shipped from Australia to Japan (HESC, 2022). In September 2022, a shipment of blue ammonia from the United Arabic Emirates headed off to Germany (Ismail, 2022). Intra-European shipping routes may also emerge. For example, the Spanish oil and gas company Cepsa and the Port of Rotterdam have agreed to create a maritime 'green corridor' to bring hydrogen produced in Spain to the industrial demand center in NWE (Wilson, 2022). These early shipments of hydrogen do not align with the historical sequence of natural gas trade in terms of transport methods. Natural gas trade in NWE started through pipeline trade in the 1960s and it was not until 2022 that LNG imports overtook pipeline imports. By contrast, the Hydrogen Council and McKinsey & Company (2021) expect the hydrogen market to start off with shipments of hydrogen derivates before 2030, with pipeline transport introduced from 2030 onward.

Views regarding long-distance seaborne transport diverge as well. Some experts project that liquid hydrogen shipping is unlikely to happen due to two main reasons. First, owing to its lower energy density, four times as many hydrogen ships would be required to transport the same quantity of energy as LNG. Second, liquefying hydrogen is a very energy-intensive and capital-intensive process. Consequently, these experts envision long-distance transport of hydrogen occurring exclusively via pipelines (Berrill, 2022). Conversely, entities like The Hydrogen Council are more optimistic about shipping hy-

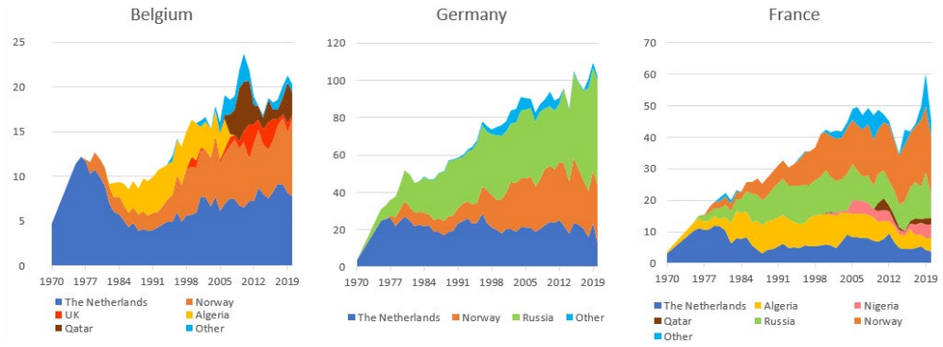
15 In theory, hydrogen and natural gas can also be transported in trucks in small quantities. However, the bulk of the volumes of the two gases is transported via pipelines or shipments.

drogen and its derivates. They expect half of the hydrogen for end-use to be exported long-distance via pipeline and the other half via shipping (Hydrogen Council & McKinsey & Company, 2022). A similar view is also projected by IRENA (2022b) and BP (2023).

Diversification of trade

Today, natural gas is traded on a global market (Van de Graaf & Sovacool, 2020). This was not the case when natural gas was first imported into NWE during the 1960s. The evolution of natural gas trade can be linked to the growth of concentric circles, both in terms of geography and diversification. In terms of geography, the first natural gas supplies were traded on a regional scale and later-on an international and global scale (Gustafson, 2020; Högselius et al., 2013). Likewise, in terms of diversification, the initial years of natural gas trade were characterized by bilateral agreements and a heavy reliance on a few, and sometimes even a sole, supplier country (see Figure 8). For example, the Netherlands was the only supplier of natural gas to Belgium, France and Germany during the 1960s. It was only in the subsequent decade that Russian, Algerian, Norwegian and British gas began to contribute to the natural gas supply in NWE. The 1990s marked a turning point as liberalization of the natural gas market, advancements in LNG technology, and the expansion of pipeline infrastructure opened up new avenues for diversification (Gustafson, 2020). As shown in Figure 8, countries such as France and Belgium benefited from enhanced diversification options, largely due to the presence of LNG terminals within their borders. In contrast, Germany, until recently, lagged behind in this regard as it lacked LNG terminals. This discrepancy underscores the pivotal role of LNG infrastructure in facilitating diversification within the natural gas supply landscape.

Figure 8: Imports of natural gas in Belgium, Germany and France per supply country in bcm (1970-2020)[16]



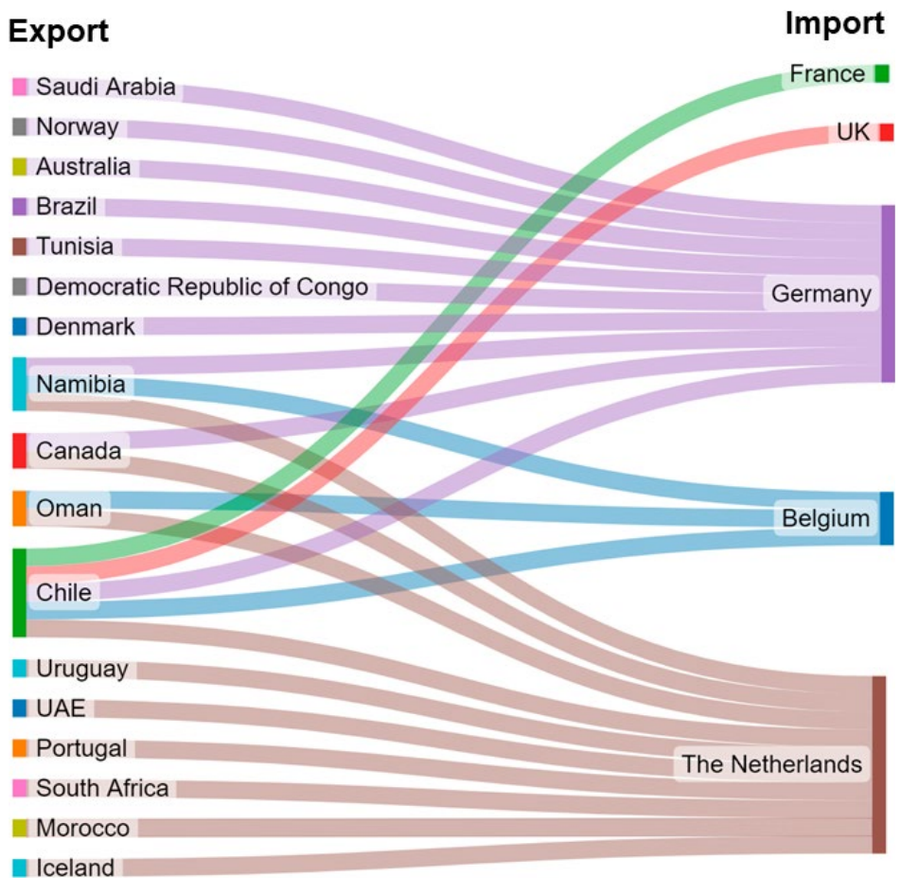
Source: Cedigaz (2022) & BP (2021)

Since hydrogen is an energy carrier and not an energy source, there are more potential supply countries to choose from. In contrast to the concentration observed in the natural gas sector, where approximately half of the conventional natural gas reserves are concentrated in just three countries (Russia, Iran, and Qatar) (BP, 2021), hydrogen

16 'Other' are low volumes (less than 1 bcm), procured via the spot market.

sourcing offers a broader array of options. While some gas exporting countries could become clean hydrogen exporters (of both the blue and green variant), a new class of energy exporters may also emerge (IRENA, 2022a). Many NWE countries have concluded agreements with various potential hydrogen supply countries, including Chile, Oman, Namibia, or Saudi Arabia (see Figure 9). This trend marks a departure from the historical import patterns associated with natural gas trade, where regional contracts were prevalent in the early phases. It is only the last months that more regional hydrogen trade flows are discussed with NWE seeking supplies from, for example, Norway or Spain. If the pace of establishing hydrogen import agreements were to mirror that of natural gas, it is conceivable that a timeframe of approximately 30 years would be required for a liquid hydrogen market to fully mature. This projection aligns with similar timelines envisaged by entities such as the Hydrogen Council and McKinsey & Company (2022). During these initial decades, hydrogen sourcing may be predominantly limited to a select few suppliers, potentially resulting in a concentration of supply akin to the early years of natural gas trade.

Figure 9: Potential hydrogen trade flows based on currently explored agreements



Source: author's own compilation based on IEA (2022b) and IRENA (2022a)

In the case of NWE, there is a consensus among key stakeholders, including the Hydrogen Council and McKinsey, that the initial stages of the hydrogen market will revolve predominantly around shipped imports of hydrogen. These imports are expected to primarily serve as replacements for existing trade in grey ammonia and methanol. Additionally, there may be some piped imports from the European periphery, such as Norway, with volumes projected to range between 10Mt and 20Mt by 2030. Only after 2050 it is anticipated that large piped volumes from Northern Africa, potentially reaching 20Mt, might become a reality, possibly supplemented by small volumes of shipped hydrogen from countries like Chile or North America (Hydrogen Council & McKinsey & Company, 2022). This outlook aligns with similar perspectives presented by organizations such as IRENA (2022b) and Deloitte (2023) (see Table 16).

This scenario stands in contrast with the extensive hydrogen diplomacy and bilateral agreements being explored with countries outside pipeline reach (see Figure 9). This divergence in approach can be attributed to the potential risks associated with physical pipeline dependencies. As a strategic choice, diversifying supplies through both shipments and pipeline transport is seen as a means to enhance resilience in the event of supply disruptions. It is important to note that Asia, where hydrogen supplies are expected to come primarily from the Middle East and Australia via shipments, may face fewer acute risks related to pipeline dependencies compared to Europe, assuming the supplies of these shipments remain flexible.

Table 16: Projected future hydrogen trade partners for Europe by 2030 and 2050

Institution	2030	2050
IRENA		North Africa, Middle East
Hydrogen Council &McKinsey	Norway (10Mt)	North Africa (20Mt), North America (small volume), Chile (small volume)
Deloitte		North Africa (44 Mt), Australia (16 Mt), North America (24 Mt), Middle East (13 Mt)

4.3 Discursive embedding

The public debate on natural gas import dependencies has evolved considerably over time. During the first years of the development of the natural gas market, there was a paucity of debates on the potential risks related to imports. It wasn't until the 1970s and the oil shocks that concerns began to surface. During this period, as an energy-saving measure, the European Community implemented a (temporary) ban on the use of natural gas in power generation (Correljé, 2016). In general, natural gas was perceived a cleaner alternative, first to town gas (Gustafson, 2020), and later to fossil fuels such as oil or coal (Szabo, 2021). In contrast, discussions regarding the evolution of the hydrogen market are currently more extensive and diverse compared to those related to natural gas. The discourse encompasses a wide range of topics, including the necessity of hydrogen imports, the various methods of hydrogen production, and the consumption of hydrogen.

Within NWE, there are different views on hydrogen imports (see Table 17). Belgium, the Netherlands, and Germany prioritize hydrogen imports due to limited renewable energy resources and land constraints. These countries prioritize local renewable energy production to green their electricity mix. Conversely, France and the UK explore their domestic hydrogen production capacity to reduce energy dependencies instead of replacing them. Meanwhile, Norway and Denmark are studying their exports due to their considerable resource potential (IEA, 2021c, 2022b; Kurmayer, 2021). This approach diverges significantly from the historical context of natural gas imports in NWE. Prior to natural gas imports, there were no national natural gas strategies akin to the national hydrogen strategies currently being formulated by many countries. There is scant evidence of public debates on the merits and risks of (over)reliance on natural gas imports in NWE during that era. Such discussions only gained prominence during the 1970s and 1980s when natural gas had already become a prominent component of the energy mix in most NWE countries (Högselius, 2013; van der Vleuten & Högselius, 2012; Van Hove, 1992).

Table 17: Country positions on hydrogen imports, exports or self-reliance based on national hydrogen strategies

Imports	Exports	Self-reliance
Belgium	Norway	France
The Netherlands	Denmark	UK
Germany		

Source: IEA (2021c) & World Energy Council (2021)

A second discussion revolves around the color of hydrogen—that is, how it is produced. Within NWE, there are notable divergences regarding which hydrogen production methods are deemed 'clean'. France, heavily reliant on nuclear energy, strongly advocates to include hydrogen produced through electrolysis powered with nuclear energy as clean hydrogen (Kurmayer, 2023). Norway favors a scheme whereby it continues to export natural gas to Europe, where it can be turned into 'blue' hydrogen, with the CO_2 being shipped back to Norway (Norwegian Ministry of Petroleum & Norwegian Ministry of Climate, 2020). Germany and Belgium, on the other hand, foresee a pivotal role for 'green' hydrogen and consider 'blue' hydrogen only in a transitional phase (Ministerie van Energie België, 2021; The German Federal Government, 2020). While criticism has been directed toward renewable hydrogen due to concerns over the potentially diverting green electricity from the electrification of the energy mix, blue hydrogen is also subject to contention as it poses risks to lock-ins of natural gas consumption, infrastructure and methane leakages (Van de Graaf, 2023). It is noteworthy that these discussions did not arise in the context of natural gas and LNG imports.

Finally, there is considerable discussion on where hydrogen should be consumed. Various end-use sectors may need different types and amounts of hydrogen or hydrogen derivates (pure hydrogen, methanol, ammonia, etc.), resulting in a variety of scenarios with different priorities in terms of infrastructure, demand and carriers. For example, the UK still considers a role for hydrogen in domestic heating (Kurmayer, 2022), while other NWE countries like Germany or Belgium are predominantly focusing on hydrogen applications in industry. This interpretative flexibility enables hydrogen technology development but makes it more challenging to steer the development of the hydrogen market into a certain direction and avoid inefficient use of hydrogen.

5. Discussion: From natural gas to hydrogen

The history of natural gas trade offers some lessons for the future of hydrogen trade. Here, we discuss three overarching lessons regarding: the drivers of change, the development of markets, and path dependencies.

5.1 Drivers of change

The adoption of clean hydrogen represents a policy-driven transition, contrasting with the predominantly market-driven adoption of natural gas. The shift to clean hydrogen is primarily motivated by the imperative to meet climate targets rather than being solely driven by cost reduction opportunities. This policy-driven shift is evident through the implementation of national hydrogen strategies and supportive initiatives, such as the Hydrogen Bank (European Commission, 2023a) and the H2Diplo program (H2Diplo, 2023). In contrast, the historical entry into natural gas trading relations did not witness a similar level of government intervention.

Given the policy-driven nature of the transition to clean hydrogen, additional measures are required to stimulate investments across the entire clean hydrogen supply chain. However, this governmental emphasis on hydrogen also introduces the risk of regulatory capture (Dal Bo, 2006), whereby companies involved in the clean hydrogen value chains wield significant influence over public sector regulations governing the industry. This influence has been underscored by the non-profit organization Corporate Europe Observatory, which has highlighted the impact of successful lobbying efforts by private energy companies in shaping hydrogen policy-making processes (Balanya et al., 2020). Additionally, the European Commission envisions a pivotal role for industrial players in its European Clean Hydrogen Alliance, underscoring the substantial sway these entities can have (European Commission, 2020b).

Another inherent risk associated with government-led technological changes is the potential selection of ‘wrong’ winners, wherein governments heavily invest in technologies that may ultimately fail to deliver on their promises. The ongoing debate surrounding methanol or ammonia as potential clean shipping fuels illustrates this point. Both chemical products are regarded as viable carriers for hydrogen and prospective clean shipping fuels. However, significant uncertainty persists regarding which option will emerge as the preferred clean (shipping) fuel (IRENA, 2022c).

5.2 Market development

The natural gas market has experienced a gradual and slow development, not only in the NWE region but also globally. In 1970, imported natural gas accounted for only 4% of total consumption (Victor et al., 2006). By 2021, this share had risen to 21%, which is still significantly lower compared to the proportion of internationally traded petroleum (Molnar, 2022). The slow and limited globalization of natural gas trade can be attributed to the high transport costs associated with natural gas. Given that transporting hydrogen is even more expensive, growing hydrogen markets to a comparable scale might similarly take decades, and the share of internationally traded hydrogen might also be constrained.

Additionally, the growth trajectory of a global hydrogen market may differ from that of natural gas. For natural gas, it took considerable time for LNG to capture a significant share of the market after the first long-distance gas pipelines were built in the 1960s and 1970s. For hydrogen, the story may be different as trade in derivatives is already well established (e.g., 10% of ammonia is traded via ships). Hydrogen trade could kick off with replacing some of the existing seaborne trade in grey ammonia and methanol with blue or green variants. This is already visible in some cargoes of blue ammonia that have been delivered, for example from Saudi Arabia to markets such as South Korea, China, Japan, India, Thailand and the European Union (Habibic, 2023).

Another reason why shipments of hydrogen derivatives might develop sooner is that Japan and South Korea, which are set to become major hydrogen importers, will have to rely on maritime imports since their access to piped imports is limited. In NWE, another major prospective hydrogen import market, a dense network of natural gas transmission pipelines is already in place, yet, refurbishing them in the short term to carry hydrogen may conflict with current needs to secure natural gas imports. For example, natural gas import pipelines from Norway, North Africa and the Caspian region have gained in importance since Europe lost access to the majority of Russian piped gas in 2022.

Consequently, the geography of hydrogen trade might diverge significantly from that of natural gas trade. For one thing, due to the diversity of derivatives and carriers, the market for hydrogen trade may be less ‘unified’ than the market for LNG. For another, initial bilateral hydrogen deals indicate the emergence of new potential supplier countries that currently do not export natural gas, such as Brazil, Namibia, Morocco, and Iceland (see Figure 9).

5.3 Path dependencies

Even though the emergence and development of the natural gas market was driven primarily by market forces rather than governments, critical decisions were made at different stages of the value chain, including choices related to supply countries, transport methods, and end-uses. Each of these choices inconspicuously created path dependencies that contributed to the severe energy crisis experienced by Europe in 2022.

Similarly, the establishment of international clean hydrogen supply chains necessitates a new set of choices that are potentially more complex. Table 18 illustrates the multitude of decision points faced by policymakers and industry leaders in the various dimensions of hydrogen trade value chains, surpassing the number of choices encountered in natural gas trade. Each of these choices carries the potential to create their own set of path dependencies. In some cases, path dependencies may even be transmitted from natural gas to hydrogen. For instance, countries with existing natural gas trade relations might build on these relations and the underlying infrastructure to establish hydrogen trade connections as well.

Table 18: Critical choices in creating natural gas and hydrogen import supply chains

	Natural gas	**Hydrogen**
Supply countries	Choice limited to gas-rich countries	Choice includes gas-rich countries (blue H_2) but more potential trading partners (for green H_2)
Transport methods	Choice between pipelines and ships (LNG)	Choice between pipelines (repurposed pipelines, dedicated pipelines, or blending) and ships (liquid H_2, H_2carrier or derivative)
End-uses	Choice between using natural gas or coal/oil in many end-use sectors	Choice between using hydrogen, a derivative, fossil fuels (with carbon capture and storage), or electricity

6. Policy implications

Policy makers seeking to reduce their countries' exposure and vulnerability to import risks and related concerns on security of hydrogen supplies can draw at least three lessons from natural gas trade.

First, diversification is crucial. Diversification encompasses various dimensions, including suppliers, routes, and carriers (the latter is especially relevant in the case of hydrogen). An energy system that is more diversified is inherently more resilient to external supply shocks, whether they result from deliberate actions such as export bans or from unforeseen circumstances. The 2022 gas crisis in Europe highlighted the importance of avoiding overreliance on a single supplier or route when importing hydrogen. While pipelines may often be the cost-effective and technically attractive choice for (pure) hydrogen imports, they may not always be the 'cheapest' option if security of supply considerations are factored in. Nevertheless, as the hydrogen market is expected to be less unified and concentrated, it features more potential supply countries, potentially reducing the risks of supply disruptions.

Secondly, managing (import) demand is essential. Some argue that governments should prioritize creating demand for clean hydrogen, given that the expansion of clean hydrogen supply is contingent upon the existence of robust demand (IEA, 2022b), for

instance, it has been suggested that governments should push for hydrogen adoption in sectors where the willingness to pay is highest, such as passenger road transport (Rolle et al., 2020). Nevertheless, decisions concerning the stimulation of demand should only be executed with judicious consideration for the potential pitfalls of creating dependencies that expose countries to import-related vulnerabilities. Moreover, it is imperative that the deployment of clean hydrogen is directed to end-uses that cannot be effectively decarbonized through direct electrification. Deviating from this principle could inadvertently impede progress in decarbonization efforts. Energy efficiency and conservation must remain core pillars of comprehensive energy security strategies. One approach to achieve this is through the implementation of measures such as prohibiting the use of hydrogen in certain sectors, reminiscent of the restrictions placed on natural gas in the 1970s.

Thirdly, enhancing resilience to shocks is critical. This can be accomplished through the storage of hydrogen or its derivatives, similar to natural gas storage. While the feasibility of storage is influenced by geological conditions, it is preferable to have storage facilities in both export and import markets for the sake of supply security (Crawford, 2020). Additionally, strategies should be devised to enable fuel switching and demand reduction policies that can effectively address potential supply shortages.

7. Conclusions

The future of the hydrogen industry remains highly uncertain. This article examined the history of natural gas and LNG markets to gain insights that can inform potential pathways and mitigate risks in cross-border hydrogen trade. Similar to natural gas, the hydrogen market is expected to develop over several decades and phases, but it may follow a distinct trajectory. In the case of natural gas, pipeline trade preceded the significant growth of LNG, whereas hydrogen trade could potentially commence by replacing some existing seaborne trade in grey ammonia and methanol with blue or green variants.

To mitigate risks related to hydrogen imports in the cross-border hydrogen and derivatives market, adopting a contractual structure reminiscent of the early LNG market, featuring bilateral agreements, long-term commitments, and take-or-pay clauses, could help reduce uncertainty. During the initial years, the global hydrogen market is anticipated to be relatively small and inflexible. Consequently, potential security of supply issues may arise, as disruptions along trade routes could result in shortages for importing nations. Therefore, it is crucial to prioritize diversification of suppliers, routes, and carriers from the outset, along with storage, even if this entails higher costs. Nonetheless, it remains uncertain who should be in charge of steering the hydrogen market development: the national governments or the market?

As with any nascent industry, critical decisions must be made to scale up clean hydrogen value chains. The history of the gas industry demonstrates that such choices can lead countries down paths that compromise their energy security in the long run. Even if significant hydrogen trade has yet to materialize, pivotal decisions are being

made today in government meetings and corporate boardrooms, shaping the pace, trajectory, and characteristics of future hydrogen trade.

In conclusion, while our research has centered on NWE, we believe that the implications of our findings extend beyond this specific region, shedding light on the broader trajectory of the global hydrogen market. Nevertheless, it is important to acknowledge the limitations of our study, which predominantly relied on qualitative and theory-driven methodologies. To advance the field, future research could quantitatively explore the technical dimensions of the international hydrogen market, including market structure, trade flows, and infrastructure, given the rapid evolution of this sector.

Article 2.
Risky Business? Evaluating hydrogen partnerships established by Germany, The Netherlands, and Belgium

Marie Dejonghe

Abstract

Following the introduction of the EU's Hydrogen Strategy in 2020 as part of the European Green Deal, some EU member states have deployed a very active hydrogen diplomacy. Germany, The Netherlands, and Belgium have been the most active ones, establishing no less than 40 bilateral hydrogen trade partnerships with 30 potential export countries in the last three years. However, concerns have been voiced about whether such hydrogen trade relationships can be economically feasible, geopolitically wise, environmentally sustainable, and socially just. This article therefore evaluates these partnerships considering three risk dimensions: economic, political, and sustainability (covering both environmental and justice) risks. The analysis reveals that the selection of partner countries entails significant trade-offs. Four groups of partner countries can be identified based on their respective risk profile: 'Last Resorts', 'Volatile Ventures', 'Strategic Gambits', and 'Trusted Friends'. Strikingly, less than one-third of the agreements are concluded with countries that fall within the 'Trusted Friends' category, which have the lowest overall risk profile. These findings show the need for policy makers to think much more strategically about which partnerships to pursue and to confront tough choices about which risks and trade-offs they are willing to accept.

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1. Introduction

The European Union (EU) envisions renewable hydrogen to play a pivotal role in its goal of becoming carbon neutral by 2050 (European Commission, 2020a). To achieve this goal, EU member states, such as Germany, the Netherlands and Belgium, explore hydrogen imports, to meet the expected domestic hydrogen demand. To facilitate these imports, the EU has articulated an External Energy Strategy, designed to create partnerships with what it terms “reliable partner countries” while taking into account the “social, economic and environmental needs of the export countries” (European Commission, 2022a).

At the same time, the changing geopolitical landscape has instilled a heightened sense of caution among countries when it comes to engaging in transnational trade relations and dependencies. In this context, more and more countries show a preference for engaging in partnerships with trusted or friendly countries, a phenomenon dubbed ‘friend-shoring’. Nevertheless, the current landscape of hydrogen partnerships reveals a more nuanced reality, showcasing a spectrum of agreements that have been concluded with both ‘friendly’ and potentially less ‘friendly’ countries. All of this raises concerns in terms energy security related to these partnerships.

Despite a growing body of literature on hydrogen trade relations and hydrogen diplomacy, existing studies often focus on identifying potential hydrogen trade partners, based on a set of mostly economic and technological criteria. They hardly address the already established partnerships and possible energy security risks. This paper aims to fill this gap by evaluating the 40 partnerships concluded between Germany, the Netherlands, and Belgium, on the one hand and 30 prospective hydrogen trade partners, on the other. The assessment covers a comprehensive set of criteria, encompassing economic and technological criteria, but also political and sustainability factors. The central question guiding this analysis is: What are the economic, political and sustainability risks related to these hydrogen partnerships?

The remainder of this paper is structured as followed: Section 2 provides a conceptual framework for hydrogen diplomacy, as well as energy diplomacy more broadly, in order to gain a deeper understanding of the scope, nature and tools of hydrogen diplomacy. Section 3 employs a content analysis to identify the indicators relevant to establishing secure hydrogen partnerships. Using a multi-criteria analysis, the existing partnerships are then evaluated against these indicators. In Section 4, partner countries are classified based on their performance on the various indicators. Finally, in Section 5, the paper assesses the overall energy security implications of the hydrogen partnerships.

2. Hydrogen Diplomacy: A New Form of Energy Diplomacy?

Diplomatic efforts to secure energy resources are not new. Therefore, before diving deeper into hydrogen diplomacy, it is necessary to provide a broader conceptualization of energy diplomacy to understand the overlaps and differences between the two.

2.1 Conceptualizing Energy Diplomacy

While the term ‘energy diplomacy’ is widely used in various academic and non-academic contexts, there is no universally accepted definition of the concept. Instead, scholars have used different terms such as ‘oil diplomacy’ (Hartshorn, 1973; McFarland, 2018), ‘petropolitics’ (Brossard, 1983), ‘pipeline politics’ (Proedrou, 2018) or ‘petroleum geopolitics’ (Overland, 2015) to describe diplomatic efforts related to obtaining energy resources. In an attempt to obtain a general definition of energy diplomacy, Goldthau (2010) defines energy diplomacy as “the use of foreign policy to secure access to energy supplies abroad and to promote (mostly bilateral, that is, government to government) cooperation in the energy sector”. In this definition, he considers states as the primary actors of pursuing energy diplomacy and puts forward national security as the main goal. Chaban and Knodt (2015) expand the definition by including non-state actors such as international organizations or the EU. Furthermore, they argue that energy diplomacy should consider development and sustainability criteria, in addition to securing access to energy. Barra and Svec (2018) provide further insight by differentiating between two forms of energy diplomacy: bilateral energy diplomacy and multilateral energy diplomacy, the latter involves collective diplomacy through international organizations like the International Energy Agency (IEA) or the International Renewable Energy Agency (IRENA).

The concept of energy diplomacy is often used interchangeably with ‘energy governance’ or ‘energy statecraft’. However, there is an important distinction between these concepts in the scholarly literature (Chaban & Knodt, 2015; Downie, 2019; Herranz-Surrallés, 2016; Van de Graaf & Sovacool, 2020). Energy diplomacy is the practice of securing energy resources with foreign policy. In this context, energy dependence is viewed as a political challenge that requires addressing to safeguard national interests (Herranz-Surrallés, 2016). On the other hand, energy governance is closely linked to the energy market (Chaban & Knodt, 2015; Herranz-Surrallés, 2016). It is based on a market-oriented approach, which assumes that energy security can be attained through the market and a well-regulated system with producing countries (Herranz-Surrallés, 2016). Finally, energy statecraft is the use of energy policy tools as instruments of country’s foreign policy, this includes for example manipulating energy prices or infrastructure for geopolitical reasons (Van de Graaf & Sovacool, 2020).

In summary, energy diplomacy is closely intertwined with geopolitics and national security concerns and is therefore frequently linked with a nation’s foreign or security policies (McFarland, 2018). Bovan, Vučenović, and Perić (2020) see this securitization of energy policy (Heinrich & Szulecki, 2018; Özcan, 2013) as a result of the growing energy demand and (over)dependence of modern consumers on energy resources.

2.2 The Energy Diplomacy Toolbox

The toolbox of energy diplomacy is extensive and can be pursued at different levels (Barra & Svec, 2018). Bilateral intergovernmental agreements and large infrastructure projects are often seen as essential instruments of energy diplomacy (Herranz-Surrallés, 2016). Additionally, energy diplomacy is closely connected to development policy, linking energy-related policies to development aid (Dornan & Shah, 2016; Goldthau, 2010).

Over the past few decades, various forms of energy diplomacy have been employed by both energy importers and exporters. Following the oil crisis of 1973, Japan, a major oil importer, faced difficulties in securing affordable oil supplies for its industries. In response, the Japanese government sent special envoys to oil-producing nations like Syria, Egypt, Sudan, and Persian Gulf countries to enhance its political relations with them. In exchange for economic and technical assistance, Japan was able to ensure a stable oil supply (Tsurumi, 1976). Another example is China’s energy diplomacy. As a significant energy importer, China has established partnerships with oil-producing African countries such as Nigeria or Angola to satisfy its domestic oil demands (Chia-yi, 2019).

Energy diplomacy is not limited to countries that rely on energy imports. Russia, a significant exporter of fossil fuels, has also employed energy diplomacy to secure market share for its national energy company, Gazprom. Another example of energy diplomacy pursued by exporting countries is Brazil’s biofuel diplomacy. The Brazilian government utilizes its knowledge and expertise in producing and trading biofuels as a foundation for creating partnerships for biofuel infrastructure projects with countries such as Nigeria, Angola, and Mozambique (Afionis et al., 2016; Paiva & Wolde-Georgis, 2010).

The transition from fossil fuels to renewable energy has set in motion a shift in power relations. The emergence of new strategic technologies and value chains, such as clean hydrogen or critical raw materials, along with rising geo-economic competition, has compelled countries to rethink their traditional energy diplomacy (Pastukhova et al., 2020). As the low-carbon energy transition continues to gain traction, countries are forming new partnerships based on technology cooperation and negotiating fresh bilateral agreements concerning the import of hydrogen and its derivatives.

2.3 Hydrogen Diplomacy

Recently, hydrogen diplomacy has gained prominence as an essential aspect of energy diplomacy. Though it involves some new approaches, hydrogen diplomacy resembles other forms of energy diplomacy. Numerous countries and other players such as ports are engaging in dialogues or signing memorandums of understanding with potential import or export partners. For instance, similar to Japan’s approach during the 1970s, the Netherlands has dispatched special envoys to potential hydrogen-producing countries to discuss future trade agreements (IRENA, 2022a). Additionally, the German government has launched the ‘H2Diplo’ initiative, which has created ‘hydrogen diplomacy offices’ in potential export countries like Angola, Nigeria, Ukraine, and Kazakhstan to foster hydrogen cooperation (H2Diplo, 2023).

Currently, existing accounts of hydrogen diplomacy focus primarily on establishing bilateral hydrogen partnerships (IRENA, 2022a). Prospective importers such as Germany, the Netherlands and Belgium are actively engaging in establishing hydrogen partnerships in the form of technological cooperation with other import countries such as Japan or

by establishing prospective trade agreements with potential export countries such as Morocco, Namibia or Oman (IEA, 2022b).

The research and practice around potential hydrogen partnerships has been dominated by a technical approach. Countries with a high level of renewable energy and water resources are considered suitable partner countries for renewable based hydrogen (Ikonnikova et al., 2023; Moritz et al., 2022; Panchenko et al., 2023; Pflugmann & De Blasio, 2020). Pflugmann and De Blasio (2020) have identified five groups of countries based on their resource potential, including categories like export champions, import countries and self-sufficient hydrogen consumer countries. Eicke and De Blasio (2022) have built on this research by adding "economic relatedness" and "the size of the current hydrogen and/or its derivates market" to examine potential changes in geopolitical relations related to establishing a hydrogen value chain.

Recently, experts are increasingly pointing out the need to assess non-technical criteria when studying future hydrogen partnerships (Brauer et al., 2022; Frontier Economics, 2018; Hanusch & Schad, 2021). For instance, Hanusch and Schad (2021) call for a social science research agenda on setting up hydrogen partnerships while Kalt and Tunn (2022) similarly argue that research from social and sustainability perspectives is crucial to avoid a technocratic hydrogen transition as they may eventually lead to path dependencies or social inequalities. In a study on hydrogen partnerships, Quitzow et al. (2023) argue that there are six dimensions that should be considered by policy-makers when engaging in hydrogen partnerships: climate mitigation, green industrial development, just transition in partner countries, geopolitics, security of supply and economic feasibility. According to their findings, these dimensions may reinforce each other, yet they may conflict as well. Such conflicts may then trigger trade-offs between the different dimensions.

Only a few studies have integrated such parameters in their assessment of hydrogen partnerships. The H2 Atlas, developed by the German Federal Ministry of Education and Research and African partners in the Sub-Saharan region, assesses the political environment of hydrogen partner countries by looking at socio-economic criteria such as the ease of doing business, the world governance indicator and current energy policies (H2Atlas, 2023). Brauer et al. (2022) have incorporated as well what they call 'soft factors,' such as political stability, ease of doing business, and a country's R&D spending per capita, when discussing prospective hydrogen partnerships. Based on their assessment, countries such as Norway, Algeria and the UK are considered suitable trading partners for importing hydrogen in Europe. Moreover, according to their analysis, countries like Saudi Arabia, Oman and Jordan perform well in terms of producing low cost hydrogen, but they score low on their soft-factor criteria. Similarly, in a study by Frontier Economics technical criteria like renewable energy potential and infrastructure are juxtaposed with socio-economic criteria (Frontier Economics, 2018). Nevertheless, in these studies, these criteria are labelled as 'soft factors,' implying the technical criteria are still considered as more important (the 'hard factors').

Furthermore, there is an increasing body of literature that addresses another blind spot, namely the implications of hydrogen trade for the hydrogen export countries. These studies start from the objective of energy justice and have taken a more critical perspective toward hydrogen partnerships (Bouacida, 2022; Heinemann & Mendelevitch, 2021; Lindner, 2022; Müller et al., 2022). Müller et al. (2022) point out that hydrogen partnerships with countries such as Morocco or Namibia risk exacerbating existing inequities rather than leading to a just transition. Lindner (2022) draws a similar conclusion, having evaluated 21 countries from the Global South that are considered for potential hydrogen partnerships. He concludes that many of those partnerships lack of an energy justice perspective, resulting not only in inequalities in terms of energy justice, but also damaging the overall long-term stability of these partnerships. The inclusion of an energy justice lens to studying hydrogen partnerships highlights that these parameters have repercussions in terms of energy security in both the short-term and the long-term for import as well as for export countries. Such implications are not assessed when solely relying on the technical potential of export countries.

In summary, the literature on hydrogen diplomacy and related partnerships has predominantly focused on defining mostly technical potential of potential partner countries and, much less on studying agreements that are actually already in place. The majority of studies scrutinize thus which countries the EU and its member states should partner with, in terms of their technical potential. This paper takes a different approach. Instead of applying a priori defined criteria to select potential import countries, it conducts a post hoc evaluative review of current agreements. The aim is to evaluate whether these partnerships and the agreements pose any economic, political or sustainability risks. Simply put, the assessment wants to determine whether Germany, the Netherlands and Belgium are succeeding in securing hydrogen imports in a secure and sustainable way.

3. Methods

To assess the prospective hydrogen partnerships, this paper employs a mixed method approach, which consists of three steps: (1) the identification of prospective hydrogen partnerships and related indicators in terms of risks, (2) the classification and analysis of the indicators mentioned in the literature, and (3) the multi-criteria analysis of the prospective hydrogen partnerships based on the indicators. In terms of data collection and analysis, a database of hydrogen partnerships and a literature review is conducted to identify partnerships and indicators related to prospective hydrogen partnerships. To identify the dominant indicators for sustainable hydrogen partnerships, a content analysis is performed on the literature on indicators related to hydrogen partnerships and related risks. Lastly, the hydrogen partner countries are analyzed using a multi-criteria analysis. A more detailed discussion of each step can be found below.

3.1 Data Collection

Firstly, a database of potential hydrogen partnerships is established using government announcements and media reports published prior to August 2023. The database includes 40 future trade partnerships between on the one hand prospective importers, Germany, Belgium or the Netherlands, and 30 unique prospective hydrogen exporters, on the other. The database covers a range of cooperation agreement types related to hydrogen, including memorandums of understanding, bilateral cooperation agreements,

letters of intent, and dialogues. Partnerships centered on technological collaboration with other potential import countries (for example with Japan or South Korea) are not included in the database as the focus of this paper is on hydrogen imports. There are other European countries, such as Hungary, Italy or Austria, that concluded a hydrogen trade partnership with future export countries. However, these partnerships are not included in the database as these agreements are rather ad hoc and less an example of hydrogen diplomacy. A complete overview of all the partnerships can be found in the Supplementary S1, Table 22.

Secondly, a literature review is undertaken to gather insights on the criteria or indicators that could be taken into account when establishing hydrogen partnerships. This review covers academic literature, including peer-reviewed journals, working papers, and books, as well as grey literature such as blog posts, reports, websites, and newspaper articles on the topic of hydrogen partnerships. The complete overview of the literature review can be found in the Supplementary S1, Table 23.

3.2 Data Analysis

Hydrogen partnership indicators

In order to identify the indicators that could be considered to establish secure hydrogen partnerships, a content analysis is conducted on 15 studies related to the establishment of hydrogen partnerships. This paper has included each indicator that was mentioned in three or more studies referring to indicators to chose hydrogen partners and minimize economic, political or sustainability risks. Factors related to technological potential to produce hydrogen, such as solar irradiation and wind speed, are not directly included in the set of indicators but they are covered indirectly by the economic dimension. The resulting eight indicators are grouped into three dimensions of energy security risks as shown in Table 19.

The economic risks are associated with the costs of hydrogen. They include (1) hydrogen production costs, which means the cost of hydrogen production and (2) the delivery ex ship (DES) costs, which are the supply costs from the export country to the import country (Brauer et al., 2022; Ikonnikova et al., 2023; Moritz et al., 2022).

The political risks are related to the investment climate within a potential partner country. They include socio-political indicators such as (3) the Corruption Perceptions Index, (4) fragile state index, (5) ease of doing business (Brauer et al., 2022; Breitschopf et al., 2022; Frontier Economics, 2018; Lindner, 2022).

The sustainability risks include the risks related to a clean and just transition. Firstly, they address the availability of clean energy within the partner country. This includes (6) local access to electricity, to align with distributional justice effects of access to green electricity and, (7) the share of renewables in a country's electricity mix, to ensure local development of green energy. This dimension aligns with the 'local first' approach (Bouacida, 2022; Bouacida & Berghmans, 2022; Breitschopf et al., 2022; Heinemann & Mendelevitch, 2021; Lindner, 2022; Müller et al., 2022). Secondly, they address risks

related to water scarcity which is measured by (8) the water stress index, considering the production of green hydrogen requires large volumes of water.

Table 19: Dominant risk categories in the literature and related indicators

Risk category	Indicator	Mentioned in
Economic Risks	Hydrogen costs: 1 Hydrogen Production cost 2 Hydrogen DES cost	Brauer et al. (2022); Ikonnikova et. al. (2023); Moritz et al. (2022)
Political Risks	3 Corruption Perceptions Index	Breitschopf et al. (2022); Frontier Economics (2018); Heinemann & Mendelevitch (2021); Lindner (2022)
	4 Fragile state index	Breitschopf et al. (2022); Frontier Economics (2018); Lindner (2022)
	5 Ease of doing business index	Brauer et al. (2022) ; Frontier Economics (2018); Lindner (2022)
Sustainability Risks	6 Domestic energy demand: access to electricity 7 Share of renewables in electricity	Bouacida (2022); Bouacida and Berghmans (2022); Breitschopf et al. (2022); Heinemann & Mendelevitch (2021)
	8 Water availability	Bouacida (2022); Breitschopf et al. (2022); Heinemann & Mendelevitch (2021); Lindner (2022)

Multi-criteria analysis of prospective hydrogen trade partnerships

Finally, the eight above mentioned indicators are applied to the 30 unique countries according to a multi-criteria analysis. Each country is first evaluated based on the eight different indicators, subsequently their performance on the eight indicators is dichotomized. In this paper, I chose for a binary approach to ensure consistency in the analysis as there is variation between the different databases of the eight individual indicators. The thresholds for the dichotomization are either theory-based or based on global averages. Below, I discuss the indicators and their respective coding.

(1) Green hydrogen production costs: The data of production costs of green hydrogen is retrieved from a study by Moritz et al. (2022). They assess the cost of green hydrogen produced by renewables by 2025. Their modelling is based on a baseline scenario with present technology levels, and with an import volume of 100TWh. A country that has a higher cost than the average production cost of 113USD /MWh is coded 'zero', a country that has a lower cost is coded 'one'.

(2) Green hydrogen Delivery Ex Ship (DES) costs: The data on DES costs is retrieved from a study by Moritz et al. (2022) and are calculated based on exports to Germany. As Germany has already concluded more than half of the partnerships that are being

discussed in this paper, and other prospective import countries are also situated in NWE, these costs are considered representative. The study assesses the cost of green hydrogen produced by renewables by 2025. Their modelling is based on a baseline scenario with present technology levels and with an import volume of 100TWh. A country that has a higher cost than the average DES cost of 189 USD /MWh is coded 'zero', a country that has a lower cost is coded 'one'.

(3) Corruption Perceptions Index (CPI): The CPI, published by the organization called Transparency International, calculates the corruption level of states (Transparency International, 2022). A country that performs above 50/100 is coded 'one', a country that scores below 50 is coded 'zero'.

(4) Fragile State Index: This index, initiated by the Fund for Peace, assesses a states' vulnerability to conflict or collapse (The Fund for Peace, 2023). When a country's score is categorized as 'warning' or worse, it is coded 'zero', while countries that are categorized as 'stable' or better are coded as 'one'.

(5) Ease of doing business index: This index by the World bank evaluates the business regulation environment of countries (World Bank, 2020). A country that performs better than the global average is coded 'one', a country that scores below average is coded 'zero'.

(6) Access to electricity: This indicator is measured based on the percentage of the population with access to electricity (World Bank, 2019). Electrification data are collected from the World bank. If in a country 100% of the population has access to electricity, the country is coded 'one,' otherwise it is coded as 'zero'. This 100% threshold is based on the 'local first' approach, that proposes that first local energy needs should be met, before hydrogen is used for export purposes (Teske et al., 2022).

(7) Share of renewables in the electricity mix: This UN indicator measures the share of renewable energy in a country's electricity mix, which is part of the SDG goal 7 (Our World in Data, 2022). Such indicator would avoid that renewable electricity is used for hydrogen production instead of decarbonizing local energy consumption. A country that has more than 28% of renewables in their electricity mix, which is the global average, is coded 'one', while a country that scores below 28% is coded 'zero' (IRENA, 2023b).

(8) Water availability: This is measured by the water stress index (WSI). This UN index calculates the ratio of renewable water supply compared to the water withdrawals in a country (AQUASTAT, 2019). According to the UN, a country that has a WSI percentage greater than or equal to 25 it is considered to be water stressed (UN, 2021) and the country is coded 'zero.' Any other percentage is coded 'one'.

The complete overview of the coding of the countries for each indicator can be found in Supplementary S1, Table 24.

The next step involves calculating an aggregated score for each risk category, based on the individual indicator scores. A country that scores 'one' on all indicators within

a distinct risk category is considered to have a 'low' risk for that category. A country that scores a 'zero' on only one indicator within a risk category is given a 'medium' risk for that category. If a country scores a 'zero' on two or more indicators within a dimension, the score for that dimension is labelled as 'high' risk. An overall overview of the risk performance can be found in Supplementary S1, Table 25.

Lastly, the countries are divided into four categories based on their risk profile on the different categories (see Table 20). While in theory, more than four categories are possible, our analysis reveals that these four categories effectively capture the overall trends and performance of the potential partner countries in this study:

- *Last Resorts: countries that contain 'high' economic risks.*
- *Volatile Ventures: countries that score 'low' or 'medium' on the economic risks but are considered to be 'high' risk in political risks.*
- *Strategic Gambits: countries that have 'low' risks for the economic and political dimension but impose 'high' risks in terms of sustainability.*
- *Trusted Friends: countries that are 'low' risk on every dimension.*

Table 20: Categorization of countries based on their performance on the three dimensions

Economic risks	Political risks		Sustainability risks	Country category
High				Last Resorts
Low	High			Volatile Ventures
Low	Low	Medium	High	Strategic Gambits
Low	Low		Low	Trusted Friends

To check the robustness of the proposed categorization, I have conducted several robustness tests, employing alternative thresholds across all indicators for the 30 countries in the dataset. The results of the robustness checks are available in the Supplementary S2. In general, the results of this robustness test affirm the categorization outlined in the paper. When different threshold values are applied to each indicator, the overall categorization remains largely consistent. However, there are a four noteworthy exceptions where alternative thresholds would result in different country categorizations. Firstly, altering the thresholds for indicators (3), (4), and (5) would reclassify Namibia from the 'Volatile Ventures' category to the 'Strategic Gambits' category. Secondly, by employing a lower production cost threshold (1), Nigeria would transfer from a 'Last Resort' to a 'Volatile Venture' country. In contrast, when employing a higher production

cost threshold (1), Brazil would transfer from a 'Volatile Venture' country to a 'Last Resort' country. Finally, an alternative threshold for the Corruption Perceptions Index (3) would transfer Saudi Arabia from a 'Strategic Gambit' country to a 'Volatile Venture' country. Nevertheless, these adjustments represent minor changes, and the categorization proposed in the paper maintains its overall robustness.

4. Results: Risk-free partnerships?

Starting in 2020, a total of 40 hydrogen partnerships were concluded between Germany, the Netherlands and Belgium, 30 of which with unique countries. The bulk of these partnerships were concluded by the German and Dutch governments, with 22 and 13 partnerships respectively. Belgium entered into 5 partnerships. Of all 30 unique prospective export countries, about a quarter are considered to be 'low risk' meaning that there are also partnerships that entail economic, political or sustainability risks. The following section discusses the four different categories of partner countries as shown in Table 21, and related risks.

Table 21: Categorization of partner countries

Last Resorts	Volatile Ventures	Strategic Gambits	Trusted Friends
Angola DR Congo Egypt Nigeria Russia Ukraine Uruguay Kazakhstan	Algeria Brazil India Kenya Mexico Morocco Namibia South Africa Tunisia Turkey	Oman Qatar Saudi Arabia UAE	Australia Canada Chile Denmark Iceland Norway Portugal Spain

4.1 Last Resorts

According to the index, seven countries are identified as 'Last Resorts'. These countries display, in the first-place high risks on the economic dimensions, meaning that both the production and the supply of hydrogen from these countries would be very costly. Notably, most of these countries also pose high risk on other dimensions, this is the case for Angola, the DRC, Egypt, Nigeria, Kazakhstan, Russia, and Ukraine. Only Uruguay poses high economic risks but medium, and low risks in terms of respectively politics and sustainability.

An example that showcases the overall high risks is the Democratic Republic of Congo (DRC), which next to high hydrogen production costs, also poses high investment and decarbonization risks. The hydrogen project that is being studied between Germany and the DRC necessitates the further construction of the hydroelectric facility at the Inga dams, of which the progress has been stymied because of market and investment risks. The building of the dams would displace thousands of individuals and lead to detrimental environmental consequences, including a reduction in biodiversity and an increase in waterborne diseases (Benoit, 2021). Furthermore, certain regions of the DRC have experienced prolonged conflict, which raises concerns about the country's political stability. Overall, despite possessing significant potential for accomplishing the energy transition, including valuable mineral resources and renewable energy sources, the Congolese population has not yet reaped the benefits of the country's resource wealth. The DRC is not the only country that has not yet profited of its resource wealth. A similar case can be made for both Angola and Nigeria, both rich in fossil fuel reserves and renewable energy potential, also are considered to be high risk on all dimensions. There is a concern that the production and exports of hydrogen from these regions to Europe may reproduce or even exacerbate the so-called 'resource curse' which those countries are experiencing already today from fossil fuels (Ojakorotu, 2018).

Egypt poses another example that is considered to be a high risk investment overall. Egypt has the ambition to develop into a hydrogen exporter. However, the country faces significant criticism from human rights organizations due to its human rights abuses, and these societal issues adversely impact its political stability (Dunne, 2020). Moreover, Egypt grapples with severe water scarcity as a result of climate change and its extensive water-dependent economy (AQUASTAT, 2016).

Furthermore, both Russia and Ukraine demonstrate high risks. Prior to Russian invasion of Ukraine, Germany had established agreements with both countries. Russia, in particular, was regarded as a potential partner for exporting hydrogen derived from natural gas through carbon capture and storage (Barlow & Tsafos, 2021). However, given the current strained relations between Europe and Russia, the future trade of any energy source, including both fossil fuels and hydrogen, is highly uncertain. Similarly, hydrogen exports from Ukraine face considerable uncertainty, and their feasibility is contingent upon the outcome of the ongoing conflict. Nevertheless, Ukraine is still considered a potential export partner in the EU's hydrogen strategy and the REPowerEU plan due to its infrastructure and renewable energy potential. However, considering the prevailing political tensions and its geostrategic location, it remains to be seen how Ukraine could fulfil this role effectively.

Finally, for Uruguay the case is slightly different compared to other countries in this category. Uruguay presents a lower level of risk in terms of political risks and sustainability compared to its counterparts in this category. This Latin American country is renowned for its commitment to social equality and political stability and boasts a significant proportion of renewable energy sources within its power generation. However, engaging in hydrogen trade collaboration with Uruguay may involve higher costs. This situation creates a trade-off between the potentially elevated costs of hydrogen trade and the overall low risks associated on political and sustainability dimensions (World Bank, 2023).

4.2 Volatile Ventures

The second category involves countries that pose low economic risks, but high political risks. This category is called the 'Volatile Ventures'. Countries that are part of this category are: Algeria, Brazil, India, Kenya, Mexico, Morocco, Namibia, South Africa, Tunisia and Turkey. Partnering with these countries is perceived to involve political risks that could potentially lead to an unstable supply of hydrogen molecules, despite their capability for cost-effective hydrogen production. This necessitates caution among investors when forming partnerships with countries falling within this category.

For example, Tunisia has experienced internal political instability since the Arabic Spring in 2011. In 2021, the president Kais Saied suspended the parliament (Kashina, 2022) and consolidated his power through a new constitution. This has led to public protests and a deteriorating socio-economic situation in the country. South Africa too, is considered to be a high risk in political terms. The most industrialized country of the African continent is confronted with daily electricity black outs that have become a source of social unrest (Mkhize, 2022). Similarly, Mexico knows a high level of corruption and the role of the military in its economy is increasing. This situation undermines the ability to govern the country (Tähtinen, 2023).

Friction between import an export country may also become a source of unstable hydrogen supply. For example, when tensions arose around the sovereignty of the Western Sahara in 2021, Berlin showed support for the contested region. Morocco, who had then concluded a hydrogen agreement with Germany already in 2020, suspended the hydrogen cooperation with Germany in 2021 (Dumpis, 2021). Another example is the relation between European countries and Turkey which has been spiraling down following the coup attempt in 2016 and the erosion of democratic freedom in Turkey. These relations may even worsen with the recent re-election of president Recep Tayyip Erdogan (Scazzieri, 2023).

Finally, both Namibia and Kenya are also considered to be risky in terms socio-political stability. Nonetheless, both Namibia and Kenya are considered emerging economies with an enormous resource potential, both for hydrogen and critical raw materials. The development of a hydrogen economy in these countries, could regardless the higher investment risks, foster an avenue for development of renewable energy and the green industrialization within these countries.

4.3 Strategic Gambits

The third category, identified as 'Strategic Gambits,' comprises countries capable of producing affordable hydrogen with low political risks. From a purely geostrategic and economic standpoint, establishing partnerships with these countries seems evident. However, such collaborations come with sustainability and energy justice risks. The focus on hydrogen production for export purposes might interfere with greening the local energy mix. This situation arises for example when green electricity used for hydrogen production competes with locally needed green electricity (Teske et al., 2022).

It is noteworthy that all the countries within this category, namely Oman, Qatar, Saudi Arabia, and the UAE, are located in the Middle East and all of them are facing high water stress levels (AQUASTAT, 2019). Therefore, the production of renewable hydrogen jeopardizes local water use in agriculture or other water-intensive industries. However, some studies suggest that the water stress level of hydrogen producing countries should not be a showstopper for hydrogen production projects (Beswick et al., 2021). Compared to other industries, hydrogen's water demand is relatively low. In addition, sea water could be desalinated to serve as freshwater for hydrogen production. This would boost the desalinization industry and could result in positive spillover effects for other industries as well (IRENA, 2022a; Rystad Energy, 2021). Nevertheless, if the toxic brine, the waste from the desalinization process, is not properly treated before being disposed in the sea, it could harm maritime ecosystems. All of these factors make the production of hydrogen in these countries more challenging than in other countries that do not face high water stress levels.

Furthermore, considering these countries are all rich in fossil fuels, hydrogen offers a potential avenue to diversify their economies and move from fossil fuel exports toward hydrogen exports (IRENA, 2022a). However, when hydrogen is used solely for export purposes and the deployment of renewable energy for hydrogen production does not go hand in hand with greening the local energy mix, hydrogen trade with these countries hampers global decarbonization efforts and slows down the transition toward net zero. As a result, there is a trade-off between importing cheap hydrogen and the environmental, justice and decarbonization challenges that such imports may cause.

4.4 Trusted Friends

Finally, eight partner countries score 'low' on all dimensions. These countries are labelled 'Trusted Friends' and include Australia, Canada, Chile, Denmark, Iceland, Norway, Portugal and Spain. All of these countries are part of the OECD, and five of them are located in Europe. Canada, Australia, and Norway are currently net exporters of energy sources, mostly fossil fuels. Their experience with trading energy sources could prove beneficial for trading hydrogen. Considering geographic distance, European countries may face competition from North East Asia, specifically Japan and South Korea, when it comes to securing volumes from Australia. It would be therefore more suitable to secure volumes that are closer to home. In the case of Norway, the existing natural gas infrastructure may serve as a good basis for setting up trade with European countries (IRENA, 2022a).

Denmark, currently a net importer of energy, sees hydrogen as an opportunity to harness its wind potential and become an exporter of both electricity and hydrogen (Copenhagen Infrastructure Partners, 2020). The partnerships with Portugal, Spain and Iceland have emerged from feasibility studies as part of the larger national hydrogen strategy of the Dutch government (Port of Rotterdam, 2021). These countries are located in the vicinity of hydrogen demand clusters in Europe and have the potential to produce hydrogen at low cost using either solar PV in Portugal and Spain (Escribano & Urbasos, 2024; Ristau, 2020) or hydropower in Iceland (Hafstað, 2020).

5. Discussion: Energy Security Implications of Hydrogen Trade Partnerships

Energy diplomacy discussions still often focus on a narrow subset of issues: how to secure access to sufficient and available fossil fuels from abroad? As the world's energy system is on the cusp of a major overhaul, new energy trading relations may emerge, including for hydrogen. The emerging practice of hydrogen diplomacy thus offers an opportunity to reinvent energy trading relations, and to move beyond narrow interpretations of energy security as security of supply. This analysis has therefore analyzed 40 hydrogen trade partnerships, not just in terms of the new dependencies and supply risks that they entail, but also in terms of other risks and trade-offs that they may trigger. The results imply that these concluded partnerships are not the result of a clear strategy, but rather an example of ad-hoc cooperation between hydrogen import and export country. Moreover, there is little to no cooperation between different import countries despite available tools such as the Energy Platform announced by the EU (Dejonghe et al., 2023). Policymakers in future hydrogen import countries face thus dilemma's as they seek to develop future trade relations.

Firstly, the countries that are deemed to be 'low risk' are mostly western democracies, with the exception, perhaps, of Chile, yet the country is also part of the OECD. These prospective partnerships with predominantly 'friendly' countries endorse the growing trend of friend-shoring, which involves moving crucial parts of the value chain of strategic sectors, such as energy, to 'trusted' countries and allies. However, a country's trustworthiness might change over time, and a country that currently is deemed to be 'low risk' may not necessarily score similarly in the future (Maihold, 2022). Moreover, such an approach could result in only a few like-minded partners left to partner with, and therefore limiting diversifications options.

Secondly, many of the countries that can produce cheap hydrogen, come with higher political risks. Therefore, this creates a dilemma between cost-efficient hydrogen and a save investment climate. This can be exemplified by previous attempts to establish energy cooperation with resource rich countries, for example by the Desertec project. In 2009, a consortium of European and North African companies proposed exporting electricity from the Sahara to Europe, with the aim of decarbonizing energy systems, improving Europe's energy security, and providing economic and social benefits to North African countries through job creation and income stability (Lilliestam & Ellenbeck, 2011). However, the project failed due to various reasons such as, economic risks, the destabilizing effects of the Arab Spring on North African countries, and concerns that the project would perpetuate colonial relations between the Global North and the Global South. Desertec was therefore deemed a "technology without a sociology" (Schmitt, 2018). This underscores the imperative of a socio-political assessment of future hydrogen trade partnerships.

Thirdly, trade-offs emerge as well between sustainable hydrogen supplies and global energy justice. Countries from the Middle East often face high water stress levels and only have a low share of renewables in their local energy mix. This raises concerns that the production of hydrogen in these countries would interfere with renewable energy

deployment for the local population or even increase fossil fuel production. Future hydrogen trade with these countries should therefore not go at the expense of a local green transition in the export country.

6. Conclusions

In recent years, the EU and its member states have actively engaged in hydrogen diplomacy by establishing bilateral agreements pertaining to hydrogen imports into Europe. However, concerns have been raised whether those partnerships are free of energy security risks. To shed light on this question, this article evaluated the 40 currently explored partnerships by Germany, Belgium and the Netherlands. The paper has identified four categories of partner countries based on the risks such partnership entails: 'Last Resorts' , 'Volatile Ventures', 'Strategic Gambits', and 'Trusted Friends'. Notably, less than one-third of the partnerships could be conceived as low risk. Consequently, there are still partnerships that pose economic, political and sustainable risks. The choice of partnerships is therefore largely influenced by trade-offs.

Yet, the risks and trade-offs are not distributed equally over the three future import countries. There is a divergence between EU member states in terms of the energy security implications of their partnerships. Germany has concluded the most agreements, followed by the Netherlands and Belgium. The Netherlands has concluded 46% of its partnerships with 'Trusted Friends' partner countries, while Germany and Belgium have respectively 22% and 40% of their partnerships with 'Trusted Friends' partner countries.

Furthermore, it should be noted that the risks associated with hydrogen partnerships are not only dependent on the partner countries. The diversification of supply countries, as well as the level of reliance on hydrogen in a country's energy mix, influence the risks related to import dependencies. In cases where countries are dependent on only a few suppliers and hydrogen is taking a prominent place in a country's energy mix, the choice of partner countries may be more important than in case of a more diversified hydrogen supply in combination with a low share of hydrogen in a country's energy mix. Moreover, energy security risks are also determined by the volumes of hydrogen coming from each individual export countries. Therefore, the assessment of the partnerships should be done on a case-by-case basis, taking into consideration its specific context.

This study has revealed how current partnerships may or may not contribute to the sustainable supply of hydrogen. However, due to methodological limitations, some parameters were not included in the data set. For example, the various production methods of hydrogen were not factored in as a parameter for evaluating the partnerships, as the focus was on renewable hydrogen. In future research, a similar assessment could be conducted by adding the hydrogen production methods to explore how they influence a country's performance. In addition, the coding of the parameters as either 'one' or 'zero' reduces the granularity that is present in the different indicators. Future research could opt for a fuzzy-set approach when evaluating the countries. However, this may yield different results and a different categorization.

Moreover, this study has not taken into account the types of partnerships that are concluded between prospective hydrogen import countries and prospective hydrogen export countries. At present, most of these partnerships have taken the form of MoUs or Letters of Intent, which serve only little legal accountability. To further advance the field, future research could build on the results of this paper by including the type of partnership as an indicator to assess the energy security risks. Such exercise would generate new insights into the energy security risks related to the type of partnerships.

Finally, this study has only focused on the risks for future import countries, and not the risks that could emerge for future export countries. For example, based on currently announced hydrogen export projects, about 16 Mt of hydrogen could be traded across the globe by 2030. Yet, only three projects have reached final investment decision, resulting in a lot of uncertainty for future export countries (IEA, 2023a). Future research could do a similar assessment from the perspective of future export countries, and the risks they may encounter from current hydrogen trade partnerships.

In conclusion, this paper has contributed to the existing body of literature by comprehensively scrutinizing the existing hydrogen partnerships and the economic, political or sustainability risks they entail. By doing so, this paper underscores the need for policymakers to think more strategically about which partnerships to pursue and confront future hydrogen import countries with tough choices about which risks and trade-offs they are willing to accept.

Supplementary materials

Supplementary S1: Supporting materials for the multi-criteria analysis

Table 22: Prospective hydrogen partnerships (until August 2023)

Prospective importer	Prospective exporter	Date partnership
Belgium	Chile	2021
Belgium	Namibia	2021
Belgium	Oman	2021
Belgium	Egypt	2022
Belgium	Norway	2022
Germany	DR Congo	2020
Germany	Ukraine	2020
Germany	Australia	2021
Germany	Brazil	2021
Germany	Chile	2021
Germany	Denmark	2021
Germany	Namibia	2021
Germany	Russian Federation	2021
Germany	Saudi Arabia	2021
Germany	Tunisia	2021
Germany	UAE	2021
Germany	Mexico	2021
Germany	Norway	2023
Germany	Turkey	2021
Germany	India	2022
Germany	Qatar	2022
Germany	Nigeria	2022
Germany	Angola	2022
Germany	Canada	2022
Germany	Kazakhstan	2022
Germany	Algeria	2022
Germany	Kenya	2023
The Netherlands	Portugal	2020

The Netherlands	Australia	2021
The Netherlands	Canada	2021
The Netherlands	Chile	2021
The Netherlands	Iceland	2021
The Netherlands	Morocco	2021
The Netherlands	Namibia	2021
The Netherlands	Oman	2021
The Netherlands	South Africa	2021
The Netherlands	Uruguay	2021
The Netherlands	UAE	2023
The Netherlands	Spain	2023
The Netherlands	Oman	2022

Table 23: Content analysis of the indicator literature

Dimension	Indicators	#	Mentioned in
Technological	Renewable energy potential	6	Aditiya & Aziz (2021); Breitschopf et al. (2022); Eicke & De Blasio (2022); Frontier Economics (2018); Ikonnikova et al. (2023); Pflugmann & De Blasio (2020)
Technological	Freshwater availability	5	Breitschopf et al. (2022); Eicke & De Blasio (2022); Frontier Economics (2018); Ikonnikova et al. (2023); Pflugmann & De Blasio (2020)
Sustainability	Domestic energy demand	4	Bouacida (2022); Bouacida & Berghmans (2022); Breitschopf et al. (2022); Heinemann & Mendelevitch (2021)
Sustainability	Water availability	4	Bouacida (2022); Breitschopf et al. (2022); Heinemann & Mendelevitch (2021); Lindner (2022)
Political	Corruption Index	4	Breitschopf et al. (2022); Frontier Economics (2018); Heinemann & Mendelevitch (2021); Lindner (2022)
Political	Fragile state index	3	Breitschopf et al. (2022); Frontier Economics (2018); Lindner (2022)
Political	Ease of doing business index	3	Brauer et al. (2022) ; Frontier Economics (2018) ; Lindner (2022)

Economic	Supply costs	3	Brauer et al. (2022); Ikonnikova et al. (2023); Moritz, Schönfisch & Schulte (2022)
Economic	Production costs	3	Brauer et al. (2022); Breitschopf et al. (2022); Frontier Economics (2018)
Sustainability	Air emissions (EPI)	2	Breitschopf et al. (2022); Teske et al. (2022)
Sustainability	Human Rights	2	Heinemann & Mendelevitch (2021); Teske et al. (2022)
Political	Rule of law index	2	Breitschopf et al. (2022); Lindner 2022)
Political	Political stability	2	Brauer et al. (2022) ; Breitschopf et al. (2022)
Political	R&D spending per capita	2	Brauer et al. (2022); Teske et al. (2022)
Economic	Strength of the economy (GDP per capita)	2	Aditiya and Aziz (2021); Brauer et al. (2022)
Economic	Experience in handling gas or renewable energy	2	Brauer et al. (2022) ; Frontier Economics (2018)
Sustainability	HDI	2	Aditiya & Aziz (2021); Lindner (2022)
Sustainability	Waste management (EPI)	2	Breitschopf et al. (2022); Teske et al. (2022)
Technological	Availability of CO_2	1	Frontier Economics (2018)
Technological	Risk index (disasters)	1	Breitschopf et al. (2022)
Technological	Ports (terminals and handling capacity)	1	Breitschopf et al. (2022)
Technological	Pipelines (domestic, reserves, export connection with EU)	1	Breitschopf et al. (2022)
Technological	Transport distance	1	Breitschopf et al. (2022)
Technological	Utilities (access to electricity, water)	1	Breitschopf et al. (2022)
Technological	Export of chemicals	1	Breitschopf et al. (2022)
Sustainability	Share of population in extreme poverty	1	Lindner (2022)

Sustainability	Share of youth not in education	1	Lindner (2022)
Sustainability	Share of population with access to electricity	1	Frontier Economics (2018)
Sustainability	Heavily indebted poor countries	1	Frontier Economics (2018)
Sustainability	Biodiversity	1	Breitschopf et al. (2022)
Sustainability	Land use	1	Heinemann & Mendelevitch (2021)
Sustainability	Protected areas	1	Breitschopf et al. (2022)
Sustainability	R&D spending per capita	1	Aditiya & Aziz (2021)
Sustainability	Local communities	1	Teske et al. (2022)
Sustainability	Perspectives for development	1	Frontier Economics (2018)
Political	Global democracy index	1	Lindner (2022)
Political	Freedom index	1	Lindner (2022)
Political	World press index	1	Lindner (2022)
Political	Attitude toward renewable energies (RES-targets)	1	Frontier Economics (2018)
Political	Voice and accountability index	1	Breitschopf et al. (2022)
Political	Regulatory quality	1	Breitschopf et al. (2022)
Political	Signatories to energy charter (EU or international)	1	Breitschopf et al. (2022)
Political	World bank RISE (regulatory indicators for sustainable energy)	1	Breitschopf et al. (2022)
Political	GII Human capital and research	1	Breitschopf et al. (2022)
Socio-political	Global quality infrastructure index	1	Breitschopf et al. (2022)
Socio-political	Government effectiveness	1	Breitschopf et al. (2022)

Economic	Costs of RES	1	Frontier Economics (2018)
Economic	Export oriented economy	1	Frontier Economics (2018)
Economic	Share of fossil fuels in national income	1	Frontier Economics (2018)

Table 24: Coding of the indicators (green is 'one', red is 'zero')

Country	Access to electricity	Water stress	% RE in electricity	CPI	FSI	EODB	Production costs	DES costs
Algeria	99,8	84,01	0,84	33	72,2	48,6	107	173
Angola	46,9	0,48	70,79	33	88,1	41,3	138	241
Australia	100	3,93	32,28	75	22,7	81,2	103	189
Brazil	100	1,55	86,94	38	73,9	59,1	113	195
Canada	100	3,73	69,74	74	20,1	79,6	97	167
Chile	100	21,62	52,96	67	43,2	72,6	100	171
DR Congo	19,1	24,94	83,96	20	107,3	36,2	139	228
Denmark	100	0,23	99,73	90	18,1	85,3	89	144
Egypt	100	141,17	11,22	30	83,6	60,1	139	216
Iceland	100	0,39	99,99	74	17,1	79	90	149
India	100	66,49	20,48	40	75,3	71	103	194
Kazakhstan	100	32,65	11,34	36	59,5	79,6	128	224
Kenya	71,4	13,13	89,78	32	88,2	73,2	98	198
Mexico	99,4	19,39	22,94	31	70,3	72,4	95	168
Morocco	100	50,75	17,38	38	70,1	73,4	93	155
Namibia	56,3	0,86	95,54	49	62,9	61,4	105	197
Nigeria	55,4	4,36	27,51	24	97,2	56,9	118	213
Norway	100	2,05	98,97	84	15,6	82,6	75	131
Oman	100	116,71	0,43	44	49,5	70	91	171
Qatar	100	431,03	0,07	58	42,3	68,7	86	155
Portugal	100	12,32	59,82	62	27,5	76,5	119	179
Russian Federation	100	4,12	18,36	28	72,6	78,2	136	222

Saudi Arabia	84,4	974,17	0,21	51	67,5	71,6	93	169
South Africa	100	63,56	9,09	43	72	67	102	201
Spain	100	26,03	42,22	60	44,4	77,9	94	161
Tunisia	100	96	4,39	40	68,2	68,7	109	172
Turkey	100	29,08	41,97	36	78,1	76,8	113	180
UAE	100	1672	4,5	67	39,1	80,9	91	161
Ukraine	100	13,73	16,52	33	68,6	70,2	220	288
Uruguay	100	9,79	84,44	74	35,2	61,5	147	228

Table 25: Overall risk performance of countries (green is 'low', orange is 'medium', red is 'high')

Country	Economic risk	Investment risk	Justice risk
Algeria	low	high	high
Angola	high	high	medium
Australia	low	low	low
Brazil	medium	high	low
Canada	low	low	low
Chile	low	low	low
DR Congo	high	high	medium
Denmark	low	low	low
Egypt	high	high	high
Iceland	low	low	low
India	medium	high	low
Kazakhstan	high	medium	high
Kenya	medium	high	medium
Mexico	low	high	low
Morocco	low	high	medium
Namibia	medium	high	medium
Nigeria	high	high	high
Norway	low	low	low

Oman	low	medium	high
Qatar	low	low	high
Portugal	medium	low	low
Russian Federation	high	high	medium
Saudi Arabia	low	medium	high
South Africa	medium	high	high
Spain	low	low	medium
Tunisia	low	high	medium
Turkey	low	high	medium
UAE	low	low	high
Ukraine	high	high	medium
Uruguay	high	medium	low

Supplementary S2: Robustness check

This supplementary material presents the results of a series of robustness tests of the multi-criteria analysis. I test the impact of changes in the dichotomization thresholds on the categorization of the countries.

Economic risks

1) Production costs: The original threshold was set at 113 USD/MWh. A first alternative and lower threshold was set at 120 USD/MWh. This alternative threshold would assign both Portugal (119 USD/MWh) and Nigeria (118 USD/MWh) a code 'one' instead of 'zero'. For Portugal, the alternative threshold does not change the categorization of the country. For Nigeria this would change the categorization from a 'Last Resort' country to a 'Volatile Venture' country. A second alternative threshold was set at USD 105/MWh. This would assign Algeria (107 USD/MWh), Brazil (113 USD/MWh), Turkey (113 USD /MWh) and Tunisia (109 USD /MWh) a code of 'zero' instead of 'one'. For Algeria and Tunisia and Turkey, this would not change the overall country categorization. For Brazil, this would change the categorization from a 'Volatile Venture' to a 'Last Resort Country'.

2) DES costs: The original threshold was set at USD 189/MWh. A first alternative threshold of 205 USD/MWh was used. This alternative threshold would assign Brazil (195 USD/MWh), India (194 USD/MWh), Namibia (197 USD/MWh), and South-Africa (201 USD /MWh) a code of 'one' instead of 'zero' on this indicator. A second alternative threshold was set at 185 USD/MWh. This would assign Australia (189 USD/MWh) a code of 'zero' instead of 'one'. However, both alternative thresholds do not change the overall categorization of the country categories.

Political risks

3) Corruption Perceptions Index: The original threshold was set at 50. A first alternative threshold of 45 would assign Namibia (49) a 'one' instead of a 'zero'. However, this does not change the categorization of Namibia. A second alternative threshold was set at 55 and this would assign Saudi Arabia (51) a code of 'zero' instead of 'one'. This would change the country categorization of Saudi Arabia from a 'Strategic Gambit' to a 'Volatile Venture'.

4) Fragile State Index: The original threshold was set at a score of 60. A first alternative threshold of 65 would only assign Namibia (62,9) a score of 'one' instead of 'zero'. However, this does not change the categorization of Namibia. A second alternative categorization of 55 would assign Kazakhstan (59,5) a 'zero' instead of a 'one' on this indicator. Yet, this does not change the country categorization of Kazakhstan.

5) Ease of doing business index: The original threshold was set at 63. A first alternative threshold of 60 would change the coding of 'zero' to 'one' for Egypt (60,1), Namibia (61,64) and Uruguay (61,7). However, this would not change the categorization of any of these countries. A second alternative threshold was set at 65. This does not change any of the coding for this indicator.

Notably, should the alternative thresholds for the aforementioned political risk dimension categorize Namibia positively across all indicators within this dimension, Namibia would transition from being a 'Volatile Venture' country to a 'Strategic Gambit' country.

Sustainability risks

6) Access to electricity: The original indicator was set at 100%. A first alternative threshold of 95% would assign Algeria (99,8%) and Mexico (99,4%) a score of 'one' instead of 'zero'. However, this would not change the overall country categorization of both countries. A second alternative threshold was not used, as there are substantial gaps within the data. For more information, check Table 24 in Supplementary S1.

7) Share of renewables in electricity mix: The original threshold was set at 28%. A first alternative threshold of 25% would assign Nigeria (27,51%) a score of 'one' instead of 'zero'. However, this would not change the country categorization of Nigeria. A second alternative threshold was set at 30%. This does not change the coding for this indicator.

8) Water stress index: The original index was set at 25%. A first alternative threshold of 30% would assign Spain (26,03%) and Turkey (29,08%) a coding of 'one' instead of 'zero'. However, this would not change the overall country categorization of both countries. A second alternative threshold was set at 20%. This would assign Chile (21,62%) and the DRC (24,94%) a score of 'zero' instead of 'one'. However, this would not change the overall country categorization of both countries.

Article 3.
Green colonialism or green transformation? The equity implications of clean hydrogen trade

Marie Dejonghe and Thijs Van de Graaf

Abstract

The rapid expansion of bilateral hydrogen trade agreements has intensified debates over their implications for global economic and political relations. This study critically examines whether hydrogen trade fosters a 'green transformation'—driving industrialization and economic autonomy in the Global South—or reinforces 'green colonialism'—replicating historical patterns of resource extractivism and dependency. Drawing on a hermeneutic literature review and elite interviews, we critically analyze the competing mechanisms underlying these narratives. We identify three core risks of green colonialism: domination, accumulation, and appropriation. Conversely, we outline three strategic responses for fostering green transformation: ensuring voice, obtaining a stake, and fostering autonomy. By positioning these perspectives in dialogue, we move beyond binary assessments, highlighting the tensions, contradictions, and possibilities embedded in the emerging clean hydrogen landscape. Our findings contribute to debates on post-colonial resource governance, energy transitions, and the geopolitics of sustainability, offering a lens to analyze the equity implications of trade and investment not only in hydrogen, but also in other resource sectors, including raw materials and biofuels.

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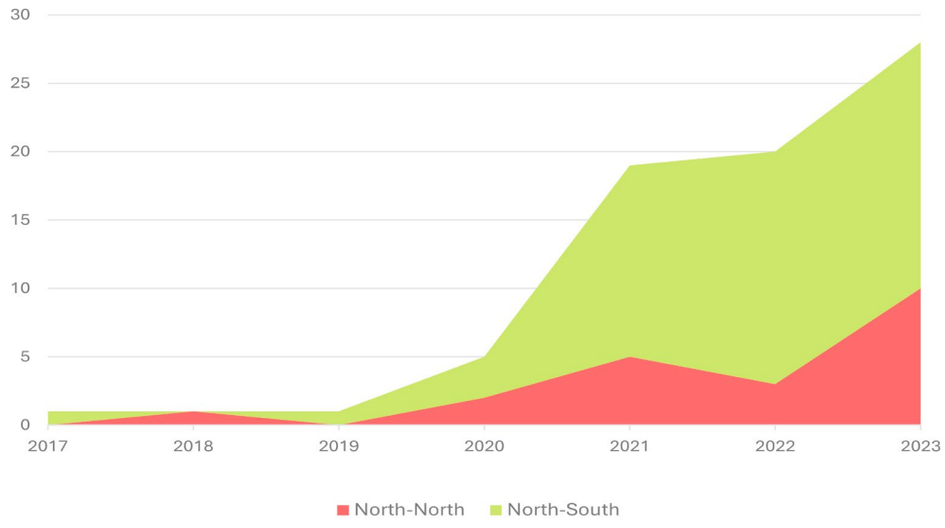
1. Introduction

Clean hydrogen has gained momentum as a potential solution for decarbonizing hard-to-abate industrial sectors and parts of transportation.[17] However, many industrialized regions—particularly in Europe and Northeast Asia—face significant constraints in green hydrogen production and are increasingly looking to imports to meet future demand. This shift has fueled an intense wave of 'hydrogen diplomacy', leading to a proliferation of various bilateral hydrogen trade agreements (Dejonghe, 2023). Most of these agreements follow a North-South pattern: approximately three quarters involve Global North countries as importers and Global South[18] countries as exporters (see Figure 10).

Figure 10: Cumulative number of hydrogen trade deals over time, by type of deal



Source: authors' own compilation based on publicly available sources, including memorandums of understanding, company websites, and news articles.

The growing interest in hydrogen trade and investment in the Global South has sparked a debate about the equity implications of such schemes. Within this debate, two broad perspectives can be identified, which we classify as green colonialism and green

17 In this paper, we consider clean hydrogen as hydrogen produced through electrolysis powered by renewable energy (i.e., 'green hydrogen') and steam methane reforming with carbon capture and storage with high CO_2 caption rates and low methane leakages (i.e., 'blue hydrogen').

18 In this paper we refer to countries as Global North when they are categorized as "developed countries" by UNCTAD. Countries categorized by UNCTAD as "developing countries" are referred to as Global South (UNCTAD, 2024). Throughout this study, we employ the term "Global South" as a relational category rather than as a fixed geographical designation. While the term typically encompasses Latin America, Africa, South and Southeast Asia, and the Middle East, its usage is contested, particularly given the increasing heterogeneity within and across these regions (see Haug et al., 2021). Rather than reifying the Global South as a monolithic bloc, we follow Berger (2021) in conceptualizing it as a position of political, economic, and epistemic subjugation within global hierarchies. This framing allows us to focus not on geographical determinism but on the structural and historical inequalities that continue to shape North-South relations.

transformation. The green colonialism perspective argues that hydrogen trade risks reproducing historical patterns of economic dependency, resource extraction, and power imbalances, ultimately reinforcing neo-colonial structures (Claar, 2022; Dillman & Heinonen, 2022; Hamouchene & Sandwell, 2023; Kalt et al., 2023; Kalt & Tunn, 2022; Lang et al., 2024; Müller, 2024; Müller et al., 2022). The green transformation perspective, by contrast, contends that hydrogen trade offers a unique opportunity for economic development, industrialization, and value creation in the Global South, breaking historical cycles of underdevelopment (Andreoni et al., 2023; Eicke & De Blasio, 2022; Lema et al., 2020; Walker & Kalvelage, 2025).

In the academic literature, the green colonialism critique has gained significantly more traction. This perspective builds on a long tradition in political geography that examines how global resource flows reinforce geopolitical hierarchies (Dalby 2004; Graddy-Lovelace & Ranganathan 2024). Scholars have highlighted the “enduring coloniality” of ecological modernization (Alkhalili et al., 2023) and broader struggles against “infrastructural colonization” (Dunlap, 2020, 2023; Dunlap & Laratte, 2022). Specifically in relation to hydrogen, scholars argue that colonial relations of dependency are “perpetuated” and “greenwashed” through hydrogen trade schemes (Claar, 2022).

By contrast, the green transformation perspective has gained traction among policymakers and international institutions but remains comparatively underexplored in scholarly analyses. Some scholars argue that hydrogen could serve as a ‘crucial’ catalyst for industrialization, offering Global South countries an opportunity to capture greater value within green energy markets (Andreoni et al., 2023). Similarly, UNIDO, IRENA, and IDOS highlight the potential of green hydrogen to “spark a transformation that drives industrial development and fosters innovation” (UNIDO et al., 2024).

This debate is not confined to academic discussions but has also sparked real-world controversy. In September 2023, over 500 African civil society groups signed the African People’s Climate and Development Declaration, denouncing green hydrogen as “a neo-colonial extraction of African energy and freshwater resources” (People’s Climate and Development Declaration, 2023). Similarly, activist NGOs have criticized Europe’s plans to import renewable hydrogen from Africa as “the latest neocolonial resource grab” (Corporate Europe Observatory, 2023) or simply, “neocolonialism painted green” (Davis, 2023). Even policymakers in the Global North have acknowledged these concerns. During a visit to Namibia—a former German colony—Germany’s former climate and economy minister, Robert Habeck, warned: “The last thing we can accept is a kind of new energy-imperialism” (Wehrmann, 2022).

Yet, other policymakers argue that hydrogen partnerships can drive industrialization and long-term economic transformation in the Global South. For example, Namibia’s Ambassador to the EU, Dr. Mekondjo Girnus-Kaapnda, describes Namibia’s partnership with the EU as a chance to leverage Namibia’s natural resources for the benefit of current and future generations (Delegation of the EU to Namibia, 2023). Similarly, European Commission President Ursula Von der Leyen has suggested that hydrogen trade could allow Global South countries to retain more economic value from their resources, stating during a visit to Mauritania: “The processing into green steel could

stay in Mauritania and that’s a huge step because this is the added value, this is where the jobs are, this is where the prosperity is” (Collins, 2024c).

In sum, some view hydrogen trade as a new form of extractivism, others see it as a means to reshape economic relations between the Global North and the Global South. This study contributes to this debate by examining the mechanisms underpinning these two competing lenses: green colonialism and green transformation. However, rather than treating them as mutually exclusive, we move beyond binary assessments by critically connecting these competing mechanisms. In doing so, our study highlights the underlying power dynamics, contradictions, and potential for structural change in clean hydrogen trade, offering a framework for assessing its broader implications within global resource trade and sustainable development.

2. Methodology and analytical approach

This study draws on two sources of data. First, our analysis is based on a narrative and hermeneutic literature review (Boell & Cecez-Kecmanovic, 2014) of academic and policy debates on clean hydrogen trade. While the green colonialism critique represents a growing body of academic literature, the green transformation perspective remains more prominent in policy documents, institutional reports, and industry white papers. To develop a more comprehensive understanding, we also draw on adjacent fields, including energy transitions, resource dependency, post-colonial political economy, and development studies.

Second, we conducted nine semi-structured elite-interviews with high-level government representatives from Global South countries engaged in bilateral hydrogen trade agreements. Interviewees included ambassadors, diplomats and diplomatic advisors based either in Brussels or in their respective capitals, representing four Latin American countries, two Sub-Saharan African countries, and three Middle Eastern and North African (MENA) countries. Interviews lasted between 30 minutes and 100 minutes, with all but two conducted in person. The interviews were inductively coded in NVivo, and responses were analyzed in relation to the conceptual frameworks identified in the literature. To ensure confidentiality, all interviewees were granted anonymity and are referenced in a non-attributable way (see Supplementary materials S3 for further details).

Our selection of interviewees was guided by one primary consideration: the existing discourse on hydrogen trade is dominated by voices from the Global North, often reflecting specific priorities and concerns. Engaging directly with high-level policymakers from the Global South allows us to counteract this imbalance and foreground perspectives that have so far received limited attention in scholarly debates. Given their role in shaping policy and negotiating international agreements, these actors provide key insights into the strategic and political considerations driving hydrogen trade.

However, we acknowledge the limitations of this approach. By focusing on policymakers and diplomatic representatives, we may exclude the views of local communities or marginalized groups, potentially introducing elite bias. This concern is widely discussed

in studies on post-colonial elites and elite capture (see Dutta 2009). To mitigate this limitation, we incorporate insights from other studies on community experiences with hydrogen projects. Several recent studies have examined community perspectives in South Africa (Kalt et al., 2023), Namibia (Tunn et al., 2025), Colombia (Combariza Diaz, 2024) and Chile (Scholvin, 2023), offering critical insights into localized impacts and contestations surrounding hydrogen trade.

By critically examining the competing narratives of green colonialism and green transformation, this study contributes to the expanding literature on clean hydrogen trade, post-colonial resource governance, and green industrialization. More broadly, we offer a framework for analyzing how Global South economies can navigate the tensions between economic opportunity and extractive dependency in emerging energy and commodity markets. While our focus is on hydrogen trade, the structural contradictions we identify—between resource-based development and persistent geopolitical asymmetries—are not unique to the sector of clean hydrogen. Similar debates unfold in the governance of raw materials, biofuels, and critical minerals.

3. The 'green colonialism' perspective

The term 'green colonialism' is widely used in activist, political and academic circles to describe a wide range of injustices associated with the global energy transition and the fight against climate change. For instance, green colonialism has been used to describe the impact of wind farms on indigenous communities in Norway (Normann, 2021), the establishment of conservation areas in Palestine (Sasa, 2022), the development of renewable energy projects in contested regions such as the Western Sahara and the Syrian Golan Heights (Alkhalili et al., 2023), as well as forest conservation, lithium extraction and green hydrogen projects in Latin America (Dorn, 2022).

Furthermore, 'green colonialism' is often used interchangeably with related terms such as 'climate colonialism' (Bhambra & Newell, 2022; Mahony & Endfield, 2018), 'energy colonialism' (Müller, 2024; Sánchez Contreras et al., 2023), 'carbon imperialism' (Sealey-Huggins, 2017) and 'green extractivism' (Andreucci et al. 2023; Bruna 2021). What underpins these different concepts is a broader critique of power imbalances in climate governance and resource extraction.

Green colonialism perspectives are often embedded in broader debates about environmental, energy, and climate justice. Climate justice is rooted in human rights scholarship and denotes the equitable sharing of the burdens of climate change (Caney, 2021). Energy justice centers around the notion that all individuals should have access to affordable, sustainable and reliable energy, while also having the opportunity to participate in and influence energy decision-making processes (Jenkins et al., 2016; Sovacool & Dworkin, 2015). These literatures have introduced different dimensions of justices: procedural, distributive, recognition, and restorative justice (Heffron & McCauley, 2017).

Drawing on the literature on hydrogen and green colonialism, we categorize the green colonialism perspective into three distinct mechanisms: domination, accumulation, and appropriation. Domination refers to both visible and invisible power structures, including

technological control, hegemonic narratives, and decision-making asymmetries that shape hydrogen politics. This expands the notion of *procedural justice* to account for implicit power dynamics that determine whose interests drive cross-border hydrogen projects. Accumulation highlights the unequal distribution of economic gains, linking *distributive* justice concerns to broader capitalist structures, debt dependencies, and growth imperatives. These factors reinforce systemic inequalities in which Global South countries primarily serve as resource suppliers. Appropriation refers to the expropriation of land and resources through practices such as green grabbing and the creation of sacrifice zones. This mechanism often results in both *recognitional and restorative injustices*.

These categories are not mutually exclusive and often overlap. For instance, land appropriation is often an accumulation strategy, while the green growth paradigm functions as a form of hegemonic domination. Some mechanisms are best understood as systemic issues, such as the structural underdevelopment of peripheral countries, while others take the form of specific injustices, such as the exclusion of local communities from decision-making processes or land disputes in hydrogen project zones. While categorizing these mechanisms introduces some risk of oversimplification, doing so clarifies the concept of green colonialism and its implications for hydrogen trade.

A summary of these mechanisms in the context of green hydrogen trade is provided in Table 26. While not all reference included in Table 26 explicitly discuss clean hydrogen trade, we argue that the underlying mechanisms they describe are equally applicable to this sector.

3.1 Domination

Political control or *domination* can be seen as a fundamental mechanism of green colonialism. Here, we highlight three main pathways: (1) procedural injustices, whereby decision-making is dominated by private companies and/or local or transnational (authoritarian) elites; (2) technology domination, whereby hydrogen trade schemes are underpinned by Western-dominated technologies, and (3) hegemonic discourses, meaning that the dominant way of thinking and talking about hydrogen trade is shaped by powerful actors and advances their interests and values.

The first pathway concerns procedural injustices. Some scholars argue that the ongoing energy transition, including future hydrogen trade, is corporate driven (Dorn, 2022; Hamouchene & Sandwell, 2023; Sánchez Contreras et al., 2023). In this corporate energy transition, a significant portion of national hydrogen strategies, regulatory frameworks, and research are controlled by transnational corporations, serving to safeguard their vested interests (Interview 4; Svampa, 2024). In the case of hydrogen, the prominence of private firms is evident in some of the bilateral hydrogen trade agreements, which often take the form of a memorandum of understanding (MoU) between private companies from the Global North and state-owned/national agencies in Global South countries. For instance, the HYPORT project in Oman is a project between Belgian company DEME and OQ, a national energy company in Oman (DEME, 2022). Similarly, a green ammonia pilot project in Egypt has been announced between Scatec, a Norwegian Company,

Table 26: Unpacking 'green colonialism' mechanisms related to hydrogen trade

Category	Mechanism	Explanation	Sources
Domination	Procedural injustices	Decision-making for hydrogen trade projects is dominated by private companies and local and authoritarian transnational elites. This often results in little active and early engagement of local communities shaping hydrogen policies and leads to regulations that serve private, corporate interests rather than the public good.	Blohm and Dettner (2023); Hamouchene & Sandwell (2023); Kalt et al. (2023); Lang et al. (2024); Lindner (2022); Patonia (2025); Tunn et al. (2024)
	Technology domination	Hydrogen trade schemes are simply means to break open new markets for hydrogen technologies, such as electrolyzers, whose innovation and manufacturing is dominated by Western firms.	Acheampong & Tyce (2024); Claar (2022); Dillman & Heinonen (2022); Hamouchene & Sandwell (2023); Lang et al. (2024); Weko & Goldthau (2022)
	Hegemonic discourse	The dominant ideas and discourses related to hydrogen trade are set by powerful actors and further their interests, marginalizing the voices and interests of less powerful stakeholders.	Acheampong & Tyce (2024); Claar (2022); Dorn (2022); Hamouchene & Sandwell (2023); Kalt et al. (2023)
Accumulation	Extractivism & structural dependency	Hydrogen trade schemes prioritize the export of primary resources and thus reinforce structural dependencies in the global capitalist system where wealthier 'core' countries exploit poorer 'periphery' countries.	Acheampong & Tyce (2024) ; Acosta (2017) ; Andreucci et al. (2023) ; Bruna (2022) ; Chagnon et al. (2022); Dorn (2022); Gudynas (2013); Kalt et al. (2023); Sultana (2022b); Tornel (2023b); Warnecke-Berger & Ickler (2023)
	Debt trap & financial subordination	Developing countries may become ensnared in debt through participation in hydrogen trade schemes, while foreign investors have access to far-reaching protections through financial de-risking schemes, underpinned by public institutions.	Blohm & Dettner (2023); Claar (2022); Gabor & Sylla (2023); Haag (2023); Haag et al. (2024)
	Growthism & consumerism	Hydrogen trade schemes perpetuate consumerist lifestyles and energy-intensive productivism, which reinforces a (corporate) quest for natural resources (energy, water, land) in Global South countries.	Acosta (2017); Andreucci et al. (2023); Claar (2022); Dorn (2022); Hamouchene & Sandwell (2023); Herman (2023); Lang et al. (2024); Sultana (2022b)
Appropriation	Land, water & green grabbing	Hydrogen trade causes large-scale acquisition of land resources and water by domestic and international actors sometimes in the form of privatizing these sectors, neglecting the impacts on local communities.	Andreucci et al. (2023); Bruna (2022); Cezne & Otsuki (2025); Hamouchene and Sandwell (2023); Monteith & Escobar (2025); Tornel (2023b); Tunn et al. (2025)
	Sacrifice zones	Hydrogen trade may rely on technologies such as carbon capture and desalination that could end up dumping waste in the Global South and displacing environmental costs from North to South.	Andreucci et al. (2023); Combariza Diaz (2024); Hamouchene & Sandwell (2023)

Fertiglobe, a fertilizer company and the Egyptian government (Martin, 2024b). The MENA Hydrogen Alliance, moreover, exists mostly out of national energy companies of the region, complemented by companies such as Thyssenkrupp, Shell and Total Energies (Dii Desert Energy, 2023).

Procedural injustices can also occur when a small (trans)national elite dominates the development of hydrogen projects or strategies in the Global South (Interview 4), failing to engage local communities (Lindner, 2022; Müller et al., 2022). According to Hamouchene and Sandwell (2023) transnational actors prefer to collaborate with authoritarian regimes to facilitate international hydrogen trade, potentially disregarding human rights and democratic principles and maintaining current hierarchies in the international order. For example, the green hydrogen project Hyphen in Namibia, is heavily criticized by local actors and communities for not including the local population in project deliberations and decision-making (Rust & Ossenbrink, 2022). In a similar vein, the green hydrogen project in Guelmim-Oued Noun in Morocco is contested for marginalizing the voices of local communities and farmers (Amouzai & Haddioui, 2023).

The second pathway, technology dominance, reflects the unequal distribution of hydrogen-related intellectual property. Europe, Japan and the US dominate hydrogen technology patents (IRENA, 2022a), controlling 72% of all hydrogen-related international patent families published between 2011 and 2020 (IEA, 2023b). This technology dependency locks Global South countries into lower-value segments of the hydrogen economy (Lang et al., 2024). For example, while the Hyphen project in Namibia aims to build solar panel manufacturing capacity, the project remains dependent on foreign expertise and capital (Guchu, 2024).

Besides direct forms of domination, a third pathway concerns the dominance of the Global North in less direct or overt ways. This pathway corresponds to the neo-Gramscian concept of hegemony, which can be defined as the persistence of social and economic structures that systematically advantage certain groups over others (Ford & Newell, 2021). Some scholars have argued that certain mechanisms of green colonialism are justified by hegemonic ontologies and green discourses such as global decarbonization or sustainable development (Acheampong & Tyce, 2024; Andreucci et al., 2023; Dorn, 2022; Hamouchene & Sandwell, 2023; Lang et al., 2024). They argue that these narratives carry a bias in favor of rich countries in the Global North at the expense poorer countries in the Global South.

3.2 Accumulation

Colonialism is widely recognized as foundational to capitalism's historical development (Bhambra, 2020; Chagnon et al., 2022). Therefore, the risks of green colonialism are often linked to capitalism's core focus on the profit accumulation (Claar, 2022; Hamouchene & Sandwell, 2023; Lang et al., 2024). Three accumulation mechanisms are particularly relevant: (1) extractivism and structural dependency, (2) debt traps and financial subordination, and (3) growthism and consumerism.

The first pathway, extractivism, refers to the appropriation of natural resources solely for export purposes (Chagnon et al., 2022; Ye et al., 2020). It typically involves an intensive form of resource extraction with limited processing activities, resulting in minimal added value creation at the point of extraction (Tornel, 2023b). High-tech inputs and skilled labour for these industries are largely sourced from Global North countries, limiting domestic industrial capabilities (Acosta, 2013). Extractivist industries often operate as economic enclaves, disconnected from broader domestic development (Gudynas, 2013; Warnecke-Berger & Ickler, 2023). Despite contributing significantly to GDP, these industries offer limited social benefits, such as job creation or social security (Warnecke-Berger & Ickler, 2023). Historically, extractivism characterized commodity exports like sugar and timber in Latin America (Chagnon et al., 2022). Today, hydrogen projects in Brazil and Colombia reflect similar patterns, prioritizing hydrogen exports over domestic industrial use (Green Energy Park, 2024; New Climate Institute, 2023).

Dependency theorists argue that this division of labour, where developing countries serve as raw materials supplier to the industrialized centers of the Global North, is a structural feature of global capitalism rooted in historical legacies of colonialism and imperialism (Dorn, 2022; Jerez et al., 2021). Overcoming this structural dependency is challenging due to deteriorating terms of trade (Acheampong & Tyce, 2024). Historically, import-substitution industrialization was proposed as a remedy, promoting domestic industries over imports through trade protectionism. This approach aims to capture more value locally and boost employment and economic self-sufficiency.

The second pathway, debt traps and financial subordination, relates to how projects are financed (Kalt et al., 2023). Hydrogen projects are increasingly linked to the financialization of development aid initiatives, a new paradigm termed the "Wall Street Consensus" (WSC) by the macro-economist Daniela Gabor (2021). The WSC promotes private investment as essential for sustainable development, with governments and international agencies using public funds to 'de-risk' projects and attract institutional capital through mechanisms like green bonds or contracts for difference.

However, Gabor and Sylla (2023) note that relying heavily on private investors can perpetuate financial dependencies of Global South countries on powerful Global North investors while also increasing the risk of debt crises, as countries often need loans to meet investor demands. For instance, Namibia's government has introduced the SDG ONE forum to facilitate blended finance, aiming to reduce the capital costs of hydrogen projects and provide fiscal protection for private investors. To secure participation in these projects, the Namibian government borrows from institutions like the European Investment Bank (EIB), which threatens to elevate the national debt, which already stands at 60 % of GDP (Haag et al., 2024). A similar pattern is observed in Chile, where the national financing facility Corfo, along with European development banks like the EIB and the German development bank KfW, as well as the World Bank, fosters a favorable investment environment with tax exemptions and green credits (Collins, 2024b). However, such financing schemes are not limited to investors from the Global North as for example the Saudi Arabian ACWA Power is investing in hydrogen projects in both South Africa (Keltie, 2022) and Egypt (Clements, 2023).

Overall, derisking strategies are often designed to benefit Global North investors, financing their decarbonization rather than fostering Global South industrialization. By shifting risks onto Global South governments, these strategies exacerbate debt rather than alleviating it (Interview 9). Moreover, early-mover incentives encourage hydrogen export projects over domestic industrial use, prioritizing short-term investor returns over long-term economic transformation (Interview 2).

The third pathway, growthism and consumerism, critiques the North's reliance on perpetual economic expansion, sustained by resource extraction from the Global South (Hamouchene & Sandwell, 2023; Lang et al., 2024). Green hydrogen trade can be seen as an effort to sustain high-consumption lifestyles in industrialized nations under the guise of sustainability. One proposed solution to green colonialism in hydrogen trade is economic degrowth, particularly in the Global North (Acosta, 2017; Hickel, 2021).

3.3 Appropriation

A final manifestation of green colonialism is the *appropriation of land and resources*, manifesting through (1) *green grabbing and land grabbing*, and (2) *the establishment of environmental sacrifice zones*.

The first pathway, green grabbing, refers to the appropriation of land and resources under the guise of environmental objectives (Dunlap, 2020; Fairhead et al., 2012). Examples include carbon sequestration, large-scale renewables, and hydrogen projects, which frequently overlook local impacts and justify displacement in the name of the green transition.

In the context of hydrogen trade, land grabbing is a key concern (Cezne & Otsuki, 2025). Clean hydrogen production is highly land-intensive, requiring large areas for solar panels, electrolyzer infrastructure, and desalination plants. Oman has earmarked about 50.000 km^2—about one-sixth of its total land—for hydrogen projects, with the Hyport project alone reserving 150 km^2 (OPAZ, 2022). In Mauritania, the Aman project spans about 8.500 km^2—nearly four times the size of Tokyo (CWP Global, 2024). While Morocco has allocated 10.000 km^2 of land (2% of its land mass) for hydrogen projects, still modest compared to 67 % used for agriculture (Martin, 2024c; World Bank, 2021a), Egypt has set aside 4 % of its territory for hydrogen—equal to its agricultural land use (Chandak, 2024; World Bank, 2021b).

Weak land tenure systems amplify land grabbing risks, particularly in Global South regions with legacies of colonial land dispossession (Chigbu & Nweke-Eze, 2023; Kumeh & Omulo, 2019). Privatization further endangers land rights, as governments increasingly favor market-driven ownership models for renewables (Interview 7). These projects often involve multinational stakeholders who prioritize investor returns over local development (Manahan & Kumar, 2021). While some states, such as Algeria, maintain strong public ownership over the hydrogen sector (notably through the state-owned company Sonatrach), others, like Uruguay's have largely privatized it.

Table 27: Unpacking 'green transformation' mechanisms related to hydrogen trade

Response	Action	Explanation	Sources
Ensuring a voice	Community consultation	Increase local community engagement in decision-making in hydrogen projects.	Adow et al. (2022); Chigbu & Nweke-Eze (2023); Krieger et al. (2024); Scholvin et al. (2025); UNIDO, et al. (2024)
	Social contract	Involve local stakeholders in drafting hydrogen certification schemes and to address socio-ecological needs, maintain the social contract and ensure positive societal spill-over effects.	Andreoni et al. (2023); Bhagwat & Olczak (2020); Hassan et al. (2024); UNIDO et al. (2024)
Obtaining a stake	Backward linkages	Create backward linkages by for example introducing local content requirements (LCR) to create local jobs and enhance local value creation.	Akhtar et al. (2023) ; Andreoni et al. (2023); Bacil et al. (2025); Brahmbhatt et al. (2017); Goga & Bell (2024); Scholvin et al. (2024); UNIDO et al. (2024)
	Inclusive ownership	Increase government participation in hydrogen projects through public ownership and reduced (financial) dependency on private investors.	Brahmbhatt et al. (2017); Goga & Bell (2024); Scholvin et al. (2024); Scholvin & Kalvelage (2025)
Fostering autonomy	Technology transfers	Enable technological innovation through knowledge transfers and increasing local innovation capacity.	Bradlow & Kentikelenis (2024); Caiafa et al. (2024)
	Forward linkages	Develop local green downstream industrial sectors within the Global South.	Adow et al. (2022); Andreoni et al. (2023); Bacil et al. (2025); Caiafa et al. (2024); Fentahun (2014); Goga & Bell (2024); Karkare & Medinilla (2024); Medinilla & Dekeyser (2024); Scholvin, et al. (2024)

The second pathway, sacrifice zones, refers to areas disproportionately burdened by environmental harm, including pollution from desalination and CO_2 sequestration (Andreucci & Zografos, 2022; Hamouchene & Sandwell, 2023). These regions are effectively 'sacrificed' for industrial development, bearing the cost of environmental pollution while benefiting the least (Scott and Smith 2018). In hydrogen projects, there are risks in terms of the desalination of water and the environmental harm of disposing the brine back into the sea, potentially harming maritime ecosystems. Additionally, in the case of blue hydrogen, there are plans that foresee the storage of CO_2 in depleted gas fields, also located in the Global South (Hamouchene & Sandwell, 2023).

4. The 'green transformation' perspective

Much like the notion of 'green colonialism,' the concept of 'green transformation' is employed across different contexts and lacks a universally agreed-upon definition. Initially popularized by Karl Polanyi (2002) to describe the societal forces that structure and restructure capitalism, the idea of transformation has been revisited and expanded over the past decades. More recently, scholars have used the term with the adjective 'green,' emphasizing the environmental dimensions of shifts in economic and technological structures (Leach et al., 2015). The concept of 'green transformation' has been applied to diverse sectors, including the offshore wind sector (Poulsen & Lema, 2017) and sustainability-oriented innovations in fashion supply chains (Da Giau et al., 2020).

Despite variations in terminology, discussions of 'green transformation' often overlap with concepts such as 'green transition' (Kemp & Never, 2017), 'green growth' (Okereke, 2024) and 'green industrialization' (Mao et al., 2019; Rodrik, 2014). A common thread running through these literatures is that green transformation disrupts incumbent industries, creating new market opportunities for sustainable goods and services. These disruptions, in turn, can create pathways for latecomer economies to 'catch up' in green development (Bacil et al., 2025; Lema & Perez, 2024). The Global Value Chain (GVC) literature similarly posits that participation in manufacturing and innovation fosters value chain upgrading, benefitting emerging economies (Amendolagine et al., 2019). Structural economists argue that transitioning from low- to high-productivity sectors is key for achieving sustainable development and social welfare improvements (Ali & Gniniguè, 2022).

Despite theoretical advancements, research on hydrogen's role in green transformation remains nascent and largely confined to policy reports and institutional studies. For instance, IRENA, in collaboration with UNIDO and the German think tank IDOS, has published a report on the industrial development opportunities for hydrogen in developing countries (UNIDO et al., 2024). Similarly, the World Bank has examined financing models for hydrogen projects in developing countries (ESMAP et al., 2023). Furthermore, the development-oriented think tank ECDPM has explored the transformative potential of green hydrogen in Africa (Medinilla & Dekeyser, 2024), while Andreoni, Bell, and Roberts (2023) have looked into the transformative potential of hydrogen in South Africa. Alongside these reports, an increasing number of peer-reviewed studies explore emerging opportunities in North-South hydrogen trade and green industrialization, offering potential pathways to overcome injustices in hydrogen (Akhtar et al., 2023; Scholvin et al., 2024; Scholvin & Kalvelage, 2025).

Drawing on this fledgling literature and the conducted interviews, we identify three key responses to overcome green colonialism risks in clean hydrogen trade: ensuring a voice, obtaining a stake, and fostering autonomy. Ensuring a voice requires meaningful participation of Global South countries and local communities in shaping trade agreements to avoid relegation to passive resource suppliers. Securing a stake entails financial and operational inclusion in hydrogen projects to prevent reinforcing economic dependency. Fostering autonomy demands investments in infrastructure, capacity building, and technology transfer, allowing Global South economies to move beyond raw material extraction into higher-value industries.

These responses are not exhaustive and frequently overlap. For example, local content requirements designed to ensure industrial backward linkages can also reinforce social contracts by enhancing domestic economic participation. A general overview of the conceptualization of green colonialism mechanisms in green hydrogen trade is presented in Table 27.

4.1 Ensuring a voice

A key response to mitigate the risks related to green colonialism is to amplify the *voices* of governments, local actors, and communities in hydrogen project development. This can be achieved by 1) engaging communities early in project planning and 2) involving local stakeholders in shaping hydrogen certification schemes to maintain the social contract.

Firstly, ensuring hydrogen projects generate local benefits requires upholding the social contract and fostering social acceptance. Since local communities often bear the greatest impact of hydrogen projects, minimizing disruptions is critical (UNIDO et al., 2024). Communities must be granted fair and informed consent regarding the establishment of hydrogen projects, addressing both environmental and social impacts (Blohm & Dettner, 2023; Sovacool & Dworkin, 2015). Early, proactive, and responsible stakeholder and community engagement needs to be integrated within the permitting process (Cremonese et al., 2023). Including local communities in decision-making can help avoid procedural injustices and conflicts with other sectors such as agriculture, housing, or water management (Krieger et al., 2024). Early engagement fosters inclusive project designs and enhances public support (Altenburg & Kantel, 2024).

UNIDO et al. (2024) highlight the social contract as central to equitable hydrogen development. This includes revenue-sharing agreements, local job creation, and investments in essential services like housing and healthcare. In emerging economies with unreliable electricity access, social contracts could require developers to allocate a share of renewable energy for local consumption, ensuring cleaner and more reliable power. Such agreements may also mandate local workforce training and employment, strengthening domestic energy industries.

Moreover, it is important that when private entities are involved, they must commit to minimizing adverse local environmental and social impacts as part of the permitting procedures, with their performance monitored by government or independent agencies (UNIDO et al., 2024). Additionally, local communities can be engaged through shared ownership models, such as energy cooperatives or other forms of distributed ownership (Interview 6; Combariza Diaz, 2024; Teske et al., 2022; UNIDO et al., 2024).

Beyond local project engagement, communities should be included in hydrogen certification discussions to promote procedural fairness (Interview 6, 8). Existing certification mechanisms, such as the EU's Renewable Energy Directive and CertifHy, primarily focus on CO_2 emissions and are formulated by powerful actors in the Global North (CertifHy, 2022; European Commission, 2021a). However, certifications could be expanded to cover social dimensions, including electricity access, land rights, and human rights protections (Heinemann & Mendelevitch, 2021; Teske et al., 2022). For example, setting standards that require domestic electricity access before exporting hydrogen can address energy poverty, while setting standards on water use may avoid water conflicts (Bouacida, 2022; Heinemann & Mendelevitch, 2021). In South Africa, provinces and municipalities hold permitting and budgetary powers, allowing them to shape hydrogen projects at a regional level (Parker, 2023).

4.2 Obtaining a stake

The second response involves ensuring that countries in the Global South obtain a substantial *stake* in hydrogen projects. This can be achieved through 1) setting local content requirements (LCR) and creating 'backward linkages', and 2) experimenting with more of inclusive forms of ownership in hydrogen projects.

Since most value creation in renewable energy occurs upstream, LCRs can drive local industrialization and job creation (Interview 3, 5, 6; Swilling et al. 2022). LCRs mandate that investors use a minimum share of locally sourced inputs, fostering technological innovation and domestic industries. For example, South Africa's extensive reserves of platinum group metals (PGMs), may provide a steppingstone toward developing electrolyzer manufacturing capacity in the country (Salma & Tsafos, 2022). In Namibia, localizing the manufacturing of wind blades or solar cells is expected to generate about 11,000 jobs by 2040 (UNIDO et al., 2024). In practice, LCRs often function as import quotas and facilitate import substitution industrialization (UNCTAD, 2014).

Research suggests that domestic manufacturing of key hydrogen components mitigates social risks such as labor exploitation, unemployment, and gender wage gaps (Akhtar et al., 2023; Goga & Bell, 2024). Several countries have already introduced LCRs in hydrogen projects. Argentina targets 50% local content in green hydrogen projects to reduce reliance on equipment imports (Parkes, 2023), while Egypt offers tax incentives tied to a minimum 20% local content for hydrogen components (Martin, 2024a). In 2024, Brazil's hydrogen framework introduced tax benefits conditioned on local procurement (Bacil et al., 2025). Studies show that backward linkages in manufacturing reduce inequality and boost employment across different development stages (Goga & Bell, 2024).

Governments should also expand their role in hydrogen projects beyond regulation, ensuring profits are reinvested into education, R&D, and infrastructure rather than extracted by foreign firms (UNIDO et al., 2024). Reducing reliance on Global North investors requires stronger financial backing from multilateral development banks and climate finance mechanisms (ESMAP et al. 2023; Interview 4). This financial autonomy would allow states to shape hydrogen markets on their own terms. In Chile and Namibia, place-based leadership and institutional entrepreneurship have driven transformative economic changes, though Scholvin and Kalvelage (2025) suggest fostering more disruptive innovation for greater long-term impact.

Beyond regulation, governments could actively participate in hydrogen projects through public ownership, ensuring control over the value chain and limiting private sector dominance (Interview 4). This approach is akin to the Norwegian model where the state captures significant welfare from energy projects (Dillman & Heinonen, 2022).

4.3 Fostering autonomy

A final response involves empowering countries in the Global South to *autonomously* manage and develop their hydrogen industries. This can be achieved through 1) enabling technological innovation and knowledge transfers and, 2) developing local hydrogen downstream industries, or 'forward linkages'.

Firstly, to effectively participate in renewable energy value chains and develop a local hydrogen industry, countries in the Global South need to establish local innovation capacity and expertise, which necessitates technology transfers, capacity-building and knowledge sharing which may require reconsidering intellectual property rights (Bradlow & Kentikelenis, 2024; Eicke & Goldthau, 2021). In practice, this involves partnering with technology providers from the Global North as well as establishing local training and research centers for hydrogen (Interview 2, 3, 7). For instance, Namibia's hydrogen strategy includes the Namibia Green Hydrogen Research Institute (NGHRI), which conducts R&D, provides training, and helps localize the value chain. The NGHRI will serve as a science and technology park for university-industry-government consortia, engaging in a broad spectrum of activities (UNIDO et al., 2024).

Secondly, countries in the Global South have significant advantages due to their abundant wind and solar resources, as well as their often rich deposits of critical raw materials (Interview 4, 9). This positions them favorably to attract energy-intensive industries and develop green industrial sectors—a phenomenon known as the 'renewable pull effect' (Samadi et al., 2023). Developing these sectors would mitigate the risks associated with extractivism by reducing exports of unprocessed hydrogen and fostering the establishment of local downstream hydrogen industries. This process is called 'forward linkages' (Altenburg & Kantel, 2024). Research indicates that developing downstream industries is a crucial conditionality for much-needed structural transformation (Goga & Bell, 2024).

For instance, 60% of today's hydrogen consumption is used to produce ammonia, with 70% of that ammonia utilized as input for nitrogen-fertilizer production (IEA, 2021a,

2023a). Many countries in the Global South, such as Brazil, India, or Argentina, boast significant agricultural sectors but often rely on fertilizers imports. Establishing a local green fertilizer industry based on green hydrogen could reduce their dependence on imports and volatile fertilizer prices (Kee et al., 2023). Similarly, existing fertilizer exporters in Africa, such as Egypt and Morocco, could capitalize on their renewable energy potential to develop a green fertilizer industry. Morocco and Egypt are leading phosphorus fertilizer producers in North Africa and have set targets to become future exporters of green fertilizer (Medinilla & Dekeyser, 2024).

A similar case can be made for green steel production in Mauritania and South Africa (Verpoort et al., 2024). Mauritania, rich in iron and other metals, could harness its wind and solar resources to produce hydrogen and convert raw iron ore into hot briquetted iron (HBI) (Collins, 2024c). By exporting HBI instead of raw iron ore, Mauritania could enhance the economic benefits derived from its natural resources and mitigate extractivist tendencies (Karkare & Medinilla, 2024). For instance, while in the first quarter of 2024 the average steel price in Europe was more than 750 USD per ton, the average price of iron ore in 2024 was only about 108 USD per ton (Business Insider, 2024; Focus Economics, 2024). These price disparities underscore the potential added value from exporting finished goods rather than raw commodities.

5. Discussion

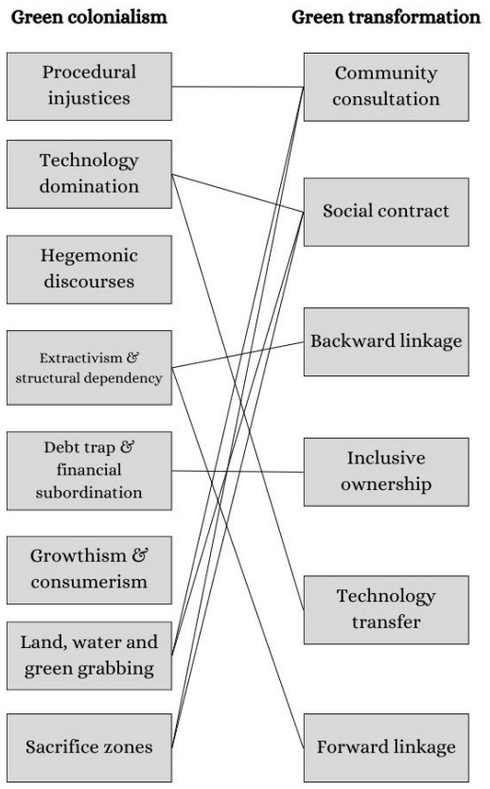
In the previous sections, we have revealed the multi-layeredness of both green colonialism and green transformation in the context of clean hydrogen trade and investment. Below, we critically assess the feasibility of green transformation mechanisms in addressing the potential injustices of green colonialism, identifying points of convergence and unresolved tensions.

First, the term ‘green colonialism’ encompasses various mechanisms, some of which have no immediate solution within the green transformation framework (as summarized in Figure 11). For example, if green colonialism is perceived as inherent to capitalism, there is no straightforward remedy within the current structures of the global economy. However, for other aspects of green colonialism that can be mitigated within the existing economic structures, solutions often involve trade-offs. For instance, blue hydrogen offers economic opportunities for fossil-fuel-rich countries like Algeria but raises environmental concerns and is exposed to asset stranding risks. Similarly, the high capital costs and infrastructure requirements of hydrogen can be addressed through greater government intervention, but this could also reinforce authoritarian and populist forms of governance and paradoxically restrict local community involvement. These complexities suggest that, while green transformation offers pathways for industrial upgrading, it does not inherently resolve the power asymmetries that underpin green colonialism.

Second, achieving genuine (green) transformation requires a shift beyond hydrogen trade itself toward a broader strategy of green industrialization. This requires linking energy, industrial, and financial policy to create a more comprehensive industrial development agenda (Goga & Bell, 2024). Historically, energy market shifts have triggered

industrial relocations, such as Japan’s relocation of its aluminum industry post-1970s oil crises (Hotter, 2022). However, evidence of contemporary renewable-driven industrial shifts (the so-called ‘renewables pull’ effect) remains largely anecdotal. For instance, car manufacturers have begun sourcing low-carbon aluminum from Saudi Arabia and Norway, where production is based on solar and hydropower, respectively (Altenburg & Kantel, 2024). These examples suggest that while green hydrogen could theoretically trigger industrial shifts in the Global South, there is currently limited empirical evidence that this process will materialize at scale.

Figure 11: Green colonialism mechanism vs green transformation response



Finally, hydrogen presents a potential avenue for low and middle-income countries to industrialize without relying on fossil fuels, but global geopolitical dynamics poses formidable obstacles. Fostering green industries in the Global South could provoke a significant geographic reconfiguration of energy-intensive sectors and associated geo-economic power dynamics. Therefore, it is likely to meet resistance. Powerful players in the Global North like the United States and the European Union have already implemented targeted industrial policies—such as the US Inflation Reduction Act and the Clean Industrial Deal—to ensure their industries remain competitive while transitioning to carbon neutrality. Thus, while green hydrogen presents opportunities for industrial upgrading in the Global South, the ultimate trajectory of global green transformation may depend as much on Northern industrial policy decisions as on Southern agency.

6. Conclusion

This paper has examined whether clean hydrogen trade offers a transformative opportunity for the Global South or simply reproduces colonial patterns of dependency. To explore this, we deconstructed green colonialism into three core mechanisms—domination, accumulation, and appropriation—and analyzed three potential responses within the green transformation framework: ensuring a voice, obtaining a stake, and fostering autonomy. Our findings highlight the contested nature of both green colonialism and green transformation, revealing how shifting power configurations will shape North-South hydrogen trade.

Our analysis reveals that the existing literature remains bifurcated between 'problem-exposing' and 'problem-solving' stances. While political geographers and critical social scientists have extensively documented the risks of green colonialism, they have paid limited attention to the trade-offs and complexities of green industrialization. Conversely, economic and policy-oriented discussions on green transformation tend to underemphasize structural inequalities. We highlight a few studies that actively bridge these debates, such as Caiafa et al. (2024) and Dillman and Heinonen (2022), but emphasize that further engagement is needed to develop a more integrated understanding of hydrogen trade's transformative potential.

Beyond its theoretical contributions, this study sought to clarify how green colonialism manifests in practice while also providing a conceptual bridge to more policy-oriented work. However, our research has limitations. Notably, our interviews focused on high-level policymakers, meaning we did not incorporate perspectives from local communities or marginalized groups. Future research should empirically assess whether the bifurcation we observe in the academic literature is also present in local discourses, as well as how these perspectives evolve in response to real-world hydrogen projects.

Additionally, while this study engages with broad North-South dynamics, it does not account for the distinct political and economic contexts of individual hydrogen-exporting countries. Future research should move beyond generalizations about the Global South and conduct detailed case studies of specific hydrogen projects, examining how local regulatory frameworks, industrial policies, and resource endowments shape the trajectory of green hydrogen development. Furthermore, the study does not address the role of China, whose position within the Global South is increasingly subject to debate. Further research should interrogate China's expanding influence in the hydrogen sector, both in terms of geo-economic competition with countries of the Global North as well as its engagement with countries considered to be part of the Global South. Such an inquiry would illuminate how China's activities complicate conventional North-South binaries.

In sum, hydrogen trade sits at the intersection of energy transition, economic restructuring, and global inequality. As hydrogen markets evolve, scholars and policymakers alike must remain attentive to both the risks of new extractivist dependencies and the possibilities for genuine economic transformation.

Supplementary materials

Supplementary S3: Overview of interviews

Function	Place	Date	Duration	Reference
Ambassador	Brussels	20/02/2024	0:36:31	Interview 1
Head of Trade	Brussels	20/02/2024	1:21:28	Interview 2
Ambassador	Brussels	28/02/2024	0:45:45	Interview 3
Head of Science & Technology	Brussels	07/03/2024	1:17:39	Interview 4
Ambassador	Brussels	07/03/2024	0:57:07	Interview 5
Minister plenipotentiary	Brussels	23/04/2024	0:52:30	Interview 6
Diplomat	Brussels	17/04/2024	1:47:63	Interview 7
Representative of the national hydrogen company	Online	29/04/2024	0:55:45	Interview 8
Head of Investment relations	Online	18/06/2024	0:35:15	Interview 9

Article 4.
The Global Hydrogen Race: Competing strategies for hydrogen technology leadership

Marie Dejonghe and Thijs Van de Graaf

Abstract

As the global energy system transitions to cleaner sources, the locus of state power is shifting—from controlling resource extraction to driving technology and innovation. This transformation has triggered a global race for leadership in clean technologies, with hydrogen emerging as a key battleground. While certain countries have secured early dominance in areas like solar panel manufacturing, the race to lead in hydrogen remains more open. This chapter examines the prospects for technological leadership across the hydrogen value chain, focusing on three strategically important sectors: electrolyzers, steel, and fertilizers. Drawing on insights from innovation studies, evolutionary economics, and historical analyses of industrial revolutions, we conceptualize technological leadership across three dimensions—innovation, manufacturing, and deployment—measured through indicators such as patents, investment flows, manufacturing capacity, and industrial uptake. Our analysis reveals a fragmented leadership landscape: Europe and Japan lead in innovation, China in electrolyzer manufacturing, while renewable-rich countries in the Global South hold untapped potential to produce cheap green hydrogen in bulk volumes. However, the rise of protectionist industrial policies across major economies threatens to slow global technology diffusion and reinforce existing inequalities. Ensuring a fair and effective hydrogen transition will require strategic industrial policy balanced with international collaboration.

This chapter is currently under review as a contribution to the edited volume: *Handbook of Hydrogen: Challenges and Opportunities in a Decarbonizing World*, edited by Anne-Sophie Corbeau, Manfred Hafner, and Giacomo Luciani.

1. Introduction

The world stands at the cusp of a profound geopolitical shift as it transitions away from fossil fuels to cleaner energy sources and technologies, centered around renewables. Renewable energy sources like solar energy or wind energy are abundant, widely accessible, and increasingly affordable. In a decarbonizing world, energy power is therefore set to move down the value chain, with the focus shifting from resource location and extraction to technology and innovation. This has sparked a global race for leadership in clean technologies—from solar panels and wind turbines to batteries, electrolyzers, heat pumps, carbon capture utilization and storage technologies (CCUS) and direct air capture (DAC) technologies.

Hydrogen-related technologies feature prominently in this global clean tech race. Clean hydrogen is increasingly seen as a critical tool for decarbonizing hard-to-abate industrial sectors and possibly heavy transportation. In recent years, no less than 66 countries, along with the EU and ECOWAS, have published national hydrogen strategies, including major economies such as Japan, Germany, and the United States (Corbeau & Nassif, 2025). Japan was the first to launch such a strategy in 2017, envisioning a hydrogen-based economy integrated across different sectors such as industry, transportation, and heating. The European Union published its hydrogen strategy in 2020 as part of the European Green Deal, which was updated in 2022 under the Hydrogen Accelerator initiative of the REPowerEU plan. By the end of 2023, the US (Department of Energy, 2023), China (NDRC, 2022) and India (MNRE, 2023) had also announced national hydrogen plans.

The development of a clean hydrogen industry brings not only environmental benefits but also significant geopolitical and economic implications. Countries that secure technological leadership in key segments of the hydrogen value chain could enhance their global competitiveness as the world shifts to a net-zero economy. Access to cheap, abundant, and clean hydrogen is poised to become essential for the success of decarbonizing heavy industries. Clean hydrogen is therefore becoming a standard fixture of the industrial policies of major powers, including the United States' Inflation Reduction Act of 2022 and the European Union's Clean Industrial Deal of 2025.

Some key technologies of the energy transition, such as solar panels, have already seen dominant players emerge. The race for technological leadership in hydrogen, by contrast, remains highly competitive, with no clear global leaders yet. This chapter examines the opportunities for technological leadership across the hydrogen value chain, focusing on three key technologies: electrolyzers, steel, and fertilizers. These technologies are strategically significant, with electrolyzers essential for clean hydrogen production, steel for national defense, and fertilizers for food security. We assess the positions of different countries in the race to dominate these hydrogen technologies and examine the broader implications for global power dynamics.

2. Introducing technological leadership

The concept of technological leadership is often invoked but rarely defined. This section therefore clarifies the concept, outlines how it can be measured, and examines how the race for technological dominance both reflects and shapes global power dynamics.

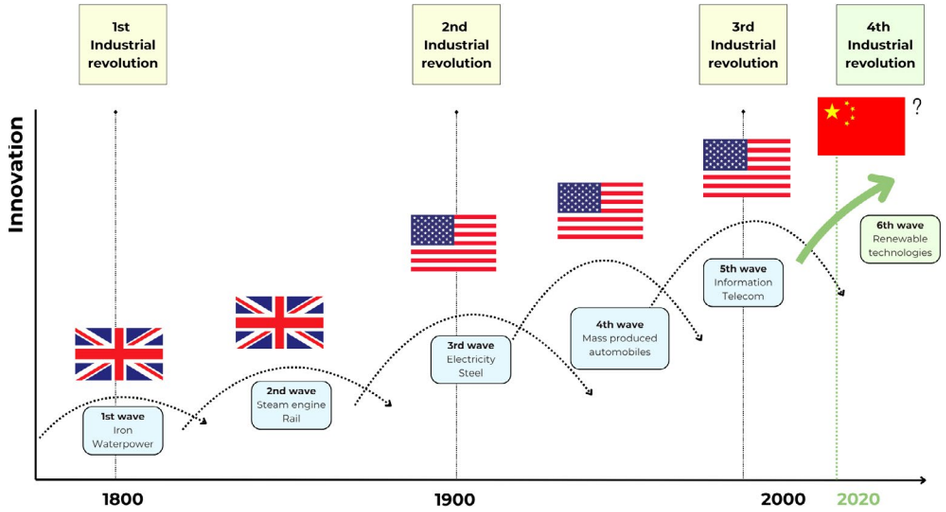
2.1 What is technological leadership?

The term 'technological leadership' lacks a universally accepted definition. It is often used interchangeably or alongside related terms like 'industrial leadership' and 'technological innovation'. Davids (2008) defines technological leadership as "a country's initiating role in the development of new technologies," placing technological innovation at its core. Moe (2007) connects technological leadership to industrial leadership, suggesting that once a country achieves technological leadership, it can build an entire industry around it. Thus, industrial leadership cannot be achieved without first attaining technological leadership. Mowery and Nelson (1999) observe that industrial leadership is often equated with 'comparative advantage,' although most research in this area focuses on internal factors at the firm level.

Throughout history, technological innovations have transformed national economies, trade flows, and the global balance of power. The adoption of new technologies has driven economic growth, influencing a country's global standing (Diesen, 2021). The cyclical relationship between technology and economic growth is central to the work of evolutionary economists like Schumpeter (1939) and long-cycle theorists such as Modelski (1987). From their perspective, the global political economy is characterized by the rise and fall of hegemonic powers. Countries can achieve hegemonic status by driving innovation in technologies in leading sectors, which create economic spillovers that impact the global economy (Drezner, 2001). Importantly, these technological 'revolutions' are not merely about developing new technologies, but about their profound impact on societal structures, labor division, and production processes, making them truly transformative (Perez, 2016).

Technological breakthroughs have historically fueled industrial revolutions (Figure 12). For instance, in the pre-modern era, the Dutch were considered technological leaders due to their technological edge in the shipping industry (Davids, 2008). Their dominance was eventually overtaken by Britain during the Industrial Revolution in the early 19th century. The 20th century saw the United States emerge as a technological leader with the advent of mass production, epitomized by Ford's Model-T (Perez, 2016). The third industrial revolution followed, marked by the digital age and the rise of the internet. Today, we are in the fourth industrial revolution (Schwab, 2016), building on the digital revolution and driven by technologies such as nanotechnology, renewable energy, and artificial intelligence (David et al., 2022). China is already leading in key technologies such as solar PV and nanotechnology (Bond et al., 2024).

Figure 12: Historical overview of technological innovation and related industrial revolutions



Source: author's own elaboration based on Perez (2016) and Bond et al. (2024)

Countries respond to shifts in technological leadership in various ways. Often, they seek to catch up (Lee & Malerba, 2017). To overtake technological leaders, countries typically have two main options: innovate or imitate. Imitation reduces the risks and costs of innovation, while innovation offers the chance to leapfrog incumbents (Chang et al. 2024). In some cases, governments may attempt to slow technology diffusion to preserve their first-mover advantage (Diesen, 2021). Not all technologies enhance state power; only those in 'leading' or 'strategic' sectors do (Drezner, 2001).

Today's intensifying geopolitical and geo-economic competition adds complexity to the global clean technology race. While a growing focus on clean technologies could accelerate the green transition, it also risks slowing progress on decarbonization as countries adopt protectionist policies—such as tariffs and trade barriers—that could result in unequal access to these technologies or the expertise behind them (Van de Graaf, 2022). This geo-economic turn is rooted in the 1990s, at the end of the Cold War, when military power seemed to make place for economic power and when productivity, market control, trade surplus, and ownership of technology became central to great power competition. Countries began competing for relative economic gains (Luttwak, 1990). More recently, geopolitical shifts—such as Russia's aggression in Ukraine and US-China tensions—have triggered fears of 'weaponized interdependence,' where states are able to exploit economic or technological dependencies to coerce others (Farrell & Newman, 2019).

This dynamic also plays out in clean energy technologies. Some countries fear that shifting from fossil fuel imports to clean tech imports replaces one dependency with another. The concern is that key technologies, or the critical minerals needed to build them, could be weaponized (Patil & Mishra, 2022). In response, many are pursuing

'technological sovereignty' (Allen et al., 2020; Seidl & Schmitz, 2024), fueling a form of 'techno-nationalism' (Diesen, 2021). This drive for strategic autonomy and resilient supply chains leads to policies promoting re-shoring and onshoring to boost self-sufficiency. Countries are also diversifying supply chains and turning to 'friendly' countries—a strategy known as 'friendshoring' (Maihold, 2022). The unequal geographical distribution of renewables and resulting divergence in electricity prices are reshaping decisions on where to locate energy-intensive industries—a trend referred to as the 'renewables-pull' effect (Verpoort et al., 2024). As a result, industrial centers, like the US and the EU, increasingly fear relocation of key production activities, reshaping global industrial value chains (Samadi et al., 2023).

2.2 Key tenets of technological leadership

Technological leadership plays a critical role in shaping state power and the global political economy, prompting countries to adopt dedicated industrial policies to bolster their position in the global technology race. Scholars have proposed both quantitative and qualitative indicators to assess a country's technological leadership (Basu et al., 2018; Davids, 2008; Diesen, 2021; Huang & Sharif, 2016; Nelson, 1999). Based on this literature, we compile a framework to assess technological leadership based on three categories of indicators. While our specific indicators are developed with respect to hydrogen technologies (see Table 28), the framework should lend itself to analyzing leadership in other areas as well.

An important indicator of technological leadership is the level of innovation. The ability to innovate and efficiently exploit innovations globally is considered a key source of technological leadership (Pelser, 2014). Innovation can be measured in several ways, with *investments* recognized by the OECD as a key performance indicator (OECD, 2024). Investments serve not merely as a financial metric but as a proxy for strategic intent, signaling whether policy frameworks effectively direct capital toward emerging technologies capable of displacing incumbent systems (IEA, 2025). Next to investments, the number of *patents* filed is an important marker of innovation as they create incentives to invent, promote innovation and encourage economic growth (Huang & Sharif, 2016).

Another sign of technological leadership is advanced *equipment manufacturing* (Basu et al., 2018). Manufacturing has historically driven economic growth through high productivity and continues to create jobs and spur innovation (Fox-Penner et al., 2021; Weiss, 2011). In renewable energy, manufacturing plays a central role in reducing costs. Unlike fossil fuels, which rely on economies of scale in extraction and refining, renewable technologies benefit from standardization and mass production (Poudineh, 2025).

Equally important is the *deployment of technologies*. While developing advanced technologies is a major challenge, the ability to deploy them is crucial for achieving and sustaining leadership. Moreover, the local market is more accessible, leading to lower transportation costs compared to foreign markets (Davids, 2008). This is supported by the demand-pull thesis, which holds that anticipated market demand is a key determinant of technological progress (Peters et al., 2012). The deployment of downstream technologies also hinges on the country's *access to resources*, both natural and human. For decades, economists have highlighted the importance of resources in driving economic activity and explaining disparities between states. These resources can include natural resources such as oil, natural gas, and critical raw materials, as well as human capital like labor forces or highly educated individuals (Nelson, 1999). However, possessing resources is only part of the picture; the ability to control access to them is equally crucial. For instance, European powers maintained dominance for centuries through colonialism, despite their limited access to natural resources (Diesen, 2021).

Table 28: Key dimensions of technological leadership and indicators

Dimension	Indicators	H_2 Indicators
Innovation	Investments Patenting	(Announced) investments in H_2 technologies H_2 technologies patents
Manufacturing	Equipment manufacturing capacity	H_2 technologies manufacturing capacity
Deployment	Resource endowment Deployment of downstream technologies	Access to H_2 related resources Green steel and green fertilizer

It is important to note that the indicators in Table 28 measure technological leadership but not the conditions for achieving it. The distribution of technological leadership across countries is influenced by a range of factors. While a full analytical framework is beyond the scope of this chapter, extensive research has explored key factors shaping technology leadership.

Joseph Schumpeter (1942) emphasized the role of disruptive innovations and creative destruction in shaping technological progress. Richard Nelson (1990) highlighted the role of national innovation systems and institutional frameworks, noting the critical roles of entities such as the US Department of Defense and NASA in securing America's dominance in the semiconductor industry. Mariana Mazzucato (2013) has underscored the significance of mission-oriented policies, where targeted government intervention helps steer innovation in critical sectors. Daniel Drezner (2001) argued that decentralized states are better equipped to maintain technological leadership, as centralized governments are more likely to protect the vested interests of a certain group. Espen Moe (2007) emphasized the importance of political consensus and social cohesion in achieving technological leadership. Additionally, industrial policy, access to capital, skilled labor, and the structure of global value chains further shape a country's ability to achieve and sustain technological leadership (Diesen, 2021).

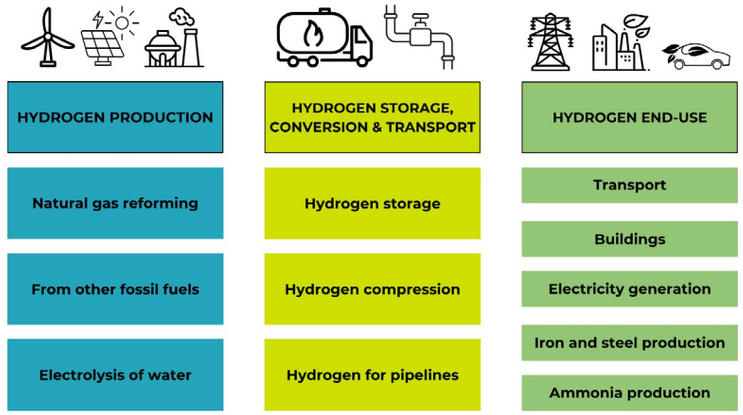
3. The hydrogen tech race

In the following section, we examine the current landscape of hydrogen technology leadership by analyzing three key indicators: innovation, manufacturing, and deployment. Before doing so, we briefly outline the hydrogen value chain and its key technologies.

3.1 The hydrogen technology value chain

The emerging market for hydrogen-related technologies encompasses a wide range of technologies — from production to conversion and end use (Figure 13). It is beyond the scope of this chapter to examine all the emerging technologies. Instead, we focus on three key technologies that can be considered strategic and for which the market potential is substantial (Ludwig et al. 2021): electrolysers, steel, and fertilizers.

Figure 13: Overview of the hydrogen value chain and related technologies



Electrolyzers are central to green hydrogen production, as they facilitate the splitting of water into hydrogen and oxygen using electricity from renewable sources. While alternative pathways for hydrogen production exist, such as steam methane reforming, these methods are typically associated with significantly higher greenhouse gas emissions. Beyond their primary role in hydrogen generation, electrolyzers could come to play a crucial role in enhancing grid stability by acting as flexible demand-side resources, absorbing surplus renewable energy and converting it into storable hydrogen. Box 5 outlines key electrolyzer technologies and their respective strengths and limitations.

Box 5: Different electrolyzer technologies

Alkaline Electrolyzer (ALK) A well-established technology that generates hydrogen by moving hydroxide ions through an alkaline solution, splitting water into hydrogen and oxygen. It is cost-effective, does not require rare metals, and is widely used in large-scale industrial applications.

Proton Exchange Membrane (PEM) Electrolyzer Uses a solid proton exchange membrane to efficiently produce high-purity hydrogen with fast response times. While compact and ideal for mobile and distributed applications, it relies on expensive platinum-group metals, increasing costs.

Solid Oxide Electrolyzer (SOEC) Operates at high temperatures, using ceramic materials as electrolytes to split water vapor into hydrogen and oxygen.

In this chapter, we do not analyze fuel cells as a separate technology, as they can essentially be regarded as electrolyzers working-in-reverse, and (more importantly) their market potential is deemed much smaller.

Additionally, we explore two critical end-use applications of hydrogen, each with substantial geopolitical and economic significance: steel and fertilizers. Hydrogen is a crucial pathway for virgin green steel-making, where hydrogen substitutes for coal or natural gas. Steel is a foundational material for infrastructure, energy systems, and defense, making it strategically important for national security. Moreover, green steel presents an opportunity for countries to position themselves as global leaders in low-carbon industrial technologies, potentially capturing a significant share of the potential international market for sustainable steel products.

Green fertilizers represent another critical application, offering opportunities for domestic agricultural security and international trade. Here, clean hydrogen is used to produce ammonia via the Haber-Bosch process with minimal greenhouse gas emissions. This is crucial for ensuring global food security while addressing the environmental impact of traditional fertilizer production, which is a major emitter of carbon dioxide. Furthermore, as hydrogen infrastructure expands, countries that want to substitute ammonia imports with local production or even exports could become pivotal players in the global agricultural market, exporting sustainable ammonia and driving the transition to low-carbon food systems. This highlights the strategic value of green fertilizers in the geopolitics of hydrogen.

Having outlined three key technologies in the hydrogen value chain, we now move on to discuss the three indicators of technology leadership.

3.2 Innovation: Investments and patents

Innovation is central to tech leadership. A country's potential for leadership can be evaluated by its investments and hydrogen-related patent filings. Innovation is often shaped by research and development (R&D) policies.

Hydrogen technology investments

Total announced investments across the entire hydrogen value chain reached USD 680 billion by the end of 2024 (Hydrogen Council & McKinsey & Company, 2024). Regionally, Europe leads in hydrogen announced investments, with USD 199 billion in announced projects by 2024, followed by Latin America, which accounted for USD 107 billion of announced investments. Africa saw a decline in announced investment from 2023 to 2024 (Hydrogen Council & McKinsey & Company, 2024). In terms of specific technologies, the majority of investments was in the deployment of hydrogen electrolyzers and associated equipment. Investment in electrolyzers continued its growing trend to reach a record high of USD 2.9 billion in 2023, nearly five times the 2022 level.

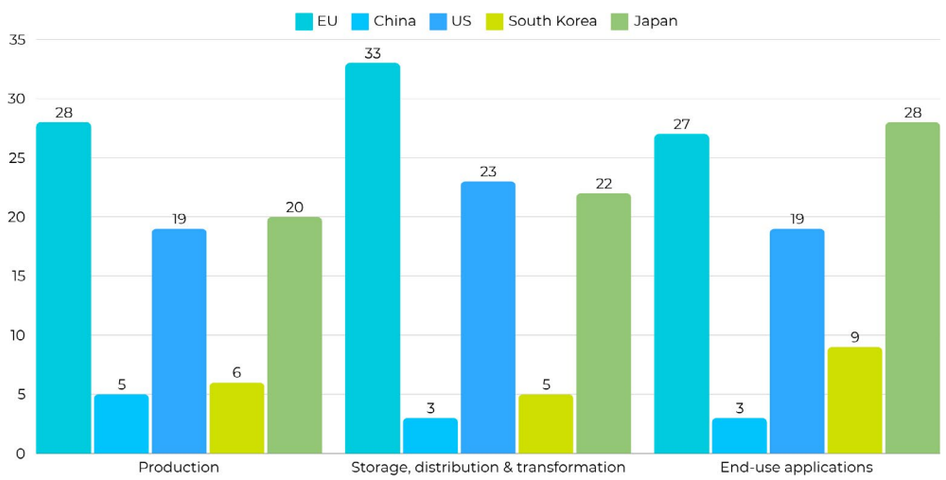
However, actual implementation is lagging. Of the USD 680 billion in announced investments in 2024, only USD 75 billion—approximately 11%—has reached the final investment decision (FID), is under construction, or has become operational. Never-

theless, this figure represents a substantial increase compared to the USD 39 billion in committed projects in 2023 (Hydrogen Council & McKinsey & Company, 2024). Overall, the discrepancy between announced investments and actual committed projects may indicate a recalibration of expectations due to rising project costs and unrealized market demand (IEA, 2025).

Hydrogen technology patents

Patenting offers a mechanism to protect and recoup innovation costs. Patent activity thus serves as a proxy for technological advancement (IEA, 2024c). In hydrogen, approximately half of patents filed between 2011 and 2020 pertain to production. Europe and Japan lead, accounting for 28% and 24% of all international patent families (IPFs), respectively (see Figure 14). Europe is strong in patents related to upstream and midstream segments of the hydrogen value chain, while Japan leads in end-use applications. In contrast, innovation rates in China and South Korea remain modest (IEA, 2023b). China contributes little to the international electrolyzer patents but invests heavily in manufacturing, with a nearly exclusive focus on the more mature and non-cutting edge alkaline technology (IEA, 2023b).

Figure 14: Share of international patenting by main world regions and value chain segments (%) (2011-2020)



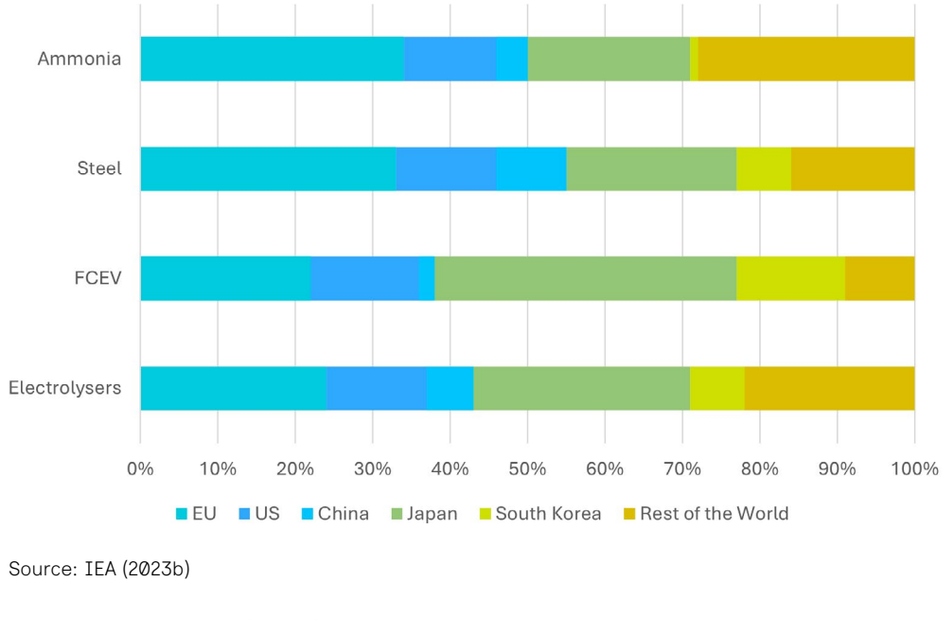
Source: IEA (2023b)

Focusing on specific technologies, Japan holds a dominant position in electrolysis patents, responsible for 28% of global patent applications in this area in the period 2011-2020, followed by the EU with 24% as a close second (see Figure 15). Leading Japanese companies are Toshiba, Panasonic and Asahi Kasei. While Toshiba and Panasonic focus mostly on PEM and SOEC technologies, Asahi Kasei focuses on patenting related alkaline technologies. However, deployment in Japan remains limited.

Conversely, the European Union leads in patent applications for hydrogen production via natural gas, representing 39% of the relevant patent filings. Historically, Japan has

led fuel cell patents thanks to its strong automotive industry. Today, fuel cell innovation targets heavy road transport like trucks, where they offer advantages over batteries (IEA, 2023b).

Figure 15: Origins of IPFs related to hydrogen technologies (2011-2020)



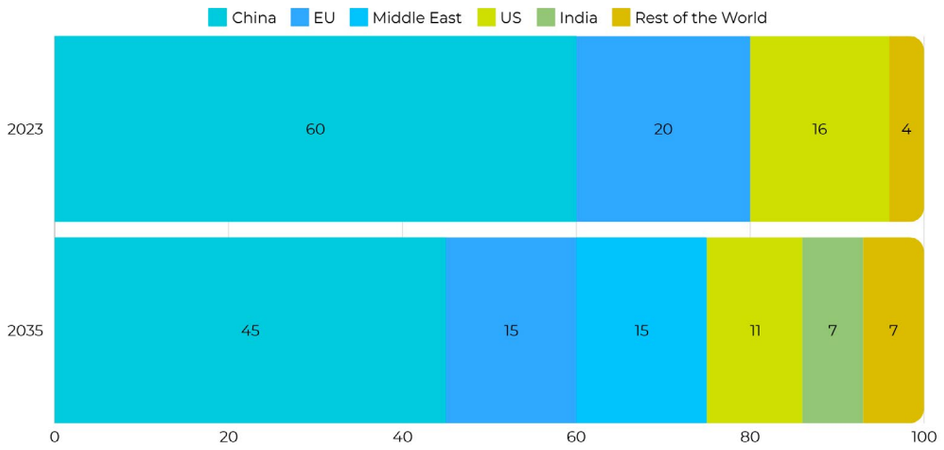
Source: IEA (2023b)

3.3 Equipment manufacturing: Electrolyzers

Equipment manufacturing is another crucial indicator of hydrogen technology leadership. China currently holds 60% of the global installed capacity for electrolyzer manufacturing (see Figure 16). This dominance is expected to drive down electrolyzer costs, as seen in the solar PV and electric vehicle industries (IEA, 2024c). However, by 2035, China's share in global electrolyzer manufacturing capacity is projected to decline to 45% as new entrants emerge. Europe and the Middle East are expected to each contribute 15%, while the United States and India will account for 11% and 7%, respectively. Rising demand in India and the Middle East is likely to spur local electrolyzer manufacturing from 2030 onwards (IEA, 2024b).

Several companies are leading the electrolyzer manufacturing sector, with a significant portion located in China, as shown in Table 29. One key factor behind China's large electrolyzer production capacity is its longstanding use of hydrogen in polysilicon production, a critical component in photovoltaic cell manufacturing. Consequently, major solar companies such as LONGi and Sungrow Power have also emerged as prominent electrolyzer manufacturers (Ouyang, 2023). Other European key players include Thyssenkrupp Nucera (Germany), John Cockerill (Belgium), and Nel (Norway), known for their PEM expertise (Collins, 2024a).

Figure 16: Share of electrolyzer manufacturing in 2023 and 2035 (%)



Source: IEA (2024b)

Table 29: Leading companies in electrolyzer manufacturing

Company	Country	Technology
LONGi	China	ALK
Peric	China	ALK, PEM
Sungrow	China	ALK, PEM
John Cockerill	Belgium	PEM
Thyssenkrupp	Germany	PEM
Nel	Norway	ALK, PEM
ITM Power	UK	PEM
Plug Power	US	PEM

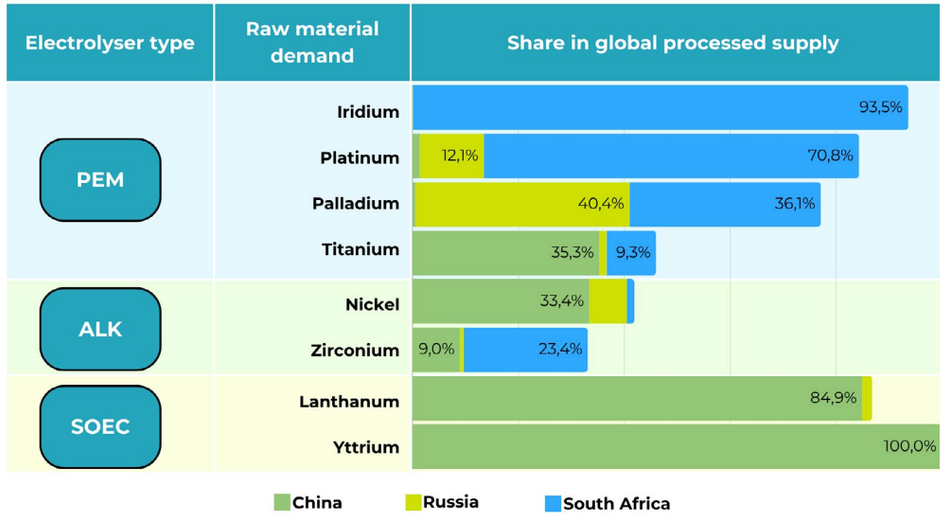
Currently, most electrolyzer manufacturing facilities are located in the home regions of the companies to meet domestic demand. While there are indications of geographic shifts in manufacturing distribution, it remains uncertain whether these will develop into long-term trends. For instance, in 2023, Chinese manufacturer GuofuHee announced plans to open a factory in Germany by 2026. In August 2024, Chinese firm Hygreen Energy, with Spanish partner Coxabengoa, also announced a facility in Spain (IEA, 2024c). Currently, only 20% of electrolyzers is exported internationally.

However, growing concerns over cheap Chinese electrolyzers are emerging (Day, 2024). This mirrors the solar PV sector, where domestic oversupply in China drove exports (IEA, 2024a). Chinese alkaline electrolyzers are projected to cost roughly 25% less than German ones, while Chinese PEM units are priced similarly to European models (Zhao & van Dorsten, 2024). China is expected to focus on mass production of alkaline

electrolyzers, while Western firms are prioritizing more advanced technologies like PEM electrolyzers. Moreover, imported electrolyzers are yet to be tested at scale under stringent European regulations. Therefore, Chinese electrolyzer exports may be more likely to be concentrated in Central Asia and the MENA region (Energy Iceberg, 2024). Thus, current fears in Europe are based on projections, not firm supply deals (Day, 2024).

Finally, some electrolyzer technologies depend on key raw materials, some of which are considered critical or strategic (see Figure 17). Alkaline electrolyzers use nickel and zirconium, while PEM electrolyzers rely on iridium, platinum, and palladium (IEA, 2021b). Nickel supplies are relatively diversified, with Indonesia (39.8%) and China (23.9%) as leading nickel smelters. In contrast, iridium and platinum supplies are heavily concentrated in South Africa, which accounts for 90% and 71.2% of global supply, respectively (IRENA, 2023a). Solid oxide electrolyzers require fewer critical materials but are less mature. Nevertheless, material dependency risks may be eased by switching technologies, as innovation continues to reduce reliance on scarce inputs.

Figure 17: Materials necessary for electrolyzer production



Source: authors' own elaboration based on European Commission (2023c)

3.4 Deployment: Green steel & fertilizers

Finally, the deployment of downstream technologies is crucial for catalyzing investment and sustaining leadership. Clean tech adoption is currently concentrated in China, the US, and the EU, reflecting their rapidly expanding domestic markets (IEA, 2024b). Looking ahead, resource-rich countries can leverage their natural endowments not only to produce clean hydrogen but also to attract investment in value-added manufacturing—a dynamic often referred to as 'renewables pull' (Samadi et al., 2023). This may offer a strategic opportunity to build or repurpose industrial capacity and foster

green industrialization. The viability of such downstream industries depends on the availability of affordable, scalable clean hydrogen. Thus, any assessment of leadership in green steel and fertilizer must begin with reliable clean hydrogen supply as feedstock.

Resource endowment

For green hydrogen, the availability of solar and wind resources is the primary indicator of potential production capacity. Countries with high potential in both solar photovoltaic and wind energy, such as Chile, Morocco, and Mauritania, are well-positioned to become potential leaders in green hydrogen production For now, green hydrogen production remains limited as it accounts for less than 0,1% of the global hydrogen production today, but it has a substantial growth potential (IEA, 2024c).

In the case of blue hydrogen, production potential mirrors the geographic distribution of natural gas reserves. Countries in the MENA region, most of which also boast significant renewable energy potential, as well as the US can be seen as potential leaders. Additionally, countries such as Iran and Russia, with their vast natural gas reserves, are also key players but their potential leadership may be depending on their position on the political scene (BP, 2023). At present, nearly half of global blue hydrogen production occurs in the United States, followed by Canada and the Middle East (IEA, 2024c).

Green steel

Green steel is a key sector for technological leadership. Although the global steel market was worth USD 1.4 trillion in 2023, only 0.1% qualifies as low-carbon. Historically concentrated in China and India due to raw material proximity, steel production has shifted toward demand centers for market responsiveness (Gielen & Lopez Rocha, 2025).

Despite conventional dominance, Europe is emerging as a green steel hub. If current projects materialize, it could produce 55% of global green steel by 2035 (IEA, 2024b). Efforts also target regions with abundant, cheap hydrogen. For instance, a hydrogen-based DRI plant launched in Namibia in 2024 (Gielen & Lopez Rocha, 2025). Additionally, Mauritania signed an MoU with ArcelorMittal to explore iron pelletizing and DRI, though no formal investment has followed (Karkare & Medinilla, 2024). Similar developments are underway in Australia and Brazil, the top iron ore producers. Both countries are investing in domestic processing to capture value and create jobs, supported by infrastructure investments in ports and railways (Gielen & Lopez Rocha, 2025).

Green fertilizer

Green ammonia and fertilizers offer a second avenue for leadership. The USD 90 billion ammonia market remains largely carbon-intensive, with only 2% of production low-carbon. China leads global fertilizer output (29%), followed by Russia (10%) and the US (9%) (IEA, 2021a).

Production typically clusters near raw materials. Morocco dominates phosphate production, while Canada, Belarus, and Russia lead in potash. Nitrogen fertilizers, the most common type, are made from ammonia, mainly derived from natural gas. Russia has been a major exporter, while China leads production, relying on coal and prioritizing self-sufficiency (OEC, 2024; Quitzow et al., 2025).

Looking forward, Global South economies may lead in green fertilizer due to renewable resources and strategic reserves (IEA, 2024b). Morocco is attracting large-scale hydrogen investments, including TotalEnergies' €9.4 billion Guelmim-Oued Noun project integrating renewables and ammonia (Africa Energy, 2018). In Mauritania, CWP Global's USD 40 billion Aman project aims to produce 10 million tons of green ammonia annually by 2027 (Atchison, 2021).

4. National strategies

Countries worldwide are increasingly adopting hydrogen strategies, advancing clean energy transitions and secure technological leadership. This ambition is reflected in a wave of industrial policies aimed at structurally enhancing industrial sectors (Chang & Andreoni 2020; Rodrik 2004, 2014; Weiss 2011). These policies increasingly focus on decarbonization and are thus referred to as 'green industrial policy' (Rodrik, 2014).

Green industrial policies employ a broad mix of tools, including tax incentives, local content requirements, R&D funding, and public procurement. Regulatory instruments—carbon pricing, emissions trading, certification schemes—are also central, alongside trade measures like tariffs and export controls. For an overview, see the IEA's Energy Technology Perspectives (2024b).

The next sections review hydrogen strategies in five major economies: China, the United States, the EU, India, and Japan. Each pursues targeted policies to accelerate hydrogen technology and achieve leadership.

4.1 China

China is a key player in the development of hydrogen though it only introduced a national strategy in 2022. The 2022 National Hydrogen Development plan prioritized hydrogen production but places limited emphasis on renewables. Its 2025 target —0.1 to 0.2 million tons of renewable hydrogen— (NDRC, 2022), represents only 0.3% to 0.6% of current global hydrogen production. However, local initiatives exceed the national target: the province of Inner Mongolia has set a renewable hydrogen production target of 0.48 million tons by 2025, which is 2.5 to 5 times greater than the national target (Yushan & Corbeau, 2023).

Chinese state-owned energy enterprises have played a crucial role in driving large-scale and capital-intensive hydrogen projects, supported by state subsidies. During the 13th Five-Year-Plan (2016-2020), China's hydrogen R&D spending rose sixfold, to over 600 million USD in 2019. In this context, companies like Sinopec and State Power Investment Corp are scaling up infrastructure and electrolyzer manufacturing capacity (Nakano, 2022).

The evolution of China's hydrogen industry is embedded within a broader framework of industrial policy, particularly evident in the Made in China 2025 Initiative (MIC2025) (García-Herrero & Schindowski, 2024). This strategic industrial plan, introduced in 2015, seeks to shift from low-cost to high tech manufacturing. It focuses on reducing depen-

dency on foreign components and achieving 70% self-sufficiency in strategic industries (Conroy, 2024). China's dominance in electrolyzer production reflects this strategy.

Despite the potential for domestic hydrogen consumption to decarbonize key industrial sectors, China's strategy emphasizes technological expertise acquisition. This domestic focus is coupled with an outward-looking investment policy designed to promote the relocation of excess industrial capacity of heavy industries, such as the steel sector within the Belt and Road Initiative (BRI). As a result, Chinese state-owned enterprises (SOEs) are actively investing in renewable hydrogen projects abroad, with notable ventures in Brazil, Pakistan, Egypt, and Saudi Arabia (Gong & Quitzow, 2024).

4.2 United States

Following China, the United States is the second-largest consumer of hydrogen, accounting for approximately 14% of global demand (IEA, 2024c). Yet, its National Clean Hydrogen Strategy and Roadmap was only introduced in 2023—later than the EU (2020) and Japan (2017). It targets 10 Mt of clean hydrogen by 2030, 20 Mt by 2040, and 50 Mt by 2050 (Department of Energy, 2023). Although the formal hydrogen strategy was announced relatively recently, hydrogen policies had been mentioned earlier in legislation, such the Energy Policy Acts of 1992 and 2005 (Bade & Tomomewo, 2024).

Like China, the US exhibits significant state-level variation. California leads in innovation, while Louisiana is emerging as an export hub (Eicke, 2023). To support its hydrogen policy, the Federal government has allocated more than 1.7 billion USD for six hydrogen-related projects through the Industrial Demonstration Program (Department of Energy, 2024a). The Department of Energy also funds Regional Clean Hydrogen Hubs (H2Hubs) to connect production and end-use (Eicke, 2023).

Under Biden, hydrogen policies became integral to broader industrial strategies. In 2021, the Bipartisan Infrastructure Law (BIL) was enacted, providing USD 750 million for 52 hydrogen projects across 24 states (Department of Energy, 2024b). Over 40% of this funding was directed toward electrolyzer manufacturing, with 20% allocated to fuel cell production (IEA, 2024c). The Inflation Reduction Act (IRA) of 2022 introduced a tax credit of up to USD 3 /kg for clean hydrogen, contingent upon the emission intensity of the production process (The White House, 2023). The IRA also introduces local content requirements for technologies related to hydrogen production, such as solar, wind, and battery components, with certain projects ineligible for tax credits if key components are sourced from outside the United States, Canada or Mexico (Eicke, 2023).

However, the future of these policies is uncertain. On his first day in office, President Trump signed executive orders reversing much of the previous administration's clean energy agenda, including hydrogen (FCW, 2025). In response, Republican senators from Washington already urged continued funding for the Pacific Northwest hydrogen hub (Parkes, 2025a). Moreover, Cummins, a major US hydrogen tech firm, warned that Trump's proposed tariffs in April 2025 could increase costs and undermine competitiveness in this key growth sector (Parkes, 2025b).

4.3 European Union

The EU articulated its hydrogen strategy in 2020 (European Commission, 2020a), setting targets, of 6 GW of electrolyzer capacity by 2024 and 40 GW by 2030. Following the Russian invasion of Ukraine in 2022, the strategy was revised through the REPowerEU plan and the introduction of the Hydrogen Accelerator, aiming to produce 10 Mt of domestic hydrogen and import 10 Mt by 2030 to reduce dependence on Russian gas (European Commission, 2022b).

In support of its hydrogen ambitions, the EU has introduced the European Hydrogen Bank, an auction mechanism designed to stimulate innovation and foster the development of hydrogen projects within the EU (European Commission, 2023a). The first auction in early 2024 funded seven projects across Spain, Portugal, Finland, and Norway (McWilliams & Kneebone, 2024). Further support for hydrogen innovation is evident through its inclusion in the Important Projects of European Common Interest (IPCEI), which covers four waves of initiatives: Hy2Tech, Hy2Use, Hy2Infra, and Hy2Move (European Commission, 2024).

Hydrogen also features prominently in the EU's broader industrial policy. The Net Zero Industry Act, part of the Green Deal Industrial Plan, targets 40% EU-based manufacturing of clean technologies and 100 GW of electrolyzer capacity to reach the 10 Mt goal (European Commission, 2023b). The second hydrogen auction, launched in December 2024, restricted Chinese electrolyzer stack sourcing to 25% (in MWe) per project. In response, some Chinese firms announced plans to establish production in Germany and Spain (IEA, 2024c).

The EU's hydrogen policy also encompasses a strong international dimension. Through its active engagement in 'hydrogen diplomacy' (Dejonghe, 2023), the EU has established strategic partnerships with countries such as Namibia, Egypt, and Kazakhstan. Moreover, it is increasingly including hydrogen projects under the Global Gateway initiative (European Commission, 2021b). Additionally, the EU is poised to leverage Germany's H2Global initiative as the international leg of its Hydrogen Bank (Zabanova, 2024). However, critics argue that these efforts risk reinforcing global inequalities, potentially giving rise to forms of green colonialism or green extractivism (Claar, 2022).

4.4 India

India, which overtook China in 2023 as the world's most populous country, is projected to see a sharp rise in energy demand due to its expanding infrastructure and manufacturing base. Hydrogen is expected to play a key role in addressing this demand sustainably. In 2023, the government launched the National Green Hydrogen Mission (NGHM), allocating USD 2.3 billion to support hydrogen production. The NGHM aims to produce 5 Mt of hydrogen annually by 2030, with a target of installing 60–100 GW of electrolyzer capacity (MNRE, 2023).

In January 2024, as part of the NGHM, India introduced the Strategic Interventions for Green Hydrogen Transition (SIGHT) scheme, offering financial incentives for do-

mestic electrolyzer manufacturing and hydrogen production from renewable sources (IEA, 2024b). The government also launched Green Hydrogen Hubs, designed to link production sites with end-use sectors and located near ports to encourage coastal industrial development (Sambasivam & Narayana Sarma, 2024).

The NGHM reflects a broader shift in India's industrial policy. The Make in India initiative, launched in 2014, seeks to position the country as a global manufacturing hub by attracting foreign investment. In 2020, the government introduced Production Linked Incentives (PLI), offering direct grants to firms that meet domestic value addition requirements. Since 2017, the National Steel Policy has promoted green steel production (IEA, 2024b). To achieve its hydrogen goals, India has stepped up its hydrogen diplomacy, establishing partnerships with countries like Japan (Gili & De Blasio, 2024).

4.5 Japan

In 2017, Japan became the first country to establish a formal national hydrogen strategy, positioning itself as an early leader in hydrogen development. In 2023, Japan announced an ambitious investment 15 trillion yen (approximately USD 98.9 billion) over 15 years, setting a target of producing 3 Mt of hydrogen by 2030, 12 Mt by 2040, and 20 Mt by 2050 (METI, 2023). Japan's initial hydrogen strategy focused on security of supply, given its limited fossil fuel reserves. However, by 2023, the strategy expanded to include industrial decarbonization and global competitiveness (Osaki & Hughes, 2024). A key objective is to develop domestic electrolyzer production, with a target of 15 GW of electrolyzer capacity by 2030 (METI, 2023). The revised Hydrogen Industry Strategy encompasses the entire hydrogen value chain (Osaki & Hughes, 2024).

Japan's hydrogen ambitions are supported by significant funding. The Hydrogen Society Promotion Act introduced 15-year contracts for difference (CfD) subsidies for both domestic and imported hydrogen production. This initiative is funded by Climate Transition Bonds totaling 3 trillion yen (IEA, 2024c). This bond issuance mechanism is the first of its kind and is designed to finance the country's green and digital transitions.

Japan also plays a central role in international hydrogen supply chains, piloting hydrogen shipments from countries like Australia, Brunei, and Saudi Arabia (IEA, 2024c). It participates in multilateral initiatives like the Asia Zero Emission Community (AZEC) to promote regional hydrogen cooperation (Osaki & Hughes, 2024). Additionally, Japanese companies aim to export hydrogen technologies and invest in applications abroad—particularly in Southeast Asia, aligning with domestic priorities like ammonia co-firing in power plants. For instance, JERA is exploring the use of ammonia in the Aboitiz's coal-fired power plants in the Philippines, an application which is widely tested in Japan (Corbeau & Kaswiyanto, 2023).

5. Discussion and conclusions

As the world moves toward a clean energy future, countries are adjusting to the new dynamics this transition entails. Whereas fossil fuel often were used by countries to exert state power, the energy transition puts clean energy technologies at the forefront of global competition, including hydrogen. This chapter examined the current landscape of hydrogen-related innovations, looking into specific emerging technologies such as electrolyzers, green steel, and green ammonia. We assessed the state of the art in hydrogen leadership by looking into three indicators: innovation, manufacturing and deployment. Additionally, we explored the policies shaping leadership in these areas. Below, we present three broad conclusions.

First, while some countries such as China, the US, as well as some European countries such as Germany have made significant progress in developing hydrogen technologies, no country or group of countries clearly dominates across all the indicators examined. For example, Europe leads in investment and, alongside Japan, in innovation, but China leads in electrolyzer manufacturing capacity. This is akin to the solar PV industry were innovation took place in Europe, but manufacturing was taken over by China. Moreover, while resource rich countries may potentially attract energy intensive industries and develop green industrial sectors, this potential has not yet been translated into actual projects reaching final stages of development. Subsequently the availability of resources may not necessarily lead toward technological leadership in the deployment of downstream technologies. Overall, these trends highlights the fragmented nature of hydrogen leadership, with no single player emerging as dominant across all segments or technologies until today, as shown in Table 30.

Table 30: Leadership indicators and potential leading countries

Leadership indicator	Leading country
Announced investments	Europe (29%)
Patenting	Japan (24%) and Europe (28%)
Electrolyzer manufacturing	China (60%)
Resource endowment	Renewable rich countries (green hydrogen) Gas-rich countries (blue hydrogen)
Green steel	Sweden (Boden Steel plant)
Green ammonia	Norway (Yara)

Second, there is a tension between green industrialization in countries in the Global South and industrial policies in the Global North. The former possess immense potential in renewable energy and critical raw materials necessary for hydrogen technologies. Research indicates significant cost advantages for relocating energy-intensive industries, such as steel production, to these regions. This so-called 'renewables-pull' effect could reshape global industrial value chains and related power dynamics (Verpoort et al., 2024). Resource rich countries such as Namibia, South Africa, and ECOWAS members have recognized this potential and formulated national hydrogen strategies (IEA, 2024c). The development of hydrogen-related industries could enable a substantial green industrialization in the Global South, posing a way out the often existing extractive structures of the global economy (Dejonghe & Van de Graaf, 2025). For example, African countries could use iron ore reserves and renewable energy to produce green steel

with hydrogen, potentially quadrupling the value of their iron ore exports to markets in Europe and Japan (IEA, 2024b). Similarly, existing fertilizer exporters in Africa, such as Egypt and Morocco, could capitalize on their renewable energy potential to develop a green fertilizer industries. Morocco and Egypt are leading phosphorus fertilizer producers in North Africa and have set targets to become future exporters of green fertilizer (Medinilla & Dekeyser, 2024).

Despite this potential, countries in the Global South face significant challenges in becoming green industrial superpowers. Industrial policies in the Global North, particularly in Europe and the US may limit opportunities for countries in the Global South to climb the value chain. Concerns over industrial decline in the Global North, exacerbated by the COVID-19 pandemic and the 2022 energy crisis, have led industrialized countries to focus on protecting the competitiveness of their respective industries. For instance, Germany, once a leader in solar panel production, has been completely overtaken by cheaper Chinese imports. Similar concerns are emerging in the electrolyzer market, where Europe's dominance in innovation is threatened by China's rapidly expanding manufacturing capacity. In response, reshoring efforts are underway to protect local industries.

Third, the rise of inward-looking industrial policies risks slowing the global clean energy transition. Countries are increasingly reshoring supply chains and supporting domestic clean tech production, but protectionist measures could drive up costs, slow the adoption of clean technologies, and make it harder for low-income countries to participate in the transition. For example, the European Hydrogen Bank's second auction introduced stricter rules on projects using Chinese-made electrolyzers, while Brussels is reportedly considering policies that would allow governments to exclude foreign bidders and prioritize European manufacturers—mirroring the US's 'America First' approach (Bounds & Hancock, 2025). However, if Chinese electrolyzer manufacturers establish production facilities in Europe, this could create jobs, attract investment, and improve trade balances—strengthening public support for the energy transition. Striking a balance between open trade and strategic industrial policy is therefore essential to accelerating global decarbonization while ensuring a just and equitable transition.

In conclusion, no clear winner has emerged yet in the race for hydrogen technology dominance, and competition remains intense. The global clean tech is increasingly shaped by geopolitical dimensions, with industrial policy playing a central role in international competition. International developments such as the re-election of Trump, the ongoing war in Ukraine, and escalating trade tensions between the US and China are intensifying this race for technological supremacy. While the pursuit of hydrogen technology leadership may unlock new decarbonization opportunities, it also carries the risk of unintended consequences, such as unequal access to clean technologies or carbon lock-in. Navigating these challenges will be crucial to ensuring that hydrogen contributes effectively to global climate goals rather than reinforcing existing disparities.

Chapter 6. Conclusions

Conclusions

In the final chapter of this dissertation, I will answer the central research question:

What are the energy security implications of large-scale hydrogen imports into Northwestern Europe?

This concluding chapter is organized as follows. I begin by summarizing the four articles that comprise this dissertation. Subsequently, I provide an answer to the central research question. Following that, I will discuss the key implications of these results and provide broader reflections on the evolving hydrogen market, along with suggestions for future research directions. The chapter concludes with policy recommendations and a look ahead.

6.1 Summary of the individual articles

This dissertation includes four articles, which explore the different aspects of the energy security implications of future hydrogen trade. Each article uses its own theoretical framework and methodology to address a specific sub-question that helps to answer the overall research question (see Box 4 in Chapter 1). Below, I summarize the findings of each article and then combine them to answer the central research question of the dissertation.

Article 1 draws on the historical evolution of natural gas trade to analyze the emerging dynamics of international hydrogen trade. The analysis is structured around three key dimensions of socio-technical regime theory—institutional, material, and discursive—which collectively lead to three core findings. First, the transition to clean hydrogen is primarily driven by policy, in contrast to the market-led development of natural gas. Second, although the hydrogen market is expected to evolve gradually, its trajectory may diverge significantly, particularly through the early prominence of derivatives like ammonia and methanol, resulting in a more fragmented and geographically diverse market. Third, the formation of hydrogen value chains involves complex decisions about suppliers, transport, and end-use sectors, potentially creating or reinforcing path dependencies with long-term implications for energy security.

Article 2 investigates the energy security implications of emerging international hydrogen partnerships involving Germany, the Netherlands, and Belgium. An analysis of 40 partnerships reveals that most were established in an ad hoc manner, with minimal coordination among importing countries and limited strategic anticipation. The article identifies three key dilemmas in partner country selection: First, a narrow reliance on ‘friendly’ countries limits diversification and paradoxically increases energy security risks. Second, a trade-off exists between cheap hydrogen from politically ‘unfriendly’

regions and potential geopolitical risks. Third, tensions arise between hydrogen exports and domestic decarbonization opportunities in producing countries. These findings underscore the need for strategic, forward-looking policymaking that balances economic interests with political risks and sustainability.

Article 3 explores the tensions between 'green colonialism' and 'green transformation' in hydrogen trade. It highlights a gap in existing research: while studies focus either on the risks or the solutions, few examine the deeper structural causes of these tensions. The article argues that if green colonialism is rooted in capitalism, it cannot be fully addressed within the current global economic system. While green transformation may create industrial opportunities, it does not automatically challenge the inequalities that sustain green colonialism. To drive meaningful change, the article calls for a more integrated approach to green industrialization—combining energy, industrial, and financial policies, in the Global South. However, achieving this is challenging due to resistance from powerful Global North countries and industries that protect and prioritize domestic industries over industrial development in the Global South.

Article 4 examines the development of hydrogen-related technologies, focusing on electrolyzers, green steel, and green ammonia. Through indicators of innovation, manufacturing, and deployment, the study finds an intensifying global race for hydrogen leadership, yet no country dominates across all domains. Europe leads in investment and, alongside Japan, in innovation, while China excels in electrolyzer manufacturing. Although resource-rich countries in the Global South show potential for green industrial development, this potential has not yet translated into technological leadership, reflecting persistent global disparities. Simultaneously, major economies—including the US, EU, China, Japan, and India—are adopting protectionist industrial policies that prioritize domestic production. Such strategies may hinder the global energy transition by restricting technology diffusion and marginalizing emerging and smaller economies. The article concludes that balancing national industrial strategies with international cooperation is essential to ensuring hydrogen's equitable and effective role in the energy transition.

6.2 Answering the central research question

This section synthesizes insights from the four articles to address the central research question of the dissertation: ***What are the energy security implications of large-scale hydrogen imports into Northwestern Europe?*** The analysis is structured around the four key dimensions that capture the multifaceted nature of energy security in relation to hydrogen. Table 31, adapted from Table 8, offers a detailed overview of these dimensions and illustrates their relevance to hydrogen.

The findings suggest that all four dimensions—national security, the economy, environmental sustainability, and justice—are salient in shaping the energy security implications of hydrogen imports into NWE. This underscores the multidimensional nature of energy security in the context of clean hydrogen trade. The analysis further reveals that these dimensions are not always aligned, and that trade-offs amongst them are inevitable. Moreover, the relative prominence of each dimension has shifted over time. While early

policy frameworks were shaped by environmental sustainability imperatives, more recent policy instruments tend to emphasize national security and economic competitiveness. By contrast, the justice dimension continues to receive limited attention, pointing to a critical gap in current policy approaches.

The following sections first examine the energy security implications of each dimension individually, followed by a discussion of the potential trade-offs across all four dimension. The section concludes with a discussion on the evolving energy security priorities in hydrogen trade.

Hydrogen and energy security

From a **national security** perspective, reliance on hydrogen imports risks creating new strategic dependencies, exposing countries to geopolitical vulnerabilities. In response, governments have taken a central role in shaping hydrogen policy, as evidenced by the proliferation of national hydrogen strategies following Japan's 2017 initiative. This trend is further reflected in the rise of bilateral and multilateral hydrogen partnerships, formalized through instruments such as MoUs and letters of intent, and in diplomatic efforts like Germany's H2Diplo initiative (H2Diplo, 2023).

Although hydrogen supply chains are less centralized than those of fossil fuels, early global trade is likely to be dominated by a few key producer countries. This concentration could lead to supply bottlenecks and increased market power of hydrogen exporters. To manage these risks, strategies such as diversifying supply sources, partnering with politically stable countries, and adopting 'friendshoring' approaches are increasingly emphasized.

Hydrogen's national security implications also extend beyond hydrogen trade. As the world shifts toward climate neutrality, geopolitical influence is moving from resource extraction to control over clean technology manufacturing—such as electrolyzers, hydrogen derivatives, e-fuels, and hydrogen-based products. This shift raises concerns that access to critical technologies and the minerals they depend on could be used for geopolitical leverage, potentially echoing past fossil fuel dynamics. In response, countries are investing in and protecting domestic clean tech industries, as seen in the US Inflation Reduction Act and the EU's Clean Industrial Deal.

Despite these risks, hydrogen offers important advantages over fossil fuels in terms of national security. Clean technologies rely on durable goods, which reduces the need for continuous energy deliveries and lowers long-term import dependencies. Moreover, disruptions in hydrogen supply chains are less likely to paralyze core energy services immediately; instead, they would primarily affect industrial sectors.

However, this shift introduces new vulnerabilities. For instance, hydrogen-derived ammonia is vital for fertilizer production, where price surges can significantly impact global food costs (Gnutzmann & Śpiewanowski, 2016). Likewise, green steel is, amongst others, essential for defense manufacturing—a single battle tank requires 50–60 tons of high-grade steel—making the resilience of these supply chains a growing national

security concern, particularly amid heightened geopolitical tensions following Russia's invasion of Ukraine (European Commission, 2025).

Second, from an **economic perspective**, large-scale hydrogen imports present a strategic opportunity to reinforce industrial competitiveness of a number of companies across NWE. This potential is largely driven by the interests of dominant corporate players—often rooted in fossil fuel industries—who are shaping the emerging hydrogen trade landscape. Traditional energy companies such as TotalEnergies, Fluxys, and Shell, along with key industrial players like DEME, Thyssenkrupp, and ArcelorMittal, are at the forefront of developing hydrogen supply chains, infrastructure, and market structures. This involvement underscores that hydrogen imports are not merely seen as essential for decarbonization targets but also as a means of preserving the commercial viability of these industries and safeguarding their vested interests.

The economic dimension is particularly salient by the selection of partner countries for hydrogen imports. Partner selection is primarily driven by the pursuit of the most competitively priced hydrogen. These cost-competitive hydrogen imports are presented as crucial for meeting industrial decarbonization goals and are also economically advantageous due to the anticipated cost differences between domestically produced hydrogen and imports from regions with abundant solar and wind resources.

To ensure that imported clean hydrogen remains economically viable compared to conventional hydrogen production, several policy instruments have been introduced. These include contracts for difference (CfDs) under the H2Global initiative (H2Global, 2022) and competitive auctions managed by the European Hydrogen Bank (European Commission, 2023a), which aim to address the current market gap by providing financial incentives to both producers and consumers.

Beyond securing affordable hydrogen supplies, imports play a crucial role in safeguarding the industrial base of NWE. Regional disparities in renewable energy availability could otherwise trigger a 'renewables-pull' effect, incentivizing energy-intensive industries to relocate to areas with more abundant and cheaper green energy (Samadi et al., 2023; Verpoort et al., 2024). By ensuring access to competitively priced green hydrogen, imports help to mitigate the risks of industrial relocation and deindustrialization, thereby supporting the retention of key industries within NWE. This dynamic is also evident in partnerships concluded with countries in the Global South, which prioritize the import of hydrogen molecules over the import of industrial products.

Third, from an **environmental sustainability** perspective, hydrogen is widely regarded as a key enabler of decarbonization. Hydrogen imports into NWE have the potential to reduce industrial emissions in the region, thereby advancing climate mitigation goals. However, central to this dimension should be the sustainable use of critical resources for hydrogen production, including water, renewable electricity, and raw materials or critical minerals.

Despite these potential benefits, several environmental sustainability risks arise in the context of hydrogen production and trade. A major concern is the continued support

for blue hydrogen. This pathway presents significant risks related to carbon lock-in, perpetuating reliance on fossil fuels and their associated infrastructure. The inclusion of blue hydrogen as a 'clean' alternative may inadvertently lock NWE into continued natural gas consumption, undermining long-term decarbonization efforts and delaying the transition to fully renewable hydrogen. Additionally, hydrogen production intended solely for export markets can hinder decarbonization efforts in producing countries, particularly if their domestic energy systems are not yet decarbonized. In such cases, diverting renewable energy to hydrogen production for export rather than prioritizing local access to clean electricity may result in minimal or even negative climate benefits.

To address these concerns, it is essential to incorporate robust environmental criteria into the emerging hydrogen certification and sustainability governance frameworks. Currently, policy and industrial discussions have primarily focused on the carbon intensity of hydrogen, while broader environmental indicators have received less attention. A more comprehensive set of ecological performance metrics is necessary to ensure that hydrogen production and trade contribute to sustainability goals and do not inadvertently cause environmental harm.

Fourth, from a **justice perspective**, hydrogen imports risk reinforcing existing global inequalities. While much of the hydrogen trade is expected to follow a North-South trajectory, this could deepen dependency between the Global North and South. Several justice concerns have already arisen with regard to hydrogen trade. Prioritizing exports may conflict with the energy needs of producing countries, limiting access to affordable and reliable energy for local populations. Additionally, hydrogen production requires substantial land resources, potentially exacerbating land-use conflicts.

Another key issue is the unequal distribution of value along the hydrogen value chain. Often, hydrogen is foreseen to be exported with minimal local processing, meaning limited value is added in the producing countries. Meanwhile, the high-tech infrastructure and skilled labor necessary for hydrogen production are typically sourced from industrialized countries, restricting opportunities for domestic industrial development and technological learning in producing countries.

To address these issues, fostering local industrial capabilities in hydrogen-producing countries is crucial. Engaging with local stakeholders early in the process can lead to more equitable outcomes and greater public support. Ultimately, achieving a just and sustainable green transformation requires a broader approach, focusing on green industrialization and inclusive economic development, rather than simply prioritizing hydrogen trade.

Table 31: Multi-dimensional hydrogen security assessment based on the analytical framework

Dimension	National security	Economy	Environmental sustainability	Justice
Central assumption	Hydrogen imports create dependencies, posing risks to national security	Hydrogen imports present opportunities for economic competitiveness	Hydrogen imports facilitate industrial decarbonization.	Hydrogen imports may reproduce existing inequalities
Central actor(s)	National governments	(Fossil fuel) companies Industrial stakeholders	Hydrogen related resources: water, raw materials, solar and wind energy	Hydrogen producing countries in the Global South
Perceived threats	Hydrogen import dependence; Unreliable hydrogen trade partners; Technology dependence	Green hydrogen molecules remain too expensive; Relocation of heavy industries	Blue hydrogen: carbon lock-in; Hydrogen imports hamper decarbonization efforts in producing countries	Limited access to energy; Hydrogen only for exports; Low added value in hydrogen producing countries
Proposed responses	National hydrogen strategies; Hydrogen diplomacy; Diversification of hydrogen trade partners	Dedicated hydrogen policies: H2Global, European Hydrogen Bank, EU Energy platform; Formulation of green industrial policies	Hydrogen certification schemes; Ecological and environmental criteria in establishing trade relations	Creating local industrial capacity; Inclusive decision making; Green industrialization

Hydrogen security trade-offs

Having laid out the energy security implications of hydrogen imports into NWE across all four dimensions, it becomes evident that these implications are highly diverse and, more importantly, deeply complex. Some energy security dimensions may overlap—for example, when industrial competitiveness is framed as a matter of national security, or when local decarbonization is considered a justice issue. Yet, more often, these dimensions give rise to fundamental trade-offs. This is the result of the multidimensional conceptualization of energy security, which is shaped by evolving geopolitical, economic, environmental and justice forces. As such, changes or actions within one dimension frequently generate risks or unintended consequences in others.

From a national security perspective, importing hydrogen from politically aligned or 'friendly' countries over cost-effectiveness can mitigate the risks of geopolitical dependence. However, focusing too narrowly on this strategy may limit diversification, which is crucial for ensuring a stable and affordable hydrogen supply chain. Similarly, striving for technological independence by increasing domestic production of key hydrogen technologies, such as electrolyzers, can enhance national control over critical infrastructure. Yet, this approach will also increase the costs, slow down decarbonization and contradict the principles of open markets and global trade. The tension between economic and national security considerations works both ways: prioritizing trade partners based solely on low costs—such as importing cheap hydrogen from politically unfriendly regions—can expose countries to significant security risks. This includes the potential for hydrogen or related technologies to be used as political leverage or even 'weaponized' in future geopolitical conflict.

A further dilemma emerges when national security and economic objectives in NWE clash with principles of global justice. Hydrogen imports are vital for sustaining domestic industrial capacity and mitigating the risk of deindustrialization in key industrial sectors in NWE. Yet, from a justice-oriented perspective, focusing exclusively on hydrogen imports from countries in the Global South risks perpetuating an unequal distribution of costs and benefits related to hydrogen trade. It may limit opportunities for local value creation and economic development in producing countries, particularly in the Global South. This highlights the inherent tension between domestic security interests in importing countries in NWE and the broader goal of fostering green industrial development on a global scale.

Additionally, trade-offs also emerge between environmental and justice considerations. Blue hydrogen production offers new economic prospects for fossil-fuel-rich countries in the Global South, yet it also raises environmental concerns related to carbon emissions and the risk of reinforcing fossil fuel dependency—known as carbon lock-in. From a justice standpoint, one might argue that emerging economies countries endowed with fossil fuel resources should retain the right to leverage them for development, just as industrialized countries did in the past. However, from an environmental sustainability perspective, continued investment in fossil fuel-based hydrogen may result in stranded assets, undermining long-term sustainability and potentially entrenching global inequality after all.

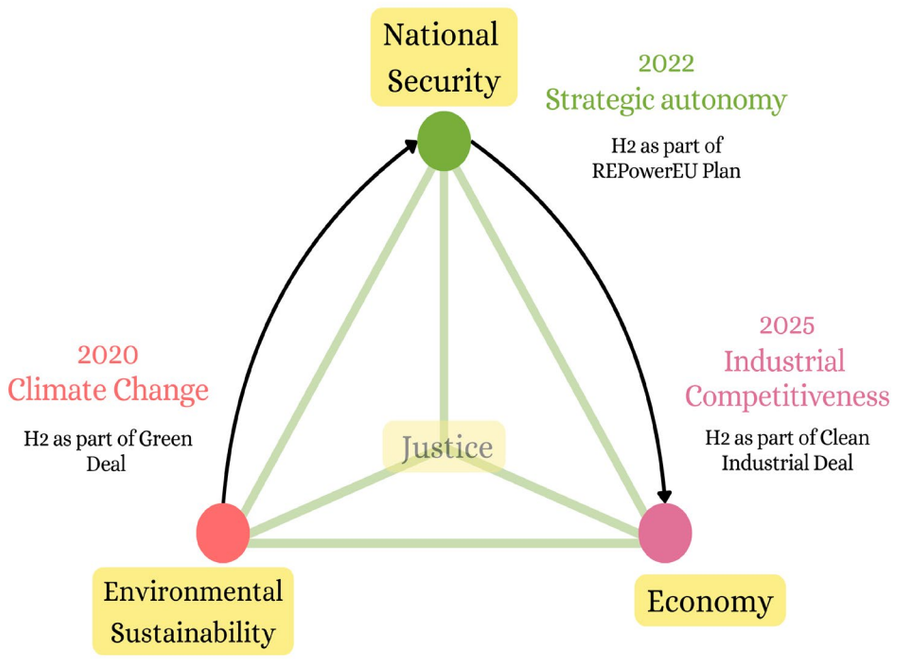
Evolving hydrogen security priorities

Finally, while aspects of all dimensions of energy security are present in the emerging hydrogen trade landscape, in practice, certain dimensions have received more attention than others. Drawing on the explanatory framework introduced in Chapter 3, this dissertation argues that the uneven emphasis on hydrogen security concerns and the shifts in these priorities can be understood through three interrelated logics: path dependence, actor-based dynamics, and shifting geo-economic power structures.

Over the years, the framing of hydrogen imports in NWE has undergone notable changes as exemplified in Figure 18. Initially, hydrogen was championed as a climate solution. The 2020 European Hydrogen Strategy, embedded within the European Green Deal, framed hydrogen imports as a key enabler for decarbonization and achieving climate neutrality. In 2022, the full-scale Russian invasion of Ukraine triggered a significant recalibration of energy security priorities. In this new geopolitical context, hydrogen imports were rapidly reimagined under the REPowerEU plan as instruments for energy independence and diversification away from Russian fossil fuels—marking a sharp pivot toward national security. Since 2023, hydrogen has been reframed yet again—this time as a cornerstone of industrial strategy. Policies such as the Net-Zero Industry Act and the Clean Industrial Deal have elevated hydrogen to a symbol of European technological leadership and competitiveness.

This evolving framing suggests that hydrogen has often been positioned to solve different, sometimes shifting, policy challenges a case of a 'solution in search of a problem'.

Figure 18: Changing hydrogen security priorities



While these shifts in emphasis reflect the evolving role of hydrogen, the economic dimension of energy security continues to exert the most significant influence on the dynamics of the hydrogen trade landscape. This dominance is reinforced by deeply rooted infrastructural path dependencies: existing fossil fuel infrastructures—vulnerable to becoming stranded assets—continue to shape investment decisions and supply chain configurations. These path dependences contribute to technological lock-ins, for instance the use of blue hydrogen, which limit the scope of decarbonization and slow down the adoption of more sustainable alternatives. This structural inertia is further reinforced by the continued influence of incumbent actors. Key actors from the natural gas, heating, industrial, and transport sectors retain significant power in shaping policy. Through regulatory capture, they steer hydrogen strategies to serve their own economic interests, pushing for hydrogen use even in sectors like residential heating and passenger transport, where electrification is already more efficient and cost-effective. As a result, hydrogen policies often prioritize commercial and economic interests over environmental goals, perpetuating rather than changing the existing energy regime.

Although economic interests are relatively more present in the extant hydrogen policy agenda, this does not mean that other dimensions are absent. National security considerations, particularly in light of the Russian war in Ukraine or increased geo-economic competition since the re-election of Trump, are gaining increasing prominence, driven by an intensifying geo-economic logic. As the global race for hydrogen resources, technologies, and supply chain control accelerates, hydrogen is no longer viewed solely as a decarbonization tool, but as a strategic asset in a rapidly changing global order. In this context, states are deploying hydrogen diplomacy and industrial policy not merely to achieve climate or economic objectives but to decrease dependence and secure a geo-economic advantage. Recent policy frameworks—such as the European Clean Industrial Deal and the US Inflation Reduction Act—reflect this strategic shift.

Paradoxically, environmental sustainability has been moved more to the background in recent hydrogen security discussions. The enduring dominance of fossil fuel incumbents and the deeply ingrained path dependencies of fossil fuel infrastructure raise serious concerns about hydrogen's capacity to truly drive decarbonization. In particular, the increasing reliance on blue hydrogen threatens to entrench carbon lock-in, undermining the transition to a truly sustainable energy system. This raises the critical observation that, while hydrogen policy may have initially been shaped by climate imperatives, these agendas appear to have been co-opted by actors whose priorities align more closely with industrial protectionism or geopolitics than with environmental transformation.

In conclusion, the justice dimension remains largely overlooked in current hydrogen trade policy discussions. Emerging North-South trade patterns, where hydrogen is sourced from the Global South to meet the needs of Global North countries, risk reinforcing historical patterns of inequality and dependency. These patterns reflect the longstanding power dynamics between the wealthy 'core' and the poorer 'periphery'. For a more just and global hydrogen economy to emerge, a fundamental shift in the international political economy is needed, one that would reshape global industrial geographies. However, such a transformation faces strong opposition from powerful, entrenched actors.

6.3 Broader reflections

As international hydrogen trade remains in its early stages, many of its energy security implications are yet to fully emerge and remain uncertain. However, this dissertation presents four broader reflections that offer insights into how the future hydrogen trade landscape is beginning to take shape.

Large-scale imports of hydrogen are a mirage

Large-scale hydrogen imports into NWE are highly unlikely in the short-term—if not entirely unrealistic in the long run. The EU is still far from reaching its overly ambitious goal of importing 10 million tons of hydrogen by 2030. Additionally, recent studies paint a very different picture than the optimistic projections in the EU's hydrogen plans (BNEF, 2024). Instead of rising sharply, hydrogen demand in the EU is now expected to be much lower than originally thought. Even in sectors like heavy industry—often seen as hydrogen's best bet—new technologies and innovations are proving better alternatives (Johnson et al., 2025). These uncertainties with regard to hydrogen demand are also reflected in the state of global hydrogen trade. Despite all the political promises and industry hype, less than 3% of planned green hydrogen projects worldwide have actually secured final investment decision (IEA, 2024c).

What then explains this obsession with large-scale hydrogen imports? The answer lies in the persistent influence of a well-organized and well-funded industrial lobby (Flath & Quittkat, 2025). Already in 2020, Balanya et al. reported that major fossil gas firms—who stand to benefit most from an extended role for hydrogen— collectively spent €58.6 million annually on lobbying efforts in Brussels. More recent figures from 2023 indicate that the top 25 hydrogen lobbying entities now allocate a combined €75.75 million per year to influencing EU institutions (Corporate Europe Observatory, 2023).

This hydrogen lobby has played a decisive role in shaping the EU hydrogen agenda to align with their own commercial interests. For instance, the European Commission's 2020 Hydrogen Strategy mirrors demands set forth by Hydrogen Europe, the industry's primary lobby group. Its inflated import targets and investment needs—€430 billion by 2030—cater directly to the corporate agenda, (Balanya et al., 2020).

Another striking example is the Belgian "Hydrogen Import Coalition"—which includes companies such as DEME, Engie, Exmar, Fluxys, and the Port of Antwerp-Zeebrugge. The coalition projects that Belgium will import 750 TWh of hydrogen annually by 2050, of which 300 TWh would be used domestically, and the rest intended for export (Hydrogen Import Coalition, 2021). Unsurprisingly, a similar figure appears in the Belgian Federal Hydrogen Strategy, which envisions 350 TWh of hydrogen consumption by the same year. Such projections reveal a substantial form of regulatory capture: vested actors artificially inflate the hydrogen narrative to justify a future of large-scale trade, regardless of the economic, societal or environmental realities.

Debate on hydrogen is restricted to industrial boardrooms

The significant influence of corporate lobbying on hydrogen policymaking is, in large part, made possible by the absence of a public debate around hydrogen imports. At present, there exists little democratic discussion on the assumptions underpinning the needs for large-scale hydrogen imports. However, even projects that are presented as purely technical or commercial—and often left to technical experts—have major geo-political, social, and environmental impacts. Building a hydrogen import infrastructure in NWE is a clear example. As discussed earlier, there are good reasons to question the motivations of many key players currently shaping the hydrogen trade landscape. Policies are often developed without meaningful public debate, allowing powerful incumbents to shape the transition in ways that protect their own vested interest.

Consequently, there needs to be a much broader well informed public conversation about hydrogen, one that focuses on (energy) consumption patterns and deeper structural changes. Take aviation, for instance. A report by Transport and Environment (2022) shows that decarbonizing of this sector cannot rely solely on sustainable fuels like hydrogen or e-fuels. What is really needed is a rethink of how and how often we travel—starting with cutting back on private and corporate flights. This means investing in alternatives like expanded intercontinental rail, rather than locking ourselves into another round of risky, speculative hydrogen infrastructure.

A similar logic applies to agriculture, food consumption, and the use of synthetic green fertilizer. While these inputs are often framed as essential to feeding the world, a closer look reveals unsustainable consumption patterns. Less than half of global cereal production is actually consumed by humans. Roughly 40% is funneled into the animal agriculture sector as feed, largely to support the highly resource-intensive meat and dairy industries (Ritchie, 2021). Shifting away from an animal-heavy diet toward a more plant-based food system would not only reduce the demand for animal feed but could also dramatically cut the need for synthetic fertilizer, and hence green hydrogen. Yet this link is all too often ignored in policy discussions.

These are precisely the kinds of conversations that must lie at the heart of any underlying assumption informing discussions about hydrogen's future role. Without them, we risk mistaking corporate strategy for climate strategy and end up with a transition that is neither green nor just.

Hydrogen risks to be a Trojan horse for prolonging fossil fuel consumption

The industrial and corporate grip on developing hydrogen roadmaps not only disregards public debate—it also reveals hydrogen's role as a Trojan horse for prolonging fossil fuel consumption. Rather than marking a clean break from the past, hydrogen is increasingly being used to justify the continued expansion of fossil fuel use and infrastructure under a green disguise.

One of the most telling examples is the rebranding of the EU's fossil gas transmission grid as the so-called 'European Hydrogen Backbone' (European Hydrogen Backbone,

2022). Originally built for natural gas, this infrastructure is now being marketed by industry as a key part of the future hydrogen economy—starting with blending hydrogen into gas pipelines and eventually switching fully to hydrogen. In reality, this strategy is riddled with technical challenges and economic uncertainties. A similar framing drives the construction of new gas pipelines marketed as 'hydrogen-compatible' such as the planned Barcelona–Marseille pipeline ('Barmar'). This pipeline connection is promoted as a future green hydrogen corridor, even though it will initially serve to transport natural gas—that is, of course, if it gets built (Porciello, 2025).

This strategy is also evident in the ongoing debates about 'clean' hydrogen certification. Fossil fuel lobby groups have been pushing for so-called 'technology-neutral' policies— an ambiguous term that blurs the line between truly clean, renewable hydrogen and carbon-intensive blue hydrogen produced from fossil gas. By blurring this line, industry players are trying to secure public funding for blue hydrogen and keep fossil fuel infrastructure intact.

In sum, instead of advancing global decarbonization goals, fossil fuel companies are using hydrogen to hold on to the current system. As a result, significant amounts of public money, political capital, and valuable time are being diverted away to projects that keep the fossil fuel system alive. This risks locking Europe into another round of fossil fuel dependence—just when we urgently need to move away from it.

Europe's hydrogen obsession risks sleepwalking into an industrial crisis

Finally, the dominant focus on hydrogen imports risk serving as a distraction from a much more important debate Europe needs to have: the future of its industrial base. Policymakers and industry are placing their hopes on uncertain hydrogen trade flows, instead of confronting tough questions about which industries Europe should maintain in the coming decade.

Research increasingly shows that global hydrogen trade is more likely to involve hydrogen-based products—like ammonia, fertilizers, sponge iron, and green steel—rather than hydrogen itself. This shift has major consequences for European manufacturing, employment, and competitiveness, yet these issues remain largely ignored amid the current hydrogen hype. As Mario Draghi (2024) highlighted, Europe urgently needs a more strategic industrial policy. Rather than trying to support all sectors everywhere, Europe must decide where to invest its limited resources —both financial and human capital—identifying which industries to retain and which may need to relocate to regions with abundant, low-cost renewable energy. Yet recent industrial strategies, such as the Clean Industrial Deal, fail to make these hard but necessary choices.

Without clear direction, Europe faces two major risks. On the one hand, energy-intensive industries may vanish entirely—driven away by high energy prices and global competition—causing an economic graveyard. On the other hand, thoughtlessly trying to avoid this through unrestricted subsidies could backfire, locking governments into expensive support schemes for industries and wasting public funds on industries with no viable future.

The current dominant focus on hydrogen imports only exacerbates these issues. It enables industrial sectors to postpone a genuine industrial transformation by dreaming of hydrogen imports and waiting for subsidies to cover their decarbonization costs. What Europe really needs is an honest, inclusive debate about which industries to prioritize—one that doesn't hide behind the illusion of a 'hydrogen economy'.

6.4 Avenues for future research

This dissertation has likely raised more questions than it has answered, which reflects the inherently exploratory nature of the research. As a result, it opens up numerous potential avenues for future research. I highlight four of them below.

First, due to the interpretative, case study research design in this dissertation, the primary aim was not to develop a general theory (Lijphart, 1971) but rather to unpack the specific dynamics of a single empirical case: the energy security implications of hydrogen imports into NWE. Nevertheless, a promising avenue for future research would be to investigate whether the complex energy security dynamics identified in the realm of hydrogen trade are unique to hydrogen or indicative of broader, generalizable patterns across clean energy carriers and technologies. The analytical approach employed in this dissertation—grounded in socio-technical systems theory and a multi-dimensional understanding of energy security—provides a useful framework for examining similar trade dynamics in other products that are becoming central in the emerging clean energy sector such as biofuels or critical raw materials.

For instance, the biofuels sector mirrors some of the contested trade-offs found in the governance and certification of hydrogen trade. While biofuels promise industrial development — particularly within the Global South and the potential strengthening of South–South cooperation (Dauvergne & Neville, 2009), they similarly raise critical questions. These include the food-versus-fuel debate, environmental justice implications, and the socio-political ramifications of land appropriation and displacement (Neville, 2015).

In a similar vein, critical raw materials and minerals—crucial to clean technologies like solar pv panels, batteries, wind turbines and electrolyzers—constitute another promising area for comparative analysis. Rising demand for these resources has heightened concerns surrounding the socio-environmental externalities of extraction, the ethical dimensions of mining, and the strategic dominance of processing capabilities, particularly by China (Hafner & Tagliapietra, 2020). Future research could thus compare hydrogen with these other adjacent technologies to elucidate cross-cutting dilemmas and trade-offs that appear endemic to the clean energy transition.

Second, a key insight emerging from this dissertation is the need to shift the analytical focus of energy security beyond the traditional emphasis on securing energy supplies toward a more nuanced, systemic examination of clean hydrogen value chains. Future research would benefit from a deeper engagement with the full spectrum of clean hydrogen value chains when investigating questions of energy security. While there is promising work on the politics of green steel (e.g., Gielen et al. 2020; Karkare & Med-

inilla 2024) and fertilizers (Kee et al., 2023; Quitzow et al., 2025), these studies remain to prioritize security of supply concerns.

To advance this agenda, two research directions are particularly promising: on the one hand, the GVC literature offers valuable conceptual tools for analyzing how production systems are structured, governed, and contested. Although traditionally focused on firms (Gereffi et al., 2001), GVC frameworks can illuminate how clean hydrogen value chains are emerging across diverse geographies and regulatory contexts. Applying GVC thinking to energy research can shed light on how technological leadership, knowledge transfer, and value capture are distributed along hydrogen supply chains. This also opens up important questions about the role of the state (Neilson et al., 2014), industrial strategy, and the political consequences of new dependencies and bottlenecks.

On the other hand, the growing strategic emphasis on hydrogen and its derivatives is part of a broader turn toward green industrial policy (Rodrik, 2014). However, what this shift means for energy security is still weakly theorized. Current research tends to bifurcate: one stream remains anchored in the geopolitics of energy (Hausemann et al., 2021; Pflugmann & De Blasio, 2020), while another examines hydrogen within the context of industrial competitiveness and green industrial policy (McNamara, 2024). This dissertation highlights the possibility to integrate both perspectives. Future research should examine how state-led industrial policies shape not only market dynamics but also national and regional conceptions of energy security. This integration can help reframe hydrogen as more than a clean energy carrier, namely as an industrial vector embedded in wider political-economic systems.

Third, one of the main limitations of this dissertation lies in its inherently exploratory character. Given the nascent stage of the global hydrogen market—and the near absence of established international trade beyond a handful of pilot shipments—this dissertation has adopted an exploratory approach. Consequently, the research design emphasizes an in-depth, case-oriented analysis, guided by established theoretical frameworks, rather than striving for broadly generalizable conclusions.

Looking forward, there is a considerable scope for future scholarship to build upon this dissertation by transitioning from an exploratory toward a confirmatory research approach. As hydrogen markets mature and tangible trade patterns emerge, researchers will be better positioned to formulate and test hypotheses regarding the geopolitical and energy security consequences of these developments. The conceptual framework of energy security developed in this dissertation, for instance, might serve as a theoretical lens through which empirical studies can assess the impacts of actual hydrogen trade flows. Ultimately, this dissertation offers a point of departure from which future empirical analysis can trace which projected energy security implications have come to fruition and which have remained hypothetical.

Fourth and finally, while social science research on hydrogen is beginning to gain traction, it remains overshadowed by technological and economic perspectives that currently dominate the research and discourse on the development of international hydrogen trade. I join and build upon existing calls for a more robust and sustained

engagement from the social sciences in this field. As Hanusch and Schad (2021, p. 85) aptly observe, “research in the social sciences and humanities can currently not cope with the pace of political action and technological development.”

Despite growing recognition of the importance of social perspectives, such contributions often remain peripheral, within the wider hydrogen research landscape. To address this imbalance, I call for an interdisciplinary approach to hydrogen research—one that transcends the traditional siloed streams of technological, economic, and socio-political research. By weaving together these distinct yet interrelated strands of knowledge, I believe we can more effectively illuminate the complex socio-technical, economic and political dynamics that shape the hydrogen trade landscape. Such integration not only enriches the understanding of the adoption of hydrogen technologies but also equips policymakers with more holistic and context-sensitive tools to navigate the establishment of an international hydrogen trade landscape.

6.5 Recommendations for policymakers

The results of this dissertation show that policymakers involved in developing hydrogen imports in NWE face several challenges. These challenges involve trade-offs, dilemmas, and practical difficulties that require careful navigation. However, since the hydrogen market is still in its very infancy, there is a lot of room to shift direction and adjust strategies. Below, I present four guiding principles for policymakers in NWE, to take into account when establishing hydrogen trade relations

(1) Stimulate a public debate on hydrogen imports
As this dissertation has shown, hydrogen is not just a technical or geopolitical issue—it has major social impacts as well. Therefore, any serious debate on the future of hydrogen imports must go beyond corporate boardrooms and expert panels and involve the wider public. Decisions about how hydrogen is produced, imported, and used affect public funds, jobs, infrastructure, and the environment, and should not be left solely in the hands of industry insiders and high level politicians.

Indeed, public debate requires more than just consultation— it calls for education. Hydrogen policy should be part of a broader societal conversation about the future of energy, one that reaches classrooms. Moreover, public engagement must go beyond technical literacy and include societal discussions about equity, sustainability, and long-term industrial planning. Taking people seriously, informing them, and addressing their needs is a precondition for a just and sustainable energy future.

(2) The most secure hydrogen molecule is the one that does not need to be produced or consumed
The safest and most sustainable hydrogen is the kind we never have to produce or use. This underscores a central point: hydrogen consumption should remain the exception, not the norm. To support this, we need a clear hierarchy of action. First, sufficiency must be prioritized by promoting more sustainable consumption patterns that reduce overall energy demand. Second, energy efficiency should be pursued by electrifying all end uses that can be electrified, as this represents the most effective way to lower

total energy use. Finally, electricity demand should be reduced further by improving the efficiency of individual appliances. Only when these steps have been exhausted should hydrogen and its derivatives be considered, and even then, only as a last resort.

In this context, Michael Liebreich's (2023) hydrogen ladder should serve as a key framework for determining which sectors should be prioritized for hydrogen application. Restricting hydrogen use strengthens energy security in all dimensions: it minimizes dependence on uncertain and expensive imports, reduces the environmental risks and supports social and economic justice by fostering industrial development in regions with limited existing industrial capacity. As electrification advances, hydrogen policy should remain flexible, evolving to support only those areas where hydrogen is truly indispensable within a decarbonized system.

(3) Use hydrogen as a vehicle for European integration

To remain competitive and improve energy security, European countries must move beyond isolated national hydrogen policies and increase cooperation. By focusing on hydrogen supply within Europe, energy security risks can be reduced. As shown in Article 2, reliable, 'risk-free' hydrogen supplies can be sourced from renewable-rich countries in Europe such as Portugal, Spain, and Denmark. However, trading electricity should take priority over trading hydrogen.

Additionally, hydrogen policy also presents an opportunity for European integration (De Blasio & Nuñez-Jimenez, 2020). Countries in NWE must recognize the limitations of their renewable energy resources and acknowledge that maintaining all energy-intensive industries in these regions is unsustainable. A coordinated European strategy that relocates industries to areas with abundant renewable energy for instance within Europe and supports intra-European hydrogen trade would boost efficiency, reduce unnecessary public spending, and enhance industrial competitiveness across Europe.

(4) Think differently about hydrogen partnerships

To engage in cross-border hydrogen trade responsibly, Europe must move beyond its extractive, one-sided partnerships with resource-rich emerging economies. Projects like the Lobito Corridor as part of the Global Gateway, which propagates the mine-to-port extractivist model, and Free Trade Agreements, which are often not negotiated on an equal footing, prioritize European interests over local sovereignty and development. Instead, Europe should pursue more balanced partnerships that emphasize technology sharing, industrial capacity-building, and mutual benefit. This shift is essential for creating a more fair and sustainable global hydrogen economy. The newly announced Clean Trade and Investment Partnerships are promising in this regard but still need to prove their value.

6.6 Hydrogen imports: a miracle or a mirage?

The prospective hydrogen imports into NWE are fraught with complexity, uncertainty, and competing interests. As this dissertation has shown, hydrogen's energy security implications and trajectory are not being shaped in a political vacuum but rather through a dense web of actors, historical legacies, and geo-economic power struggles. Far from a neutral or purely technical solution, hydrogen is emerging within—and often reinforcing—established political and economic paradigms.

Contemporary policy debates position hydrogen frequently as a technical fix—an innovation that can be slotted into existing energy systems with minimal change and is led by incumbent actors whose actions are often guided as much by institutional inertia and self-preservation as by genuine commitments to change. This dynamic mirrors what Antonio Gramsci (1971) termed 'trasformismo': the process by which dominant coalitions co-opt radical or disruptive ideas, diluting their transformative potential and assimilating them into existing power structures.

Still, I want to conclude this dissertation with a sense of cautious hope: hydrogen holds the potential to catalyze profound, systemic change. Yet this potential cannot—and should not—be left in the hands of industrial actors alone. It will take sustained political effort and commitment—grounded in principles of justice and aimed at rethinking global industrial geographies and power structures. Because of this, hydrogen sits on contested ground. Will it become a miracle—helping to transform unsustainable industrial sectors and address global injustices—or a mirage, offering only the illusion of change while reinforcing the status quo?

The answer will hinge on whose interests drive the transition and who gets a voice in shaping what a hydrogen future should look like. Unless these underlying political questions are openly addressed, hydrogen risks becoming not a tool for transformation, but a vehicle for sustaining business as usual beneath the veneer of a green transition.

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Appendix

Author contribution statement

Below, I expand on my own contribution of the co-authored articles and those of my co-authors. I was the first author for all of these articles and approval for adoption in the dissertation has been given.

Title	Contribution
Article 1: From natural gas to hydrogen: Navigating import risks and dependencies in Northwest Europe **Co-authored with Thijs Van de Graaf & Ronnie Belmans**	The original research idea for this article emerged from discussions among the three of us. However, I took the lead in carrying out the research process. I prepared the interviews, which were conducted collaboratively—one with Thijs Van de Graaf and the other three with Ronnie Belmans. I served as the primary author of the main text, with Thijs Van de Graaf providing active input throughout the writing process, specifically on the analytical framework.
Article 3: Green colonialism or green transformation? The equity implications of clean hydrogen trade **Co-authored with Thijs Van de Graaf**	I introduced the original research idea as part of an invitation for a special issue on hydrogen in the Global South. I was the principal investigator, leading the literature review, preparing and conducting the interviews, coding them in NVivo, and performing the analysis. Thijs Van de Graaf was actively consulted throughout the process and contributed during the analytical and writing phase.
Article 4: The Global Hydrogen Race: Competing strategies for hydrogen technology leadership **Co-authored with Thijs Van de Graaf**	Thijs Van de Graaf invited me to contribute to this book chapter as part of an edited volume on the geopolitics of hydrogen. I took the lead in the research process, developing the analytical framework, overseeing data collection, and conducting the data analysis. Thijs Van de Graaf was actively consulted throughout the process and contributed during the writing and reviewing phase.