

**Natural Gas Lock-in:
Does Hydrogen Pose a Risk to a Natural Gas Phase-out in
the Netherlands?**



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Abstract

Considerable scholarly literature has been dedicated to exploring carbon lock-in, yet limited research exists on the phenomenon of Natural Gas (NG) lock-in and its causes. This study addresses this research gap by conducting an explorative case study of the Netherlands. Specifically, it zooms in on the dynamic interaction between NG and hydrogen, with hydrogen emerging as the leading sustainable molecule to power the energy transition. The study aims to analyze the influence of the established NG regime on the developing hydrogen niche and the subsequent implications of hydrogen's increasing role on NG lock-in. The research combines academic work with grey literature and interview data to support a material and actor analysis through separate techno-economic, political, and socio-technical perspectives. The research finds five significant mechanisms through which existing NG production and consumption shape Dutch production and utilization of hydrogen: 1) the extensive availability of NG infrastructure that facilitates the growth of the hydrogen niche; 2) the historical abundance of NG, which has contributed to an economic structure conducive to the hydrogen niche; 3) an institutional environment that empowers incumbent NG actors, granting them influence on hydrogen-related policies; 4) a strong synergy between the robust NG regime and the burgeoning hydrogen niche that largely avoids regime resistance to the hydrogen niche; 5) the strong integration of state-owned enterprises within the NG sector, further bolstering incumbent support for the hydrogen niche. Additionally, the research identifies two distinct lock-in mechanisms: 1) techno-economic lock-in resulting from sunk costs associated with blue hydrogen; 2) discursive lock-in, whereby the legitimization of existing or new NG infrastructure can perpetuate its continued use. Moreover, the research finds a need to study the concept of 'CO₂ opportunity cost' concerning renewable hydrogen, as suboptimal utilization of renewable electricity may prolong the production and use of NG in the short-term.

Keywords: Natural gas lock-in, hydrogen niche, material analysis, actor analysis, socio-technical transitions.

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Competing interests

During the last stages of writing this thesis, the author has become employed by the hydrogen cluster of the Dutch Ministry of Economic Affairs and Climate, in the team responsible for developing the instruments aimed at stimulating renewable hydrogen production and use. Therefore, competing interests appear. Data collection in the form of interviews were collected beforehand.

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Abbreviations & definitions

- **ATR:** Auto Thermal Reformer
- **BECCS:** Bio-energy Carbon Capture and Storage
- **CCS:** Carbon Capture and Storage
- **CCGT:** Combined Cycle Gas Turbine
- **CSWW:** Cross-Sectorale Werkgroep Waterstof
- **DA:** Delegated Acts
- **DSO:** Distribution System Operator
- **EBN:** Energie Beheer Nederland
- **ETS:** Emissions Trading System
- **EZK:** Ministerie van Economische Zaken en Klimaat
- **GHG:** Green House Gasses
- **GWP:** Global Warming Potential
- **IRA:** Inflation Reduction Act
- **IPCEI:** Important Projects of Common European Interest
- **IPCC:** International Panel on Climate Change
- **I&W:** Ministerie van Infrastructuur en Waterstaat
- **LCA:** Life Cycle Assessment
- **LH2:** Liquefied Hydrogen
- **LNG:** Liquefied Natural Gas
- **LOHCs:** Liquid Organic Hydrogen Carriers
- **MLP:** Multi-Level-Perspective
- **NAM:** Nederlandse Aardolie Maatschappij
- **NGO:** Non-governmental organization
- **NIMBY:** Not in My Backyard
- **NWP:** Nationaal Waterstof Programma
- **REDIII:** Renewable Energy Directive III
- **RFNBO:** Renewable Fuels of Non-Biological Origin
- **SAF:** Sustainable Aviation Fuel
- **SDE++:** Stimulerend Duurzame Energieproductie en Klimaattransitie
- **SLCs:** Static Landscape Characteristics
- **SMR:** Steam Methane Reformer
- **SNM:** Strategic Niche Management
- **SOE:** State-owned enterprise
- **TSO:** Transmission System Operator

1. Introduction

1.1 Research relevance

A recent survey among a group of Intergovernmental Panel on Climate Change (IPCC) authors showed only 20% believe nations will succeed in limiting global warming to 2°C (Tollefson, 2021). For even a 50% chance of staying below this 2°C, the world only retains a carbon budget of 1,350 Gt CO₂. This means a significant portion of the world's proven fossil fuel reserves must remain in the ground, including at least half of all Natural Gas (NG) reserves (IPCC, 2022; Oxenaar & Bosman, 2020). Yet, global demand for NG reached a new all-time high in 2021, accounting for over 35% of the growth in CO₂ emissions since 2009 (Brauers, 2022; Kemfert et al., 2022).

All this increased NG use can partly be explained by its characterization as a 'bridge' or 'transition' fuel as it is considered relatively 'clean' (Brauers, 2022). However, recent research indicates that the Greenhouse Gas (GHG) emissions for NG are higher than previously estimated due to underreported methane leakages, particularly upstream. (Gilbert & Sovacool, 2017). Therefore, quite some scholars in the literature subscribe to Howarth's (2014, p. 57) conclusion that: "Natural gas is a bridge to nowhere."

Still, even in the European Union (EU), which often positions itself as a frontrunner in the energy transition, Russia's invasion of Ukraine has only further increased already existing plans for expanding NG (FEE, 2022). However, if global warming is to be limited to 2°C, lower utilization rates of NG and early decommissioning of existing assets will likely be required (Kemfert et al., 2022).

The success of phasing out this mostly privately owned infrastructure partly will in part depend on elements of resistance in the energy system. A seminal work by Geels (2014) inspired burgeoning literature on how carbon technologies are embedded in institutions, discourses, and infrastructure. At the same time, powerful actor networks with a vested interest in the status quo tend to resist changes to carbon-based energy systems. This phenomenon has become known as '**carbon lock-in.**' This means a path-dependent interdependence between carbon-intensive technologies, actors, institutions and policies (Seto et al., 2016). Considering the variety of intertwined factors, studies on energy transitions and lock-in are generally situated in multi-disciplinary 'socio-technical transitions' literature, which includes political science.

1.2 Problem statement

However, despite substantial research on lock-in effects in the coal industry, almost no research has been done regarding **NG lock-in**. A systematic literature review carried out by Brauers (2022) concludes that "there seems to be little energy transitions research specifically addressing NG and its use" and that "academic transition studies are not yet targeting the risks of NG" (Brauers, 2022, p. 2). She asserts that "in the context of strong lock-in mechanisms and simultaneous rapid changes to total GHG levels, the deliberate acceleration of transitions is an important field of research" and that "**importantly, case studies on the diverse forces of NG lock-in mechanisms are still lacking, except for one article on LNG projects in Germany**" (Brauers 2022, p. 13). Hence, additional case study research on the causes and effects of NG lock-in is justified and warranted.

One under-researched potential cause of NG lock-in revolves around the new prominent role in the energy transition of sustainable synthetic gasses. Both Brauers et al. (2021) and Szabo (2021) emphasize the role of **hydrogen** as a critical energy carrier with possible interaction effects with NG lock-in. Brauers et al. (2021) suggest that "even strong growth of synthetic niches would not constitute a competition for the NG regime but mostly a useful new element to it" (Brauers et al. 2021, p. 13). This study aims to further investigate the relationship between NG and synthetic gasses. Given the anticipated role of hydrogen, as illustrated by the Inflation Reduction Act (IRA) and the EU Hydrogen Strategy, it zooms in on this particular sustainable molecule through the following research questions:

- (i) How do actors' perceptions and the interaction with material conditionalities regarding existing NG production and consumption influence the production and use of hydrogen?
- (ii) To what extent can interactions between actors' perceptions and material conditionalities with increased production and use of hydrogen affect NG lock-in?

1.3 Research objectives

In response to calls from the academy put forward by Brauers (2022) and Szabo (2022), this research examines the intricate interplay between NG lock-ins and the emerging hydrogen niche. By addressing the abovementioned research gap regarding NG lock-ins, this study makes a valuable contribution to the literature on socio-technical transitions, particularly regarding the pioneering work on regime resistance by Geels (2014). Additionally, it adds to the understanding of the synthetic gas niche, which has received limited scholarly attention in the literature due to its recent emergence as a significant component of the energy transition. Considering the current heightened interest in hydrogen, this research holds immediate practical insights for understanding the energy transition and identifying policy challenges.

To this end, this study utilizes the Netherlands as an ideal case study for an **explorative research design**, due to the combination of its historically strong NG regime and its ambitious hydrogen policy goals. As causal mechanisms and hypotheses for the relationship between hydrogen and NG lock-in are not yet apparent, this research sets out on an exploratory path to discover causal mechanisms by which NG lock-in shapes the hydrogen niche and how hydrogen can impact NG lock-in. It builds upon the suggestion by Ahmadov & van der Borg (2019, p. 369), advocating for a comprehensive investigation of causal mechanisms of energy research by “carefully investigating the choices made by relevant actors and the effect of these choices on policymaking.”

The research design encompasses both a **material analysis** based on expert interviews and desk literature and an **actor analysis** that examines the perceptions and interests of key actors. This part builds on semi-structured interviews with actors spanning the NG and hydrogen industry value chain, government actors, academics, and civil society actors.

2. Literature review

To place this research in its field and provide the necessary context, it is essential to first scope the existing body of literature. Section 2.1 briefly overviews current modes of hydrogen consumption and production and the state of policy surrounding it in Europe. Section 2.2 gives an overview of the limited research on the relationship between hydrogen and NG. Section 2.3 discusses the existing socio-technical transitions literature, situates the research in its field, and reviews and justifies the frameworks chosen for this research. Section 2.4 examines the literature on carbon lock-in and synthesizes it with the framework discussed in section 2.3.

2.1 Background on hydrogen

2.1.1 Why is hydrogen relevant in the energy transition?

Understanding the NG lock-in and hydrogen debate is essential to comprehend hydrogen's role in the energy transition. Many see hydrogen as crucial for GHG-emission reduction, mainly as a substitute for NG. A broad range of scenario studies show the necessity of hydrogen in the energy mix for 2050 due to a need for sustainable molecules (den Ouden et al., 2020; IEA, 2021; Netbeheer Nederland, 2023a). As a rule of thumb, the direct use of electricity in the energy system is preferred, as direct electrification tends to create the most efficient energy use. Yet, not all energy applications are electrifiable. Additionally, direct electrification is constrained by the limitations for the rollout of electricity infrastructure due to high costs and spatial constraints. This creates a need for sustainable molecules like hydrogen or biogas.

As argued in the abovementioned scenario studies, hydrogen has three prominent roles in decreasing emissions and reducing fossil fuel consumption: 1) as a replacement for NG and coal in firing industrial processes, particularly in hard-to-abate sectors such as steel manufacturing; 2) within the mobility sector for long-distance transport, such as the production of Sustainable Aviation Fuels (SAF); 3) for 'storing' excess renewable electricity to provide flexible electricity generation during periods when there is little renewable energy generation as a consequence of weather fluctuations.

2.1.2 The colors of hydrogen: Grey, blue and green (renewable)

Currently, there are several ways to produce hydrogen on an industrial scale, with the typical method referred to as 'grey hydrogen.' This relates to hydrogen produced from NG, coal, or oil. The predominant technique is transforming methane into hydrogen via a Steam Methane Reformer (SMR) or the more technologically advanced Autothermal Reformer (ATR). This process creates significant GHG emissions, with two main mitigation pathways: blue- and renewable hydrogen.¹

The name 'blue hydrogen' is an umbrella term for a range of hydrogen techniques that employ Carbon Capture, and Storage (CCS), through which up to 60-100% of scope 1 and 2 CO₂ emissions can be reduced (Bauer et al., 2021). The level of CO₂ reduction is mainly dependent on costs and the technique applied, as higher capture rates can be achieved at a higher price and newbuilt ATR installations allow for higher capture rates than existing SMRs (Oni et al., 2022). A specific type of blue hydrogen concerns the decarbonization of fuel gasses, an inevitable by-product of some industrial processes. These are usually used as an industrial heat source but can also be decarbonized by first funneling them through an SMR with CCS.² Whether this constitutes blue hydrogen is a matter of opinion, as it is a difference between pre-combustion vs. post-combustion CCS. This means the CO₂ can be captured by first turning the fuel gasses into hydrogen or through capturing the CO₂ after directly burning the fuel gasses. The European Commission (EC) formally differentiates on hydrogen through its use of the term 'low-carbon' hydrogen, which refers to hydrogen with a minimum CO₂ reduction of 70% compared to grey hydrogen. Many blue hydrogen projects in the Netherlands are unlikely to meet this percentage. Hence, this paper will use blue hydrogen to maintain consistency and readability.

Secondly, there is 'green hydrogen,' for which this paper will adopt the EC term, referring to it as 'renewable hydrogen.' This is justified on the basis that while the term green hydrogen is popular, the term renewable has been adopted by the EC and it is becoming increasingly adopted in public discourse as most

¹ Other types that, so far, play a marginal role are hydrogen from nuclear power (pink), methane pyrolysis (turquoise), solar power (yellow), and naturally occurring hydrogen (white).

² One example is the Dutch H-vision project.

renewable hydrogen projects will likely seek to comply with EC regulation. Renewable hydrogen is produced via an electrolyser, an installation that uses renewable electricity to split the H₂O molecule into oxygen and hydrogen. This technique has existed for decades but is very costly and has not been deployed on the scale necessary for industrial production. An overview of the three main types of hydrogen is given in Figure 1.

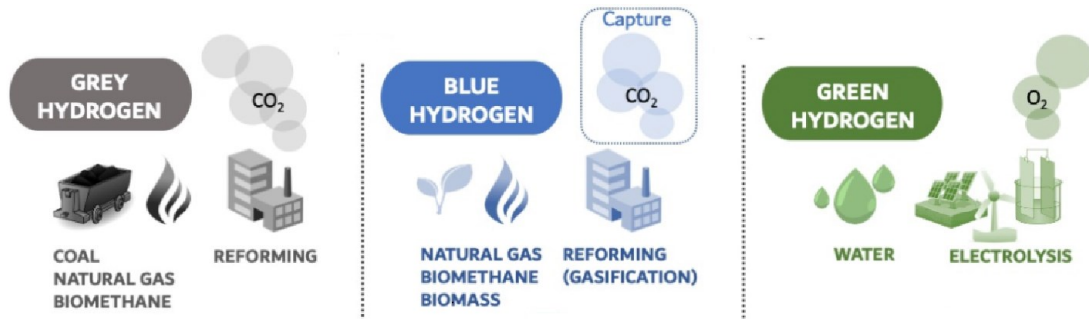


Figure 1: Types of hydrogen
Source: Aurore (2023)

There has been an ongoing debate in the academic community in recent years regarding GHG emissions of the different types of hydrogen, particularly concerning the alleged underestimated emissions of blue hydrogen. Howarth & Jacobson (2021) spurred a lively debate by claiming that blue hydrogen differs only slightly in emissions from grey hydrogen due to upstream methane emissions and the additional energy demand created by CCS. However, this paper received widespread criticism, with other scholars signaling a ‘pick and choose’ approach for the assumptions made in the article (Bauer et al., 2021; Mac Dowell et al., 2021). Arguably, a clean difference regarding carbon intensity, meaning the associated emissions, is not cut across blue or renewable lines but depends on the specific configuration of supply chain emissions. For instance, according to Mac Dowell et al. (2021), if the electricity used for electrolysis is in the range of 30-140kgCO₂/MWh_e, the carbon intensity of hydrogen produced with an electrolyser is greater than when an SMR installation with a 90% capture rate is employed. Still, even for Moreover, even if the energy supply for electrolysis is fully renewable, the hydrogen produced can still not be considered a ‘net-zero product’ due to emissions associated with manufacturing wind turbines, solar panels, and electrolysers.

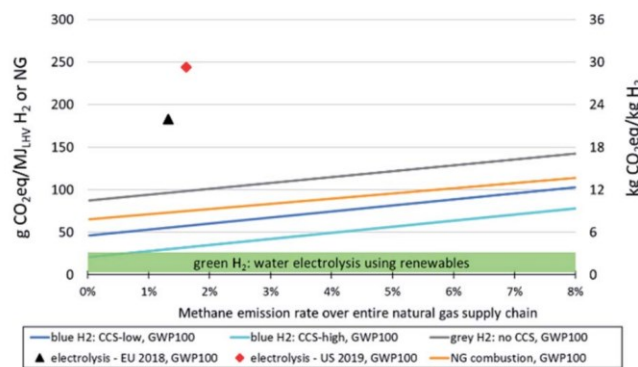


Figure 2: Carbon intensity of different types of hydrogen production
Source: Bauer et al. (2021)

Figure 2 shows the global warming potential over a hundred years (GWP) of the various sources of hydrogen production depending on upstream methane emissions, as modeled by Bauer et al. (2021). NG-based ‘grey hydrogen’ creates most GHG emissions but that the GHG emissions of blue and green hydrogen depend on specific factors such as upstream methane emissions and the lifecycle emissions associated with producing equipment like solar panels. These results suggest that with low methane emissions, blue hydrogen can be in the same range as renewable hydrogen. This would lend credence to assessing hydrogen not based on its input source but on its carbon intensity.

2.1.3 Hydrogen in Europe

Following the publication of the EC hydrogen strategy in July 2020, EU countries have initiated various ambitious initiatives for hydrogen production and consumption (EC, 2020). In the hydrogen strategy, the EC proposes the installation of 6GW worth of electrolyzers in the EU in 2024, to be expanded to 40GW by 2030. They estimate investments in electrolyzers would require between €24bn and 42€bn, as well as €220-340€bn to scale and connect 80-120GW of solar and wind energy production. CCS retrofitting is estimated at €11bn and 65€bn worth of investments. The EU also announced various supportive measures to incentivize investment, including subsidies for production, infrastructure, demand, and research. Perhaps most importantly, the EU has set in motion the creation of regulatory frameworks and mandatory goals to encourage hydrogen adoption, with two policies being particularly vital.

First, the EC published two Delegated Acts (DA) on renewable hydrogen, which stipulate the conditions by which hydrogen is classified as renewable or low-carbon. The first DA defines when hydrogen can be considered a renewable fuel of non-biological origin (RFNBO). RFNBOs are an umbrella term for renewable hydrogen and renewable hydrogen carriers like sustainable ammonia (de Vries et al., 2022). These conditions include that RFNBOs need to be produced from ‘additional,’ meaning new, renewable energy installations, and that renewable hydrogen needs to be generated very close to the same time and in the same area as renewable energy. The second DA stipulates the methodology for calculating GHG emission savings for RFNBOs and recycled carbon fuels. While the criteria in the DAs are strict, they were initially stricter, they were significantly loosened after lobbying and an intervention by the European Parliament (EP) (EP, 2022).

Second, the Renewable Energy Directive II revision, called the REDIII, institutes binding targets for member states to use RFNBOs in industry and mobility (Klessmann et al., 2023). These include a target for 42% RFNBO use as a total hydrogen demand in the industrial sector in 2030, increasing to 60% by 2035, and a 1% target for the transportation sector. The industrial target compromises significantly higher absolute volumes, although the denominator for this target exempts sources of industrial hydrogen use (Leguijt et al., 2022). Figure 3 depicts the four streams of hydrogen in industrial processes. Stream A is called merchant hydrogen, meaning it is externally sourced. Source B is called captive hydrogen, meaning it is produced on-site. Stream C refers to hydrogen within fuel gasses and is exempted from the denominator under the REDIII, as residual gasses are produced as an inevitable by-product of chemical processes. Therefore, something has to be done with them, either through pre-combustion or post-combustion CCS, making it illogical to replace them with RFNBOs. Likewise, stream D is exempted as this constitutes pure hydrogen as a by-product of chemical processes that are unavoidable.

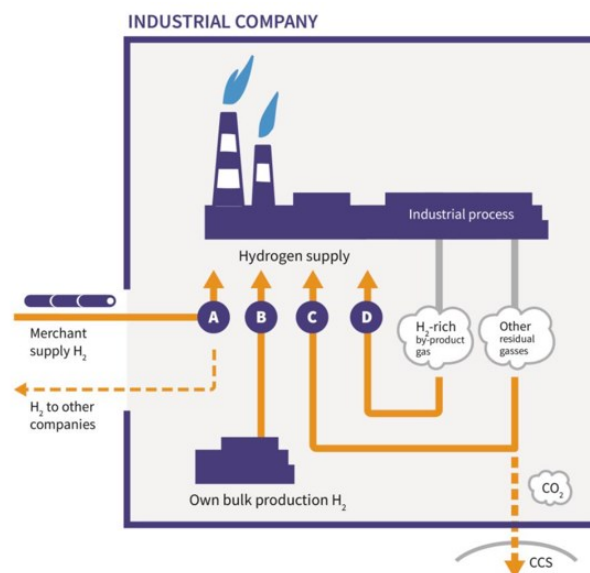


Figure 3: Streams of hydrogen use in industrial processes in the REDIII.
Source: de Vries et al. (2022).

2.2 Existing research on NG lock-in and hydrogen

So far, academic research on NG lock-in is limited, with the most direct research done by Brauers et al. (2021) on the potential lock-in for new LNG terminals in Germany. The need for further research is supported by Szabo (2022, p. 1), who claims that “scholars have only recently begun to explore how NG interests respond to climate policy and the energy transition,” calling it a “gap in the literature.” Brauers (2022, p. 13) confirms this via a systematic literature review, finding that “there is little research regarding the obstacles NG poses in potentially delaying the sustainability transition.” From a diverse literature that often only indirectly addresses aspects of NG lock-in, she distills four potential sources of NG lock-in: techno-economic lock-in, institutional lock-in, behavioral lock-in, and discursive lock-in. In section 2.4, this paper will return to these lock-in types, addressing them in more detail.

As a limitation in her research design, Brauers (2022, p. 13) points out that she did not include papers on alternatives to NG but that a focus on synthetic gasses could “contribute to understanding the potential drivers and hurdles to NG use.” Her earlier research supports this, showing that new German LNG infrastructure is often claimed to be ‘hydrogen ready’ with minor modifications, which might legitimize NG in public discourse (Brauers et al. 2021). In this paper, the authors argue that “even strong growth of synthetic niches would not constitute a competition for the NG regime but mostly a useful new element to it” (Brauers et al. 2021, p. 13). Still, she stresses that “preliminary conclusions for other countries need to be interpreted with caution” Brauers (2022, p. 15).

Oxenaar (2017, p. 77) supports the need to study synthetic gasses and hypothesizes that “on the long-term, investments in ‘green gas’ could have a lock-in effect on gas-based infrastructure, possibly leading to a prolonged use of natural gas.” Likewise, Szabo (2021b, p. 1) argues that the hydrogen niche and the NG sector are intertwined, which he dubs the “The Natural Gas-Hydrogen Nexus.” Szabo finds that incumbents propose blue hydrogen as a bridging technology until renewable hydrogen matures. He argues that the entrenched position of existing NG actors empowers the hydrocarbon sector to capture and shape future hydrogen markets and “appropriate the notion of a hydrogen utopia” (Szabo, 2021b, p. 104). Notably, he argues that this may strengthen the push for blue hydrogen in the short-term, as the “carbon lock-in based on economic infrastructural, political, and ideological elements is sustained through blue hydrogen” (Szabo, 2021b, p. 105). This is supported by Machado et al. (2022), whose work on the shaping of national hydrogen strategies in Germany, Portugal, and the UK argues that incumbent NG producers, transporters, and consumers emphasize the decarbonization of ‘grey hydrogen’ based pathways in the near term (Machado et al., 2022).

Thus, it is evident that the concept of NG lock-in remains under-researched within the socio-technical transitions literature, underscoring the need for further understanding of its relationship with synthetic gasses, particularly hydrogen. This interaction exhibits an endogenous relationship, as hydrogen and NG can be expected to mutually influence each other. This relationship manifests through their interaction in the energy system and various political and social dynamics within the energy transition. Therefore, it is imperative to look at how the established production and use of NG might shape the role of hydrogen in the energy transition and how the emerging hydrogen niche shapes dynamics surrounding NG lock-in.

2.3 Socio-technical transition studies & dominant frameworks

Having given an overview of the existing hydrogen and NG research, an examination of the socio-technical transitions literature, and its treatment of technologies and mechanisms of lock-in, is necessary to find the most compatible analytical tools to analyze the dynamic between hydrogen and NG. Additionally, to benefit the readability of the research, further elaboration of the literature is needed. This is because, to those outside the energy transitions literature, the variety of conceptual frameworks tends to create a ‘cannot see the forest for the trees’ effect that easily leads one to become lost. For instance, terminology like ‘energy transitions’ as opposed to ‘sustainability transition’ presents a different scope, as the latter includes topics like biodiversity preservation (Cherp et al., 2018). Such detail is unfortunately unavoidable, as the scale of the energy transitions “poses challenges for mainstream explanatory formats” (Geels, 2022, p. 2).

The perspective of the socio-technical transition is the dominant strain of research for analyzing energy transitions, technological lock-in and disruption. In a meta-theoretical review, Markard et al. (2012, p. 1) identified four significant frameworks that “paved the way” for energy transition studies: transition management (TM) (e.g., Kern & Smith, 2008), strategic niche management (SNM) (e.g., Kemp et al., 1998), technological innovation systems (TIS) (e.g., Jacobsson & Johnson, 2000) and the multi-level perspective (MLP) (e.g. Geels & Schot, 2007). These are broadly employed within the diverse literature and provide

tools that can be used as “heuristic analytical concepts that help to explain both how systems operate and how they change” (Kuzemko et al., 2016, p. 97). While these distinctions can be helpful, Cherp et al. (2018, p. 176) argue that they can all be incorporated under social-technical transition studies, as they share similar interdisciplinary roots, concepts, and operationalized variables.

At the core of socio-technical transitions lies the concept of socio-technical systems like energy systems, transport systems or agri-food systems. These are “analytically separable but dynamically interrelated areas” (Kuzemko et al., 2016, p. 97). Their components include, for instance, policies, civil society, infrastructures, and technologies. For energy systems, these combine to create a technological system that enables the production and consumption of energy provision (Schot et al., 2016). The locust of research on these socio-technical systems research is the emergence and diffusion of new technologies (Cherp et al., 2018).

However, most socio-technical transition frameworks are limited in their treatment of techno-economic and political aspects of energy transitions which require the expansion of the frameworks mentioned above. Cherp et al. (2018) argue that these socio-technical transition studies regard socio-technical systems “as a ‘seamless web’ where there is no a priori distinction between the technological, the socio-economic and the political” which “runs contrary to the idea of co-evolution [of systems]” (Cherp et al. 2018, p. 181). For instance, Grubb et al. (2015, p. 291) point out the limited intellectual integration of transition studies with other theoretical streams like economics and argue that scholars have a hard time informing coherent policy without understanding market forces. Likewise, Brisbois (2019) and Hess (2019) argue that the political perspective on transitions is unevenly neglected. This is noteworthy for the present research, as Szabo (2021) notes the role of incumbent industries in the emerging hydrogen markets, challenging the established notions of clear-cut coalitions in energy politics. Appreciating the criticism of subsuming different components of socio-technical transitions into one, it becomes clear that a multi-angled approach is necessary.

Cherp et al. (2018) propose treating political, techno-economic, and socio-technical systems as semi-autonomous, evolving independently in sub-systems while exhibiting interconnected effects. This is illustrated in Figure 4, showing how both institutions and actors exist or act in separate realms, but may also interact between them. This builds on Ostrom’s (2007, p. 15182) work on socio-ecological co-evolutionary systems. She stresses the “decomposability of complex subsystems” that are still “greater than the sum of their parts.” This avoids, for instance, political aspects being analyzed solely through a social or technological lens. However, while the division into different realms is useful, the overlap between the realms can still exist. Brauers et al. (2021, p. 5) stress that it is vital to “focus on how key actors walk across realms, play different roles in different realms, and thus facilitate their co-evolution.” For instance, an industry firm may play an essential role in the techno-economic realm while using its influence in the political sphere to block policies. Thus, this research builds on Ostrom’s recommendation to divide into sub-systems while seeing actors as an essential interaction variable between these systems. This allows more flexibility as this framework can integrate concepts from dominant frameworks like the earlier mentioned SNM and the MLP (Brauers et al., 2021). Such an approach allows for creativity, with Maxwell (2012, p. 80) noting that “you don’t have to adopt theories as wholes, you can borrow particular ideas from different theories and use these to construct a conceptual framework that best fits your particular topic or problem.”

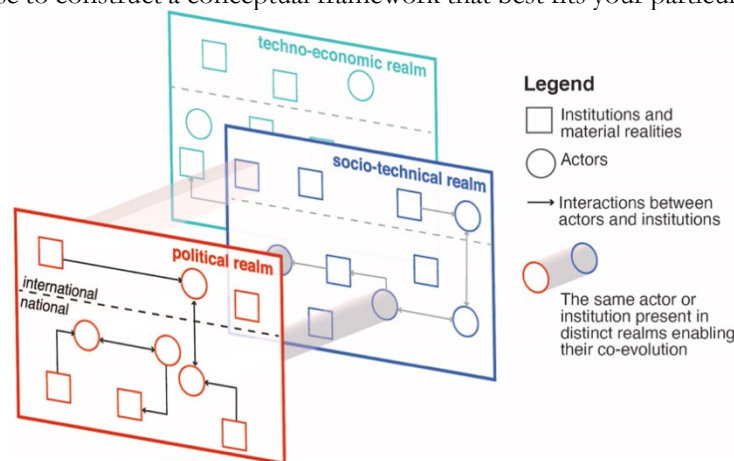


Figure 4: Co-evolution of realms
Source: Brauers et al. (2021)

This research subscribes to the validity of the abovementioned criticism and chooses to use the meta-theoretical framework proposed by Cherp et al. (2018). It justifies this on the basis that further decomposition of socio-technical transitions grants room for an interdisciplinary approach while serving as a clear organizing principle for mapping variables of interest. The choice is bolstered by influential scholar Frank Geels (2022), who argues that broader use of configurational causality in socio-technical transitions research is necessary and lauds the attempt by Cherp et al. (2018) to develop this framework.

2.4 Explaining lock-in via the techno-economic and political, and political perspectives

While the broader theoretical framework choice is apparent, the present research also requires a targeted conceptualization of 'lock-in' and how this concept is integrated into the socio-technical transitions literature.

The contemporary scholarship on lock-in leans primarily on the work of Seto et al. (2016). This contribution has been influential through its identification and grouping of patterns of lock-in (Rosenbloom & Rinscheid, 2020). The authors identify three types of lock-ins: (i) infrastructural and technological lock-ins, (ii) institutional lock-ins, and (iii) behavioral lock-ins (Seto et al. 2016). Buschmann & Oels (2019) add that (iv) discursive lock-ins are overlooked in research on carbon lock-ins. Brauers (2022) argues that all four of these lock-in types should be examined when researching NG lock-ins. The following paragraphs will elaborate on these types of lock-in while relating and integrating them into the socio-technical, techno-economic, and political perspectives set-out by Cherp et al. (2018).

2.4.1 Socio-technical perspective

The socio-technical perspective is traditionally broadly conceptualized, with previous research subsuming elements of the techno-economic and political perspectives under this term. However, in the framework designed by Cherp et al. (2018), the emphasis is on the emergence and diffusion of new technologies.

The multi-level perspective (MLP) has been particularly influential for analyzing socio-technical transitions, with a strong dominant influence on the development of other frameworks (Kuzemko et al., 2016; Sovacool et al., 2020). This makes it a helpful reference tool to map the analytical concepts dominant in the socio-technical transitions scholarship, which bolsters explanatory potential while retaining synergy with the literature.

Within the MLP, the central unit of analysis is the 'socio-technical regime,' which constitutes "a shared, stable and aligned set of rules or routines that guide the behavior of actors [...] embedded in the various elements of a socio-technical system" (Schot et al., 2016, p. 2). For energy systems, this translates to regulations, practices, and norms that enable the dominance of existing modes of energy production and use (Verbong & Geels, 2007). These regimes can foster innovations but may also explain technological lock-in "when beneficial innovations are hindered because they are incompatible with a dominant regime" (Cherp et al., 2018, p. 180). Through their historical development, vested interests are often entrenched themselves in political and economic positions. This gives them influence and allows them to preserve the status quo by building on institutionalized networks and practices, creating a lock-in effect in which the 'regime' remains stable over time (Smith et al., 2010). These positions are stabilized over time by 'path-dependent effects,' which create increasing returns that make existing institutions, rules, and norms rigid (Pierson, 2004). For example, Kern & Smith (2008) argue that energy policy in the Netherlands during the early 2000s was dictated by tight networks between fossil-fuel firms and civil servants. This resulted in incumbent firms being highly influential in deliberative processes, giving them more sway over policies, rules and who is involved in the deliberative process.

The socio-technical regime is situated between two other levels: technological niches and the socio-technical landscape (Kuzemko et al., 2016; Sovacool et al., 2020). The niche level encompasses the innovation space for immature technologies that require shielding to protect them from competition with the dominant socio-technical regime (Geels & Schot, 2007). Above the regime lies the socio-technical 'landscape,' often referred to as an 'external context.' First, there are 'static landscape characteristics,' which include electoral coalitions (Kuzemko et al., 2016), constitutions (Haas, 2019), supra-national institutions (Geels et al., 2016), governing traditions (Ahmadov & van der Borg, 2019; Moe, 2012) and patterns of civil society activism (Kungl & Geels, 2018). Second, there are sudden landscape developments, including global market developments, natural disasters, and wars (Kuzemko et al., 2016). The MLP theorizes that niche technologies accelerate their growth through innovation and learning processes within the semi-persistent

affordance structures of the static landscape characteristics, meaning the actions allowed by the environment to the actors. These allow actors to pursue endogenous institutional change. In this research, this institutional change is studied primarily through the political perspective. Meanwhile, landscape pressures may destabilize the regime, allowing niche innovations to break through lock-in at the regime level (Geels, 2014). An often-used example is the 1973 oil crisis, which allowed niche actors to push for support for innovation policies aimed at wind- and solar energy (Trencher et al., 2020).

A focal point of socio-technical research on lock-in has been termed ‘regime resistance’ by Geels (2014). He argues that actors' effectiveness in influencing the development of energy systems depends on their ability to mobilize their resources. This includes “instrumental, discursive, material and institutional forms of power” (Geels, 2014, p. 28). This is relevant for this research as lock-in effects can arise from “conscious efforts by powerful economic social and political actors” (Seto et al., 2016, p. 6). In particular, the incumbent actors can contribute to lock-in effects, with three factors being particularly important: actor composition and power balances, actor networks, and vested interests (Trencher et al., 2020).

One specific form of lock-in associated with the socio-technical regime and regime resistance is behavioral lock-in in decision-making, where “single, calculated choices become a long string of non-calculated and self-reinforcing habits,” through established norms and social processes (Seto et al., 2016, p. 445). Brauers et al. (2021) find that established practices of NG industry actors to favor large-scale infrastructure or trade and customer preferences for heating systems can lead to behavioral lock-in in the energy industry. They find that LNG does not threaten these existing norms and practices. Similar dynamics might be found with hydrogen and its compatibility regarding current behaviors and norms in the energy system.

Additionally, Brauers (2022) points to how ‘discursive lock-in’ can be created, with the use of concepts such as NG being a ‘bridge fuel’ possibly strengthening the position of NG. This fits with the socio-technical perspective, with regime resistance through actors influencing public discourse, although overlap exist with the political perspective. This public discourse impacts government actions, policy gridlock may result from competing coalitions within discursive debates. An example is the sowing of scientific doubt by the tobacco industry on the health risks of smoking. For energy transitions, Supran and Oreskes (2021, p. 1) show that ExxonMobil’s rhetoric mimics tobacco industry propaganda by downplaying climate risks and stressing the individual responsibility of consumers. Likewise, Bosman et al. (2014, p. 56) find that incumbents in the Netherlands “frame their storyline as ‘partners of renewable energy’ and natural gas as ‘transition fuel,’ to retain their central position in the energy regime.” Considering the effect such discourses can have, discursive lock-in needs to be taken as an essential variable of analysis.

2.4.2 Techno-economic perspective

The techno-economic perspective emphasizes energy systems as “energy flows, conversion processes and uses coordinated through energy markets” and encompasses alterations in supply, demand and prices that can change in energy systems or even stabilize them (Cherp et al. 2018, p. 179). For instance, increased demand for electricity through population growth or mobility electrification can stimulate investments in new supply technologies. Correspondingly, the techno-economic perspective primarily concerns the cost of energy transitions. This relates to lock-in through, for instance, the potential of stranded assets or sunk cost of production or infrastructure investments (Brauers et al., 2021).

The closest corresponding lock-in mechanism is ‘infrastructural and technological lock-in’ (Seto et al. 2016). This mechanism theorizes that technological and economic forces, such as the cost-competitiveness of technologies, significant investments, sunk cost, and technological network effects, can “lead to inertia” in the energy system (Seto et al. 2016, p. 445). For instance, infrastructural lock-in can be created by building new NG infrastructure that creates economic lock-in effects, as investors would try to avoid stranded assets (Brauers et al., 2021). Such effects can create spill-overs in the political realm, as the prospect of stranded assets may generate resistance to energy policies like increased CO₂ taxes that can make infrastructural investments economically uncompetitive. Furthermore, additional NG investments serve as direct substitutes for investments in low-carbon technologies, delaying GHG reduction and postponing learning curves (Brauers, 2022).

2.4.3 Political perspective

Cherp et al. (2018, p. 181) state that “the central focus of the political perspective on national energy transitions is on change in policies which affect energy systems.” Correspondingly, the state tends to be the

central unit of analysis because energy policy is generally made by national, regional, or local governments. Considering the current level of EU integration, this research additionally incorporates a multi-level governance perspective, placing the EU level on equal footing to other governance in regard to research relevance. Cherp et al. differentiate between two approaches proposed by Hall (1993). These two approaches look at what “governments are pressed to do by different groups in society, and what they [actually] can do” (Lockwood et al., 2016, p. 15). These concepts can be incorporated into the political perspective.

First, state-centric approaches “emphasize the autonomy of the state from societal pressure groups” (Hall, 1993, p. 276). Hereby, state actions are considered to be dictated by state goals that comply with the national interest, like “a secure supply-demand balance” (Cherp et al. 2018, p. 181). A primary factor in this approach is ‘state capacity,’ which refers to how states can achieve their goals.

Second, state-structural approaches emphasize the competing interests of actors, with the state structure determining the force and demands of these actors (Hall 1993). Different groups like industry organizations, social movements, political coalitions, unions, and civil servants exert pressure and shape policy. Hence, the state is attributed less autonomy in this approach. Yet, combining both the state-centric and state-structural perspectives gives a more comprehensive approach, in which “institutional arrangements that give a stronger voice for those in favor of change, and that give governments a greater capability to bring about change, will tend to favor more rapid transitions” (Lockwood et al., 2016, p. 15).

This state structural approach overlaps strongly theoretically with the interaction between the regime level and the static landscape characteristics from the MLP (Geels et al., 2016; Lockwood, 2015). Both these approaches look at how the environment provides opportunities for actions that determine the agency and influence of actors. This synchronizes with work on historical institutionalism like Lockwood et al. (2016), which argues that institutions shape competing interests. These include formal and informal policies, rules, and norms, which North (1991, p. 97) conceptualized as “the humanly devised constraints that structure political, economic, and social interaction,” which create incentives for collective action and lower the cost of information. Actor groups can change these but also shape how actors pursue their own interests (Thelen, 1999).

This can lead to the ‘institutional lock-in’ proposed by Seto et al. (2016, p. 445), where institutions are designed to stabilize and “powerful economic, social and political actors seek to reinforce the status quo that favors their interest. Especially ‘incumbent coalitions’ have gained attention for their influence on shaping state policy regarding energy transitions (Hess, 2019; Roberts et al., 2018). These coalitions constitute broad networks including fossil-fuel producers, transporters and distributors, think tanks, politicians, and bureaucrats (Hess, 2014). Through this, actors can try to influence the goals and policies of the state. Brauers (2022, p. 9) points out that a particular theme related to NG is “the ‘energy policy trilemma’ – providing sustainable, affordable and secure energy.” As governments often prioritize direct economic and citizen concerns, emphasizing affordability and security can be a way for actors to solidify the role of NG. Therefore, research on the effect of hydrogen on these dilemmas is an essential avenue of research regarding NG lock-in.

3. Research Design

3.1 Exploratory research

The present research aims to provide a preliminary investigation regarding the relationship between hydrogen and NG lock-in. While some hypotheses on this synergy have been hinted at by Szabo (2021) and Brauers et al. (2021), specific research on the causal mechanisms involved in this dynamic has not been carried out yet. Therefore, this research sets out on an exploratory path to discover causal mechanisms by which NG lock-in shapes hydrogen markets and how hydrogen can impact NG lock-in.

As its research design, a choice is made for a qualitative case-study approach that employs process tracing. This grants a detailed perspective of observable phenomena with high internal validity when studying complex processes (Asenahab, 2019). Geels (2022, p. 11) notes the need to “demonstrate the epistemological validity and relevance of causal reconstruction of single cases, longitudinal process, tracing and narrative explanation, which is widely used in transitions research.” This is supported by Varvasovszky and Brugha (2000, p. 341), who argue that qualitative approaches are essential for studying complex phenomena to preclude premature focusing on a limited number of aspects of the issue. With few concrete hypotheses, quantitative techniques that might more rigorously examine causal dynamics are not worthwhile. Given the complexity of investigating energy transitions, a quantitative approach is not ideally suited for “explaining single cases and struggles to accommodate complex causalities and phenomenological characteristics of socio-technical transitions” (Geels, 2022, p. 12).

3.2 Case Selection

This research consciously adopts a single-case approach, as opposed to Mill’s method of difference (Levy, 2008). This is justified based on its explorative research design, which aligns with a solid research tradition that uses single-country case studies to elicit theory generation and uncover causal mechanisms (Pepinsky, 2019). This means that external validity may be constrained due to inherent challenges for the generalizability of small-n research. Nevertheless, this risk is deemed acceptable, as the primary objective of the research is to generate causal mechanisms for further exploration via additional case study research and potential quantitative investigations.

The Netherlands is selected as a compelling case, as it has a long history of producing and consuming NG while simultaneously being an early adopter of ambitious hydrogen policies. Due to its long history as an NG producer and the strong interconnections between the state and the fossil fuel sector, the Dutch NG industry poses an interesting case for understanding NG lock-in due to strong expected regime resistance (Ahmadov & van der Borg, 2019). Additionally, existing research exists on the phasing out of NG in the Netherlands mainly focuses on the heating sector (Brauers, 2022; Linders et al., 2021). Meanwhile, the Netherlands has undertaken significant efforts to become a leader in establishing hydrogen production and consumption (Hoek, 2021). Thus, the Netherlands emerges as an ideal case for examining the dynamic between NG lock-in and the hydrogen niche.

3.3 Methodological approach and framework operationalization

To understand the possible interlinkages between NG lock-in and hydrogen, this research will utilize the methodological approach developed by Brauers et al. (2021) and Brauers (2022). This approach combines and operationalizes the theoretical frameworks developed by Seto et al. (2016) and Cherp et al. (2018).

This approach consists of two separate but linked analyses, divided over the three perspectives discussed in section 2.3. The first part consists of a material analysis. Besides academic literature, the research will rely on grey literature, such as government documents, research institutes publications, NGO reports, market consultations, and newspaper articles. Informational interviews with independent experts and NGOs will supplement this information. An additional second part consisting of an ‘actor analysis will research the perceptions and interests of involved actors. This helps to identify how perceptions and interests interact with material reality to produce a better understanding of the dynamic between hydrogen and NG.

As put forward in the metatheoretical framework devised by Cherp et al. (2018), a hierarchy of variables of interest exists, with previous literature used to identify the variables of interest in the present research. The following paragraphs will identify the variables of interest to each perspective.

Top-level and selected second-level variables in the three perspectives framework.

Techno-economic	Socio-technical	Political
Resources <ul style="list-style-type: none"> - Fossil fuels types, resources, reserves, extraction costs - Import and export of fuels and carriers - Type and potential of renewable resources; cost of relevant technologies 	Innovation systems <ul style="list-style-type: none"> - Presence and structure of national, sectoral and technological innovation systems - Performance of innovation systems with respect to their functions e.g. R & D activities, knowledge stock 	State goals <ul style="list-style-type: none"> - Type of state goals (e.g. energy security, access to modern energy, climate change mitigation, technological leadership) - Factors affecting state goals e.g. import dependence, international competition.
Demand <ul style="list-style-type: none"> - Types and scale of energy uses - Energy intensity - Factors driving demand growth and decline, e.g. population and economic growth/decline; industrial restructuring 	Regimes and niches <ul style="list-style-type: none"> - Structure, resources and coordination of incumbent regimes - Structure and resources of newcomers' niches - Niche-regime interaction including external support mechanisms 	Political interests <ul style="list-style-type: none"> - Special interests (e.g. industrial lobbies) - Party ideologies and organized social movements - Voters' preferences
Infrastructure <ul style="list-style-type: none"> - Existing infrastructure for extraction, transportation, conversion, and use - Age of infrastructure - Manufacturing, import and export of equipment - Cost of operation and construction of infrastructure 	Technology diffusion <ul style="list-style-type: none"> - Global maturity of relevant energy technologies - Location on core/periphery of technology - Possibilities for technology export 	Institutions and capacities <ul style="list-style-type: none"> - State capacity e.g. economic and other resources, political stability - Institutional arrangements, e.g. varieties of capitalism, party system, government system - International processes: e.g. policy diffusion, international agreements

Figure 5: Variables in the metatheoretical framework.
Source: Cherp et al. (2018).

Techno-economic perspective

Concerning the techno-economic dimension of this analysis, the principal variables identified by Cherp et al. (2018) are *resources (or supply)*, *demand*, and *infrastructure*. This research will consider the factors influencing the supply, demand, and infrastructure of NG and hydrogen within the Netherlands and how these two energy forms interact. For this, it considers the data on existing and planned NG and hydrogen infrastructure, the total consumption of NG and hydrogen, and cost curves for various blue and renewable hydrogen. It primarily relies on grey literature for the material analysis, supplemented with expert interviews. The actor analysis regarding economic interests is informed mainly via interviews and previous academic research.

Political perspective

For the political perspective, Cherp et al. (2018) identify *institutions*, *state capacity*, *state goals*, and *political interests* as the most important variables of interest. In terms of state goals, the research primarily relies on government documents to gauge state goals. Political interests are primarily measured via actor analysis, supplemented by previous academic work. For Germany, Brauers et al. (2021) do not sufficiently justify the lack of an in-depth investigation of *institutions*. However, both Kooij et al. (2018) and Brisbois (2020) argue that Dutch ‘corporatist’ or ‘consensus-oriented’ politics tend to have a noticeable centralizing effect within the policy system. Therefore, this research will take institutions into the analysis as it hypothesizes it to be a possible vital variable of exploration. The institutional environment is measured via existing academic literature on policymaking in the Netherlands, supplemented by information gathered from interviews and grey literature on recent political trends.

This research will also explore *state capacity*, in contrast to Brauers et al. (2021) who argue that this is not a constraining variable in the German context and can therefore be neglected. In recent years, scandals of Dutch state incapacity in carrying out its goals have gained significant attention, such as the ‘child benefits scandal,’ the ‘Groningen earthquake debacle,’ and the inability to provide basic living conditions for asylum seekers. Therefore, this research argues that the ability of the state to seamlessly execute its desired policies should not be taken for granted, warranting the inclusion of state capacity into the analysis. To measure state capacity, it uses literature and perceptions of actors from interviews, although these may be imperfect measures.

Socio-technical perspective

Concerning the socio-technical dimension of this analysis, Cherp et al. (2018) have identified the key variables of *innovation systems*, *regimes and niches*, and *technology diffusion*. This research focuses on *regimes and niches* to analyze the regime dynamics in the socio-technical system. It also includes an examination of regime resistance by actors, which is treated as part of the political perspective, and includes trying to influence public discourse. It does not explicitly address *innovation systems* and *technological diffusion*. It does this due to the limited time available for the research. Examining innovation systems would require a more technical approach and does not fit well into the lock-in framework. An innovation studies approach would require

technological lock-in, which the researcher lacks the expertise and methodological tools to undertake. Still, it tackles innovation systems implicitly through the techno-economic realm regarding the development of blue and hydrogen technologies and regime dynamics within the socio-technical analysis and developments of technological niches. In contrast, the variable *public discourse* is examined in detail, as it is seen as critical for understanding discursive NG lock-in as highlighted by Brauers et al. (2021) and Brauers (2022). Preliminary investigation of public discourse mainly relies on the perceptions of actors via interviews.

3.4 Data Collection

For the actor analysis, this research follows the method proposed by Brauers et al. (2021), which is built on the stakeholder analysis model developed by Varvasovszky and Brugha (2000). This methodological procedure is divided into five steps:

1. Identifying and clustering actors

The research begins by identifying and clustering the relevant actors, using the relevant actors involved in the Cross-Sectorale Werkgroep Waterstof (CSWW) as a starting point. This is a key Dutch public-private working group involved in creating the so-called ‘roadmap hydrogen.’ Due to the research’s limited scope and time, data-rich interviews are necessary, which can be achieved through the purposive sampling of key informants (Palinkas et al., 2015). As Varvasovszky & Brugha (2000, p. 341) argue, a “premature focusing down on a limited number of stakeholders can have pitfalls through omitting important ones.” This requires supplementation of other relevant actors identified via desk research and snowball sampling, such as from local government and research institutes, to balance the private sector-dominated group of actors in the NWP.

2. Narrowing down the field

By taking the first samples out of the group of actors identified in the previous section, this step bypasses the step of narrowing down the field. Instead, it leaves room for broadening the group of actors that emerge from the snowballing and desk research process.

3. Categorizing actor groups

Through the members of the CSWW, the research finds four main actor groups involved in the policy process: state actors, the private sector, and civil society. Moreover, while public institutions may not have any profit interest in a specific technology, there may exist “tribes” in public institutions that prefer and push for certain technological solutions (Trencher et al., 2020).

4. Interviewing the relevant actor groups

The interviews were conducted following a semi-structured interview process, with consideration of ethical concerns addressed through a form in Appendix 1. Given that all interviews were in Dutch, the form is provided in Dutch. The interviews adhered to the interview phases that Robson & McCartan (2016) identified to ensure maximum data-richness, including a warm-up, main body, cool-off, and closure. Without rigid order to allow for a natural flow and an exploratory approach, respondents were asked the respondents regarding their assessment of the impact of hydrogen on NG and vice versa, as well as the interests and perceptions of their organization regarding the future role of NG and hydrogen. Additional questions were formulated based on the answers of respondents and in regard to specifically relevant interests, dynamics, and uncovered causal mechanisms. In Table 1 an overview is provided of respondents that are part of the energy system. Table 2 shows actors that are primarily informational sources, although these may influence discourse and policy.

Respondent	Sector	Respondent	Sector
Policy officer [Gov_1]	National Gov.	Asset manager [DSO_1]	DSO
Policy officer [PGov_1]	Provincial Gov.	Business developer [Port_1]	Port
Senior analyst [NGO_1]	NGO	Sr. consultant [Cons_1]	Consultancy
Policy officer [Prod_1]	Energy firm	Policy advisor [Branch_1]	Lobby
Sr. advisor RE [Prod_1]	Energy firm	Sr. policy advisor [Branch_2]	Lobby
Sr. strategic advisor [TSO_1]	TSO	Sr. advisor [Branch_3]	Lobby
Managing Director [TSO_2]	TSO	Sr. advisor [SOE_1]	SOE
COO [Mob_1]	Industry		

Table 1: Respondents that are actors in the energy system.

Respondent	Sector	Respondent	Sector
Independent [Jor_1]	Journalism	Senior researcher [Gri_1]	Gov. research (1)
Independent [Jor_2]	Journalism	Senior researcher [Gri_2]	Gov. research (1)
Senior analyst [Pri_1]	Research institute (1)	Senior researcher [Gri_3]	Gov. research (2)
Senior analyst [Pri_2]	Research institute (1)	Academic [AC_1]	University
Senior analyst [Pri_3]	Research institute (2)	Academic [AC_2]	University
Senior analyst [Pri_4]	Research institute (2)		

Table 2: Informational respondents.

5. Analyzing the interview results

Following the interview data collection, this data was processed using inferential qualitative thematic coding based on the variables identified in section 3.2. This included various aspects per variable. For instance, for state goals, codes were used for ‘affordability, sustainability, and energy security.’ This was supplemented by inferentially discovered codes concerning themes that regularly returned in the data, in particular regarding the mechanisms that answered the research questions and which are listed within the discussion. This method is utilized for “identifying, analyzing and reporting patterns (themes) within data” (Castleberry & Nolen, 2018, p. 808). Through this approach, one can create structure in the results gained from open-ended interview questions, which allows incorporation in the broader context without being bound to the restrictive rigor of a survey (Castleberry & Nolen, 2018; Robson & McCartan, 2016). These results were triangulated with results from the material analysis.

4. Results

The results are structured based on the perspectives explained in the literature review and operationalized in the methodology section. Section 4.1 analyses the *supply* and *demand* for NG and hydrogen and looks at *infrastructure*. This is done by first giving an overview of these variables for both NG and hydrogen, with a separate section to discuss interaction effects between NG and hydrogen to enhance readability. Section 4.2 overviews the relevant actor's economic interests and perceptions. Section 4.3 contains findings concerning the political realm, where state-centric and state-structural ideas are incorporated via the analysis of *institutions*, *state capacity*, and *state goals*, while section 4.4 maps *political interests*. Lastly, section 4.5 analyses the socio-technical realm, paying attention to *regimes and niches*, while the actor analysis in section 4.6 further discusses regime resistance and in particular *public discourse*, as this is best examined via authors' perceptions.

4.1 Techno-economic dimension: material analysis

4.1.1 Natural Gas

While the consumption of coal in the Netherlands has drastically decreased over the last decade, NG consumption in the electricity mix of the country rose from 45.819 GWj in 2015 to 72413 GWj in 2020, raising its share in the total energy supply by 9,8% between 2015 and 2020 (IEA, 2022). Therefore, the Dutch dependency on NG remains high, particularly for electricity generation, residential heating, and industrial use (Chong et al., 2020).

The management and infrastructure for NG extraction are managed through a complex structure called 'The Gas Building.' This includes significant government involvement across the value chain via state-owned enterprises (SOEs) (Oxenaar, 2017). The involvement is separated into two governance structures. First, the 'small fields' policy has SOE 'Energie Beheer Nederland' (EBN) taking a 40% stake in all fossil fuel projects, with an additional role in providing technical and operational support (Ahmadov & van der Borg, 2019). For the enormous Groningen field that kickstarted major NG production in 1959, a separate entity was created called the Nederlandse Aardolie Maatschappij (NAM). This is jointly owned and operated by Shell and ExxonMobil (Ahmadov & van der Borg, 2019). The NAM is connected to the state via a joint partnership called the 'Maatschap Groningen,' in which EBN has a 40% stake (Oxenaar, 2017). Through the Maatschap Groningen, the state extracts rents from NG extraction. For transport, the SOE Gasunie acts as Transmission System Operator (TSO) for Dutch NG infrastructure, meaning it operates the transport network for NG and hydrogen (Oxenaar & Bosman, 2020). Additionally, the state partly controls Gasterra, which acts as a wholesaler, mainly for the Groningen field.

Through this interconnected system of providing investment support via EBN, the facilitation of transport via Gasunie, and an obligation for Gasterra to buy the gas as a wholesaler, the Dutch built an institutional infrastructure that eradicated risks for investment, demand, and transport, creating favorable conditions for NG exploration (Oxenaar & Bosman, 2020).

During the 2000s, with the prospect of NG reserves declining, the Dutch government sought to solidify the future role of NG in its energy infrastructure through a plan called 'The Gas Roundabout,' meant to safeguard the Dutch role as the 'gas hub' of North West Europe (Oxenaar & Bosman, 2020; Schipperus & Mulder, 2015). This included 8.2bn worth of additional infrastructure investments via EBN and Gasunie between 2005 and 2014, including pipelines, storage, and LNG terminals (Oxenaar, 2017). According to the National Court of Auditors, the decision-making process behind this strategy was opaque, noting the lack of evidence and arguments to justify how these policies were meant to strengthen energy security or economic prosperity (Rekenkamer, 2012).

4.1.2 Hydrogen in the Netherlands

Hydrogen production and consumption play a significant role in the Dutch economy in producing artificial fertilizer, methanol, and the desulphurization of crude oil. Currently, the Netherlands is the second largest consumer of hydrogen in the EU, behind Germany, although it has a much larger per capita consumption (Leguijt et al., 2022). The current sources of consumption for hydrogen are displayed in Table 3 below.

Application type	Estimated amount of hydrogen		
	bcm/y	kton/y	PJ/y (LHV)
Ammonia ^{a)}	5.3	480	58
Refinery ^{b)}	6.0	544	65
Other pure hydrogen use ^{c)}	1.6	143	17
Methanol ^{d)}	1.1	102	12
Fuel gas ^{e)}	2.6	231	28
Total	16.7	1,500	180

^{a)} SMR-natural gas

^{b)} SMR-natural gas and refinery gas; Shell Gasifier; Naphtha catalytic reforming

^{c)} SMR/ATR-natural gas; by-product chlor-alkali; water-electrolysis

^{d)} SMR-natural gas

^{e)} Various catalytic reforming; naphtha steam cracking; by-product chlor-alkali; Flexicoker fuel gas (but excluding small fractions of hydrogen that may be present in other residual refinery gas) and coke oven gas.

Table 3: Dutch hydrogen consumption.

Source: Weeda & Segers (2020).

The adoption of the EU's REDIII obligates the Netherlands to ensure 42% RFNBO uptake as a share of the total hydrogen used for final energy and non-energy purposes in the industry by 2030, with separate non-binding targets for mobility. There are several exemptions from the denominator for the industry target, including hydrogen as a by-product and the majority of use in refineries, with the latter counting under the mobility goal. Table 4 provides an overview of the industry goal.³ Notably, ammonia and methanol count as an RFNBO in the numerator while not being included in the denominator. This creates a multiplier effect when imports of ammonia replace direct hydrogen use.

Company/sector	Product	Kt H2 & PJ	%REDIII	Options RED-III target	RED-numerator	RED-denominator
YARA: Sluiskil	Ammonia	330kt - 40PJ	~49%	1) Renewable H2 2) Import RFNBO ammonia 3) Import blue ammonia	Numerator ↑ Numerator ↑	Denominator ↓ Denominator ↓
OCI: Nitrogen	Ammonia	150kt - 18PJ	~22%	1) Renewable H2 2) Import RFNBO-ammonia 3) Import blue ammonia	Numerator ↑ Numerator ↑	Denominator ↓ Denominator ↓
OCI: Bio MCN	Methanol	108kt - 13PJ	~16%	1) Renewable H2 2) H2 from gasification 3) Methanol to mobility	Numerator ↑	Denominator ↓ Denominator ↓
Refinery	Naphta's, lubricate oil	32kt- 4PJ	~5%	1) Renewable H2	Numerator ↑ Numerator ↑	
Other (~55)	Chemicals	57kt - 7PJ	~8%	1) Renewable H2	Numerator ↑	
Total H2 use		678kt - 81PJ				
REDIII-target 42%		284kt - 34PJ				

Table 4: Dutch use of industrial hydrogen under the REDIII (art. 22a).

Current Dutch hydrogen production predominantly stems mostly from onsite (captive) SMR installations for industrial processes in the fertilizer, methanol, and refinery industries (Leguijt et al., 2022). Additionally, some hydrogen is produced by Air Products and Air Liquide and sold as merchant hydrogen to industrial customers [Pri_1]. Current grey hydrogen production emits around 13Mt CO₂ yearly (Rijksoverheid, 2020). Dutch companies currently have expansive plans for producing both blue and renewable hydrogen.

For blue hydrogen, projects are looking to apply CCS to existing SMR installations or new ATR installations through the large-scale CCS projects 'Porthos' (Rotterdam) and 'Aramis' (Amsterdam), which can reduce up to 60% of the CO₂ emissions against economically viable prices (PBL, 2022). This is primarily motivated by companies seeking to reduce CO₂ emissions to comply with climate goals. However, this also serves their own benefit, with the increasing ETS price making CCS an increasingly cost-effective measure (Akerboom et al., 2021).

The Netherlands still has nearly zero supply of renewable hydrogen production, although the state and the energy industry have high ambitions. In 2022, a consultation process between the Ministry of Economic Affairs and Climate (EZK), industry actors, and other stakeholders, called the National

³ Data in this table compiled based on bilateral contact with researchers from government institutes.

Hydrogen Program (NWP), produced the ‘Roadmap Hydrogen.’ This document stipulates an ambition for realizing 500MW electrolysis capacity by 2025 and 4GW by 2030 (EZK, 2021). In December 2022, the Dutch Parliament approved a motion to increase this goal to 8GW in 2032 (Savelkouls, 2023). In the summer of 2022, 783,5 million euros worth of production subsidies were handed out to seven electrolyser projects to realize 1,15GW (Savelkouls, 2022). These projects are developed by Shell, BP, Air Products, Engie, Air Liquide, HyCC, and Ørsted, which shows that incumbent industries are the core of the renewable hydrogen niche. Only Shell has so far taken a final investment decision (FID).

Currently, blue hydrogen costs in the Netherlands are lower than renewable hydrogen costs by a factor two or three. Aurora Energy Research predicts that blue hydrogen will be the lowest-cost form of hydrogen until around the mid-2030s (Tracey, 2023). This is due to the competitive advantage of existing SMR installations in the Netherlands, existing NG infrastructure, and the available CCS infrastructure (van den Beukel, 2021). Yet, renewable hydrogen is expected to become increasingly competitive. Bloomberg New Energy Finance expects renewable hydrogen to beat blue hydrogen on costs by 2030 (Liebreich, 2020). As shown in Figure 7, the production costs of renewable hydrogen are decreasing rapidly. However, these figures do not mirror market prices, which could vary depending on the distribution of subsidies, regulation, and consumption obligations.

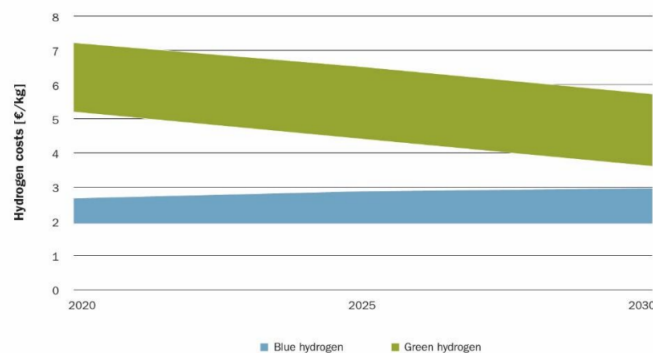


Figure 6: Estimation costs for blue and renewable hydrogen in the Netherlands. Source: Detz et al. (2022)

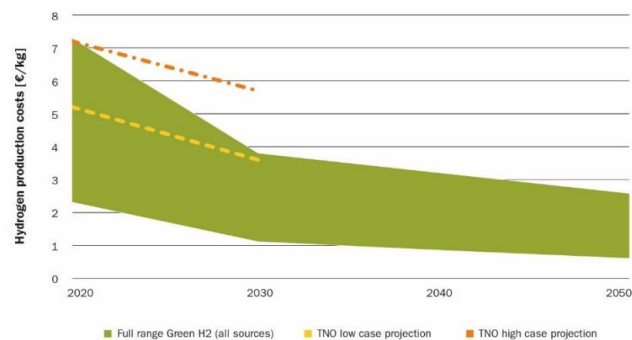


Figure 7: Potential cost reduction for renewable hydrogen based on literature. Source: Detz et al. (2022)

While Dutch renewable hydrogen production ambitions are high, they are trumped by ambitions for RFNBO imports. In particular, the Port of Rotterdam (PoR) has taken a pioneering role in coordinating international projects, seeking to become a ‘hub’ for importing RFBNOs for the Netherlands and Europe. In the hydrogen roadmap, cumulative ambitions for Dutch ports are set at 3Mt to 5Mt hydrogen (360-600PJ) in 2030, and 20Mt (2400PJ) in 2050. To put this in perspective, the industry goal for RFNBO uptake in 2030 is around 34 PJ. These ambitions can likely be considered overly optimistic [Gov_1, Pri_2]. Still, the Dutch government actively supports hydrogen imports, for instance, via international diplomacy, with multiple memorandums of understanding (MoU) signed with potential exporting countries and subsidies for setting up import corridors (Jetten et al., 2023).

The long-term competitive position of Dutch electrolyzers compared to imported hydrogen is difficult to predict. Still, production costs for renewable hydrogen will likely be cheaper in countries with more abundant renewables (Tracey, 2023). Final prices primarily depend on the development of hydrogen production and shipping costs. The IEA estimates that ammonia as a carrier of renewable hydrogen will be the cheapest RNFBO in 2030, although hydrogen trade by pipeline could mature in the long-term (IEA, 2023). This ammonia is most likely to first replace current ammonia production, as using it as hydrogen requires cracking the ammonia, resulting in additional conversion losses and costs (Goldman Sachs, 2020).

In the short-term, however, imports will likely come from sources with the highest support for RNFBO development. In particular, the US stands out, as the Inflation Reduction Act (IRA) provides generous subsidies to renewable and blue hydrogen development, as shown in Figure 8. In response, companies are considering shifting investments from the EU toward the US (Simon, 2023).

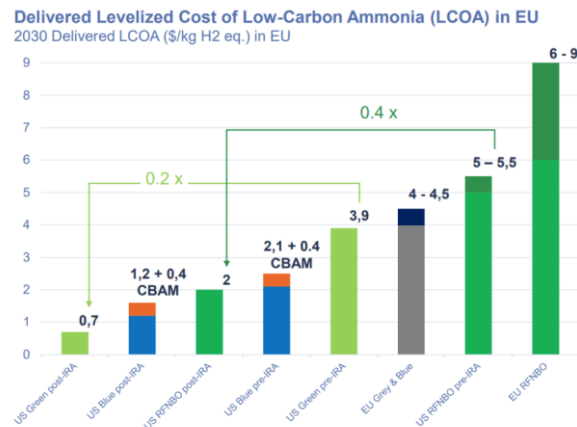


Figure 8: Cost comparison of hydrogen EU and US post-IRA. Source: NWP (2023).

To create a liquid market for the wide-scale application of renewable hydrogen in industrial processes, the Dutch state has planned a major hydrogen transport network called the ‘backbone.’ Expectations are that it can be done for 80% by retrofitting existing NG pipelines [TSO_2]. The need for such infrastructure arises because the location of production and consumption of hydrogen will become separated due to the availability of renewable resources, which differs from the existing predominance of on-site production and use [DSO_1]. In the long-term, the backbone is supposed to connect 1150km of potential hydrogen pipelines in surrounding countries, as shown in Figure 9.



Figure 9: Plans for the hydrogen ‘Backbone.’ Source: (Gasunie, 2023)

Besides pipelines, import infrastructure is required, including terminals for the import of renewable ammonia and other RNFBOs. Some projects have already been announced, with industry firm OCI expanding its ammonia import terminal from 20PJ to 36PJ (Sluiers, 2022). Additional infrastructure would be required for the potential transfer to Germany and Belgium. A recent study mapped possible scenarios

for demand for RFNBOs that could be transferred via the Netherlands (Vijen & Jetten, 2023). It concluded that in the medium and high hydrogen demand scenarios, ammonia transport could increase from a few thousand train carriages to more than a hundred thousand, leading to significant breaches of safety protocols and risk caps. This has prompted an evaluation of guidelines for transporting dangerous fluids, which could play an influential role in the debate on hydrogen imports in upcoming years due to the role of safety in public discourse (Vijen & Jetten, 2023).

4.1.3 Techno-economic interaction effect hydrogen and NG

For the techno-economic perspective, there are three main areas for interaction between NG and hydrogen: 1) the interaction with NG on the supply side for energy input for the production of both blue and renewable hydrogen; 2) the demand side for hydrogen usage, which affects the magnitude of the effect on the interactions on the supply side; 3) interaction regarding infrastructure.

Supply

For blue hydrogen, the interaction effect between the supply of hydrogen and the use of NG is considerably straightforward, as NG is its primary input, meaning new investments can create at least some ‘lock-in’ for NG use via new sunk costs [Gov_1, Gri_2, Pri_1]. This is because companies are interested in exploiting their investments until they are discounted. These sunk costs are higher when new ATR or SMR assets are built, while the sunk cost of adding CCS to existing installations depends on the remaining lifetime of the existing asset. Consequently, if plans for new installations, like the Dutch ATR projects by the H2Gateway Project and Onyx, are realized, they could remain in use for a significant period (Baljeu & Castelein, 2021; van der Lugt, 2023).

For renewable hydrogen, the interaction with NG is more complex. It comes down to two intertwined causal mechanisms: 1) the systemic effect of increasing demand for renewable electricity and associated increased NG demand; 2) the ‘CO₂-opportunity cost,’ meaning the potential forgone emission reductions by using renewable electricity for hydrogen production.

First, renewable electricity has various applications, of which electrolysis technology is relatively inefficient due to low conversion efficiency during production and additional energy loss during incineration (Younas et al., 2022). Therefore, using renewable hydrogen to replace fossil hydrogen has a relatively low CO₂ reduction potential per 1 kWh compared to decarbonizing electricity generation, as depicted in Figure 10.

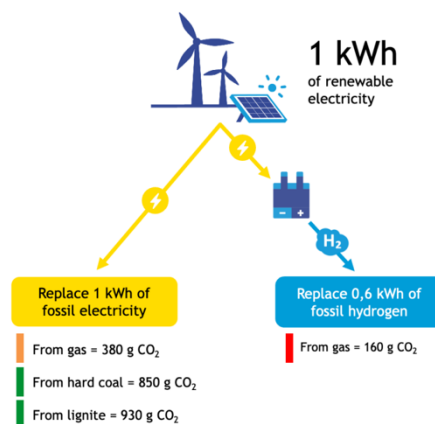


Figure 10: Emission reduction potential of 1 kWh renewable electricity.

Source: de Vries et al. (2022).

Consequently, if a country still substantially relies on NG or coal for electricity generation, more efficient CO₂ reduction can be achieved by replacing fossil electricity rather than grey hydrogen production. As shown in Figure 11, Mac Dowell et al. (2021) calculate that as long as the carbon intensity of the electricity grid is higher than 30-70kgCO₂-eq/MWh, incorporating renewable energy into the grid reduces more CO₂. As a result, if the level of renewable energy production in a country is taken as static, adding an electrolyser, even if it has a Purchase Power Agreement (PPA) with a renewable energy source, results in higher total demand for electricity. Subsequently, more grey electricity generation is required. This leads to a rise in CO₂ emissions in the system, which is not sufficiently compensated by reductions elsewhere through the

application of renewable hydrogen elsewhere due to the low conversion efficiency. Therefore, renewable electricity production “is above all essential to decarbonize the electricity grid” [Branch_2].

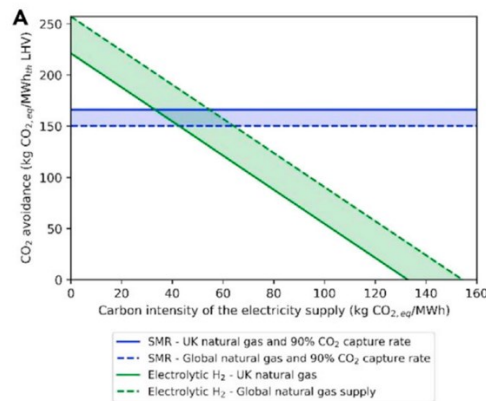


Figure 11: Relationship between grid carbon intensity and CO₂ reduction potential of hydrogen.
Source: Mac Dowell et al. (2021)

To limit these unintended side effects of renewable hydrogen production, the EU has added an ‘additionality’ clause to the DAs for renewable hydrogen. It requires that the renewable electricity installation used is not older than 36 months. This is meant to stimulate new production, thereby altering the ‘static’ assumption from the previous paragraph (de Vries et al., 2022).

However, in practice, this additionality rule can be flawed, as in the Netherlands there are limitations to the ability to deploy additional renewable energy in the short-term. This causes competition between end-users of renewable electricity. In the Netherlands, renewable hydrogen plans primarily rely on prospective offshore wind energy [Gri_2, Gri_3]. In 2022, the government, after extensive investigation, increased its target for offshore wind from 11GW to 21,5GW in 2030 (Rijksoverheid, 2023). This is considered the absolute maximum because faster roll-out is constrained by permitting, insufficient supply of materials, capable personnel and limitations to grid capacity [TSO_1, Pri_1, Prod_2, Gri_3]. Consequently, the 21,5GW means the ‘static’ assumption is granted a specific value, as no additionality can be ensured as this 21,5GW is planned to be built anyways. And as long as there is alternative demand for every kWh of this electricity, there are other more efficient ways to reduce CO₂ emissions. Consequently, as long as NG is used for electricity generation or in a process that can be directly electrified, producing renewable hydrogen can delay phasing out NG consumption.

Meanwhile, in the Netherlands, Figure 12 and Figure 13 show that significant fossil fuel electricity generation can still be expected. The PBL estimates renewable electricity generation at 60% in 2025 (PBL, 2022). Simultaneously, Shell is constructing the first large electrolyser (200MW) meant to come online in 2025 (Westerveld, 2022). Therefore, such electrolyser projects could result in lower CO₂ reduction and higher NG consumption in the short-term compared to alternative electricity allocation [Gri_2, Gri_3].

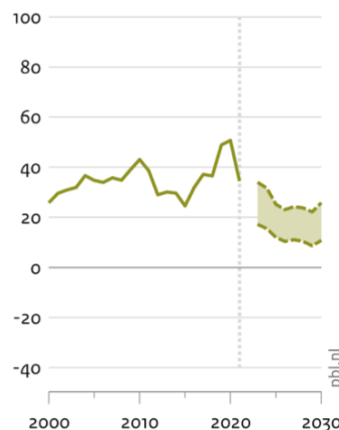


Figure 12: Dutch centralized NG use in TWh
Source: PBL (2022).

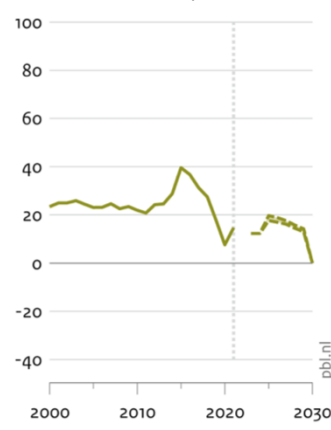


Figure 13: Dutch coal use in TWh
Source: PBL (2022).

However, the abovementioned dynamic in the Netherlands requires some nuance, as grid congestion and a potential lack of flexible electricity demand towards 2030 could result in electrolytes becoming essential for integrating planned offshore wind capacity into the energy system. As shown in Figure 14, the Dutch electricity network is overstrung, with red areas signaling where no new connections are possible, and orange areas signaling where no grid connection is possible pending investigation. This shows that barriers to electrification will be a significant issue during the upcoming decade (Netbeheer Nederland, 2023a). Respondents estimate that around 8GW of offshore wind cannot be easily integrated into the generalized electricity network without causing congestion or the forcible curtailment of renewable production [TSO_1, Gov_1].

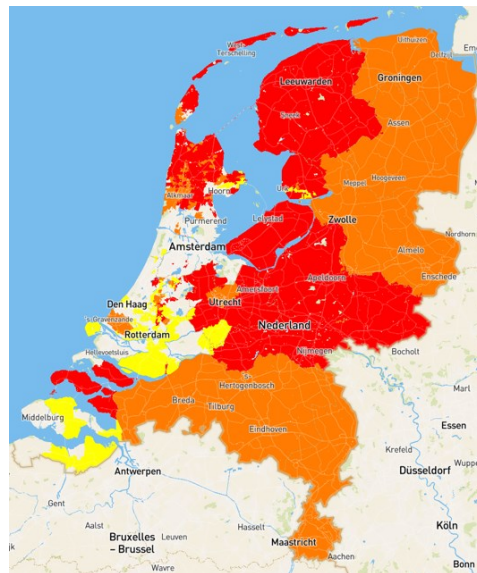


Figure 14: Net congestion in the Netherlands for new input connections (3x80A>).
Source: Netbeheer Nederland (2023).

This grid congestion creates a need for flexible electricity near coastal areas. Additionally, a TNO study by Gonzalez-Apricio et al. (2022) identifies the risk that in both low-electrification and high-electrification scenarios, a lack of flexible demand would pose a threat to the commercial viability of the wind parks and create a need for curtailment. As a result, they point out that electrolyzers are potentially essential for creating flexible demand to realize offshore wind parks towards 2030. Additionally, CO₂ opportunity costs can be avoided when electrolyzers only use electricity when favorable weather conditions lead to excess renewable electricity generation. According to the PBL, by 2030, renewable electricity generation will already involve a significant amount of hours with the excess generation, although exact numbers are not provided (PBL, 2022). If offshore wind parks would not be realized without electrolyzers, true ‘additionality’ would be ensured, canceling out concerns around CO₂ opportunity cost of renewable hydrogen.

Demand: interaction NG and hydrogen

Policies that either stimulate blue or renewable hydrogen demand, which provide a higher willingness-to-pay for these energy carriers, can exacerbate lock-in effects for blue hydrogen or increase the CO₂ opportunity cost effect for renewable hydrogen. The Netherlands faces rising electricity demand for applications like industry, heat pumps, and electric vehicles (PBL, 2022). As stated, direct electrification is preferred to options where electrons must be converted into molecules. Some applications, like heat pumps, can even increase energy efficiency, utilizing one electricity unit to generate three to four units of heat (Rosenow, 2022). However, policies leading to increased renewable hydrogen demand would raise prices for RFNBOs. This enhances the business case for electrolyzers, risking the subversion of renewable electricity for direct electrification purposes [Pri_1, Branch_1, Gov_1]. Therefore, technologically neutral policies might be more favorable for reducing emissions and NG use. Still, as discussed before, this is also dependent on the availability of electricity infrastructure and sufficient flexible demand for renewable energy production [Pri_2, Gri_2].

Arguably, because renewable hydrogen competes with direct electrification, specific policies targeting blue hydrogen demand could be more favorable for decreasing emissions, despite causing possible lock-in effects. In the electricity sector, blue hydrogen is currently envisioned by EZK as a way to replace existing NG use for hours where an adjustable power supply remains necessary (Soest, 2023). This is because no EU directives target renewable hydrogen in the electricity sector (Rooijers et al., 2022). Higher blue hydrogen demand would lead to a net increase in NG consumption because replacing the direct NG use with blue hydrogen results in an energy conversion loss. However, even if primary NG demand rises, the application of CCS may still result in a net-CO₂ reduction, depending on CO₂ capture rates and associated upstream methane emissions [Pri_1, Gri_2].

Transport infrastructure: interaction effect hydrogen and NG

An interaction effect for hydrogen and NG concerning infrastructure exists, as existing NG pipelines can be repurposed to transport hydrogen instead. In the ‘Highway 27’ study, Tezel & Hensgens (2021) find that Dutch pipelines used for NG transmission can be retrofitted and that the transmission network is made up of parallel pipelines. In effect, part of the NG transport network is already being repurposed for hydrogen transport, which means it is not used to legitimize continued NG consumption [Prod_1, TSO_2, DSO_1]. Therefore, while Dutch NG use positively contributes to the adoption of hydrogen for national transportation infrastructure, there are no apparent direct ‘lock-in’ effects.

A lock-in could exist for regional infrastructure if hydrogen were used for heating in the residential environment, as no parallel pipeline infrastructure exists. However, this effect seems limited in the Netherlands. Rosenow (2022, p. 1) finds in a meta-review of 32 independent research publications that “compared to other alternatives such as heat pumps [...], hydrogen used for domestic heating is less economical, less efficient and more resource intensive”. Still, for DSOs, there is some interest in exploring hydrogen for this purpose, with ongoing subsidized pilot projects in the Netherlands. Some respondents suggest that from a systemic perspective, a limited application of hydrogen for domestic heating could be necessary [DSO_1, Pri_1]. Yet, in a recent letter to parliament, minister Jetten stated that the government does not seek a substantial role in residential heating in the short-term (Jetten & Adriaanse, 2023). Therefore, while hypothetically the prospect of using hydrogen for residential heating could be used to legitimize the continued use of NG in heating until renewable hydrogen matures, this effect seems very limited in the Netherlands.

A lock-in effect is possible for constructing new LNG terminals, as the convertibility of these terminals for hydrogen imports is uncertain. According to the IEA, repurposing LNG terminals for liquefied hydrogen is a significant challenge due to the different properties of methane and hydrogen, and new construction for import facilities would possibly be more economical (Ferris, 2023). This is supported by a 2022 Fraunhofer institute report, which concludes that the use of LNG terminals for renewable energy is uncertain, “which poses a risk for them to become stranded assets in the medium term” (Schreiner et al., 2022, p. 6). This corroborates the findings of Brauers et al. (2021), who warn that building new LNG terminals could lead to stranded assets, as their convertibility for renewable energy carriers is questionable.

4.2 Techno-economic dimension: actor analysis

Ahmadov & van der Borg (2019) point out that the **Dutch state’s** participation and revenues connected to NG have created dependencies of the state on prolonging NG use, as illustrated by Figure 15. During the past decade, the Dutch NG industry experienced profound change due to increased seismic activity in Groningen. As a consequence of subsidence via lowered pressure in the sandstone due to NG extraction, thousands of low-scale earthquakes started occurring from 1986 onwards. However, public perception changed fundamentally after a 3.6 magnitude earthquake in 2012 put the issue into the spotlight. The physical damage to houses and psychological stress caused by earthquakes generated huge social backlash in Groningen (Bakema et al., 2018). This transformed NG production in Groningen into a headache for successive governments. Because safety and environmental concerns started to outweigh economic benefits, output from the Groningen field was lowered after 2013 to avoid further seismic activity (van den Beukel & Beckman, 2019). Consequently, NG revenues for the Dutch state declined from 15,4 billion in 2013 to only 1,1 billion in 2019, a reduction from 5,3% to 0,3% of government revenue (Chong et al., 2020). This means that “a tipping point in the production of natural gas [had] appeared with far-reaching financial effects for the government,” meaning less future dependency on NG revenues (Oxenaar 2017, p.

12). For hydrogen, no significant revenue effects appear apart from general stimulation of economic activities and associated tax revenues.

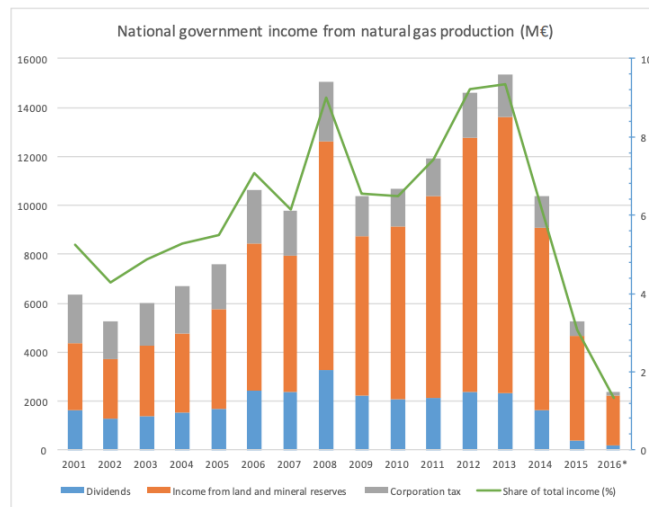


Figure 15: Dutch government income from natural gas production (2001-2016).
Source: Oxenaar (2017).

The NG extraction industry is interested in creating new business opportunities to reproduce existing business models around NG and capture business opportunities in the emerging hydrogen niche [Branch_1, Prod_1, Pri_1, Pri_3]. For **producers of industrial gasses**, such as Air Liquide and Air Products, electrolyzers provide an opportunity to continue their delivery of merchant hydrogen to industrial consumers [branch_2, Prod_1]. These groups benefit from production subsidies and high off-take targets for industrial users, guaranteeing an offset market.

For **industrial consumers** of hydrogen that produce their own ‘captive hydrogen,’ RNFBOs present a way to continue their business model sustainably [Pri_1, Branch_3]. However, while in the long-term RNFBOs can allow them to avoid retiring due to the zero-emission ETS goal in 2040, in the short-term, they have opposing interest to mandatory offtake of renewable hydrogen due to its high cost. This has validity, as CE Delft calculates that a 50% mandatory offtake of RNFBOs could lead to a 30-70% increase in the price of ammonia and a 45-65% increase for methanol, depending on RNFBO costs (Leguijt et al., 2022). Hence, short-term obligations for using renewable hydrogen run counter to the economic interests of these firms.

Utilities see hydrogen as a possible solution for adjustable power production when no wind or solar energy is available and can seek to capture part of the hydrogen production niche [Branch_1, Prod_2]. In time, hydrogen can provide an opportunity to suppress cost, providing a cheaper alternative to NG under the ETS. This would allow them to retain existing (retrofitted) Combined Cycle Gas Turbines (CCGT) or create new business opportunities through newly built units designed for adjustable power supply via hydrogen. However, they might have an opposing interest in national regulation that forces them to use hydrogen if other EU countries have no such regulation, as high fuel cost could put them at a disadvantage in the merit order within Europe’s integrated electricity market.

The Ports want to recreate their business model as a bunker fuel harbor and safeguard their interests as a supply hub for the rest of Europe [Port_1, Prod_1, Gov_1].

TSO Gasunie has its business model threatened by the phasing out of NG, meaning it might have a natural interest in making its business model energy transition-proof [DSO_1, DSO_2, Branch_2]. The hydrogen infrastructure is a future business model that could fulfill this role by creating the backbone. Meanwhile, for both CCS and offshore electrolyzers, the interest of Gasunie clash with those of **NG producers**, who are interested in retrofitting their offshore pipelines themselves. At the same time, Gasunie would prefer to create their own [Prod_1, Branch_2]. Similarly, some respondents claim Gasunie opposes the ‘delta-corridor,’ a PoR and Shell plan to build a pipeline to Germany, wanting other actors to use its own infrastructure network [Port_1, Branch_2].

Likewise, **DSOs**, like Stedin, Liander, and Enexis, are interested in making their business models energy transition-proof. Thereby, they could gain from repurposing their existing hydrogen infrastructure.

As distribution networks for NG are concentrated mainly around the industry and the residential environment, the DSOs have an economic interest in the use of hydrogen in these specific sectors. Yet, unlike the TSOs, they are not bound to one energy transportation form, handling both electrons and molecules [DSO_1]. As both TSOs and DSOs are SOEs, they do not have a profit goal, respondents argued that their economic interest are limited, as ultimately, they fulfil their mandate for the state [TSO_1, TSO_2, DSO_1].

For the **mobility sector**, hydrogen can be perceived as a feasible to fossil fuels like oil [Mob_1]. For industrial players this might provide a new business model, particularly in long-distance trucking, long-distance shipping, inland vessels, and aviation. However, use of hydrogen for cars or trucks is met by skepticism by several respondents, who see direct electrification as a more efficient option [Branch_2, NGO_1].

4.3 Political dimension: material analysis

The dynamic between NG lock-in and hydrogen cannot be decoupled from political developments. Here, the political realm is conceptualized as the pursuit of *state goals* by political actors, while private and civil society actors seek to influence policy outcomes according to their *political interests*. All actor groups' agency depends on *state capacity* and the *institutions* that shapes the affordance structures for political action.

State goals

The two main state goals for the Netherlands are GHG emission reduction and energy security, which contrast and compete through sub-goals.

The overriding state goal for Dutch climate policy is the **direct reduction of GHG emissions**, with a commitment to reaching a 55-60% reduction in 2030 and 95% by 2050 (Koster et al., 2022). These ambitions create legally binding consequences, as demonstrated by the 'Urgenda' case, in which the NGO Urgenda won a case mandating the state to commit to its 2020 reduction goals. Additionally, there are binding EU goals stemming from the Fit-For-55 and RepowerEU packages, including the REDIII. Such EU legislation constrains domestic actors' agency to shape state goals while providing an additional avenue for policy influencing (Geels, 2022).

The progress towards reaching various climate goals is monitored by the Dutch environmental assessment agency (PBL), which concluded in 2022 that the Netherlands was on track toward a 39-50% GHG emission reduction in 2030. This falls well short of the aspired 55-60%, meaning additional climate policy is required (PBL, 2022). The first significant steps came in May 2023 via a 28bn euro climate package, including 120 measures for speeding-up GHG emission reduction (NOS, 2023b). This included 9bn euros for renewable hydrogen development meant to reach the government goal of 3-4GW worth of installed electrolyser capacity in 2030 and implementation of the REDIII.

At the same time, the Dutch state seeks to maintain **energy security** which involves balancing the supply and demand of energy. Following Cherp et al. (2018) and Brauers et al. (2021), this paper defines energy security as a situation with a 'low vulnerability of vital energy systems.' Worries around energy security were recently reinforced by Russia's invasion of Ukraine and the ensuing price spikes in European NG markets. The Ukraine war constitutes a 'landscape development' in which an external shock caused sudden changes to the status quo, with significant consequences. In the summer of 2022, EZK minister Jetten was forced to re-open the previously shutdown of coal-fired electricity generation due to the crisis, exposing the tension between climate and energy security goals (NOS, 2023b).

This paper also subsumes the Dutch state goal of maintaining the **affordability** of energy supply under the concept of energy security (Rijksoverheid). As discussed by Brauers (2022), these three factors create the energy trilemma between sustainability, energy security, and affordability, which often exclude each other. When considering that the discussion regarding the interaction effect of hydrogen and NG on sustainability and reducing GHG emissions is tackled in earlier sections of this paper, operationalizing the remaining variables leaves creates three risk areas: a) energy security risks from political origin, b) the need for resilience of the energy system, c) affordability.

- a) **Political risks:** due to the decreased Dutch NG production and with falling imports from Russia, there is an increased reliance on the US, Qatar, Algeria, and Nigeria (Consilium Europe, 2023). Wherever NG use is substituted by domestically produced hydrogen, import dependency on foreign states, and associated political risks, decrease. However, if blue

hydrogen leads to higher sustained gas usage, import dependency will be sustained parallelly. Yet, while NG imports might decrease, new hydrogen imports might create new dependencies. However, these risks seem mild due to the worldwide availability of opportunities for RFNBO production and a renewed emphasis on import diversification in the Dutch import strategy following the Ukraine war (Jetten et al., 2023).

- b) **Resilience:** through technological upscaling of electrolysers, diversification of energy carriers could be achieved. This aids the robustness of the Dutch energy system, although the system's resilience to supply shocks will depend on diversity of supply and, thus, on the balance between domestic production and diversification of imports.
- c) **Affordability:** the 2022 scramble to protect consumers in the EU underscores the importance of affordability, with the EU managing to pay its way out of the gas crisis by redirecting LNG shipments from Asia (Tani, 2022). Yet, while a supply shortage was avoided, price effects on industry and consumers were severe (Bella et al., 2022). With hydrogen prices likely remaining higher than NG prices in the upcoming decades, hydrogen upscaling is unlikely to positively impact affordability (IEA, 2019).

State capacity

According to Cherp et al. (2018, p. 181), “the concept of capacity signals that a state is not able to pursue any energy policy it desires.” The Dutch state has come under fire in the past decade after a series of mismanagement scandals, most notably surrounding the Groningen earthquakes and the child-benefit scandal. Therefore, state capacity could be an obstacle to phasing out NG and developing the hydrogen niche.

A possible cause for this could be a decline in the institutional capacity of the Dutch executive Branch, although this would require further in-depth research. According to recent historical work by Mellink et al. (2022) and van den Brink (2020), beginning in the 1980s, New Public Management (NPM) theory became increasingly influential in Dutch governance. This school of thought mainly sought to structure government more efficiently, resembling the image of the private sector. Following the 2008 financial crisis, a drive for austerity led to a hiring freeze in the civil service, with few new employees hired [Gov_1].

The consultancy sector has increasingly taken a larger role for government in recent decades (Goldenberg & Saris, 2023). Between 2012 and 2022, Dutch ministry spending on external personnel almost tripled from 900 million to 2,7 billion, with EZK topping the list with a 32,1% share of external hire in expenditure on personnel in 2022 (Frijters & Hoogenraad, 2023). While respondents emphasize the competence of civil service personnel, multiple respondents do stress the high turnover and the number of new personnel in the public sector, with the accompanying practical and institutional inexperience that may complicate effective policymaking [Gov_1, Pri_1, Pri_3, Prod_1, Jor_1, Branch_3]. In the parliamentary inquiry into the Groningen earthquake crisis, one of the responsible ex-ministers, Henk Kamp, signaled the lack of in-house knowledge at EZK for effective decision-making (Start & Ekker, 2022; van den Berg, 2022). Therefore, a drive for optimization and cost reduction might have caused erosion in the institutional capacity of the ministries. This may translate into a sub-optimal execution of state goals and increased reliance on external actors for both information and implementation for the phasing out of gas and scaling up hydrogen production and use. However, these results remain speculative and would require specific further research on Dutch state capacity.

Institutional environment and affordance structures

The institutional environment can be examined through state structural approaches determining the affordance structures for actors to influence political and policy-related outcomes.

Regarding static landscape characteristics (SLCs), Brisbois (2020) identified the Netherlands as having a consensus-oriented approach to policymaking with extensive inclusion of actors external to the government. This resonates with the common perception of Dutch politics as characterized by consociationalism and ‘polder politics,’ meaning deliberative private sector and civil society involvement rather than a top-down political infrastructure (Bogaards, 2021). However, several studies find this consensus structure to be strongly centralized, with limited access to the policy process and strongly dominated by incumbent energy industry actors creating advantages in terms of lobbying efforts and political access (Ahmadov & van der Borg, 2019; Kern & Smith, 2008; Kooij et al., 2018; Oteman et al., 2017).

Concretely, the Groningen earthquake scandals lay bare the vital role of pro-NG interests have had on Dutch energy policy as a consequence of formal and informal governing processes (Kern & Smith, 2008). As discussed in previous sections, the NG production in Groningen was significantly reduced due to the 2012 earthquake. Yet, controversially, 2013 saw production at its highest level ever. The 2022 parliamentary inquiry into decades of NG production management concluded that revenue concerns had dominated the decision-making process and that energy security-related arguments were used as a smokescreen (Tweede Kamer, 2023). The inquiry concludes that the parties in the Gas Building and the Dutch state had allowed themselves to be led by financial interests, with significant formal and informal lobbying for gas production by the Gas Building parties. This is reflected by Bosman et al. (2014) and Oteman et al. (2014), who note the historically strong influence of Shell, Exxon, Gasunie, and Gasterra on energy policy. Notably, the inquiry highlights the strong links between civil servants and the Gasebouw participants, noting the role of the bureaucracy in not informing the minister responsible, leading to a policy being dictated by the bureaucracy and vested interests.

For hydrogen policy, a similarly strong presence NG regime actors can be observed in policy networks. This supports the assertion by Szabo (2021) that incumbent actors seek to capture the hydrogen niche (Branch_1, Branch_2, Branch_3 Gov_1). In 2020, EZK started the cross-sectoral workgroup for hydrogen (CSWW), which would lay the foundation of the National Hydrogen Program (NWP), serving as the leading platform for public-private sector deliberation (CSWW, 2021). Table 5 shows that within the CSWW, industry firms and lobby organizations are well represented. For instance, most NG production firms, such as Shell, are present. Likewise, utilities and industrial users are well represented, in particular via lobby organizations for energy producers (E-NL), the energy-intensive industry (VEMW), and the chemical industry (VNCI). NGO Natuur & Milieu (N&M) is the only true civil society actor.

Node	Sector	Node	Sector	Node	Sector
EN-NL	Lobby	H2P	Partnership	AirLiquide	Gas
VEMW	Lobby	IPO	Lobby	FME	Lobby
VNCI	Lobby	N&M	NGO	PoR (Port of Rotterdam)	Corporation
NVDE	Lobby	Shell	Fossil	RAI	Lobby
GasUnie	Grid Network (partially state owned)	Equinor	Fossil	VNG	Local government
TenneT	Grid Network	UniPer	Energy	Shell-En	Fossil
TNO	Research	Vattenfall	Energy	RWE	Energy
ECCM	Advisory	GasTerra	Gas	WinGas	Fossil
Shell-Chem	Chemical	Linde Gas	Gas	Tata	Steel
AirProducts	Gas	Messer	Gas	TOTAL	Fossil
Westfalen Group	Gas	WRT	Fossil	SABIC	Fossil

Table 5: Actors in the Cross-Sectorale Werkgroep Waterstof.
Source: Reyes Ricardo (2021).

Such close-knit policy networks have significant potential for influence, which according to one respondent is primarily a function of the effort put in by the actors [Gov_1]. This tends to translate into increased influence for incumbent actors, which have more resources and manhours available (Downie, 2017; Geels, 2014). This is reflected by the ‘Roadmap Hydrogen,’ which functions as a non-binding joint letter of intent between the government and the private sector on the future of hydrogen. Production firms actively wrote parts of the document, with the government meaning for the plan to reflect private sector interests and vision, showcasing the level of cooperation [Gov_1]. Where such co-writing is not apparent, access and exposure can already be effective. For instance, Sühlsen and Hisschemöller (2014, p. 6) argue that frequent regular and personal contact “is the single most important element of an effective lobby.”

Besides these institutionalized technocratic policy networks, direct lobbying of politicians is equally possible. Sühlsen and Hisschemöller (2014) argue that accessing top-level politicians is more effective than contacting civil servants. One illustrative case stands out. Through an open government information request, Dutch investigative journalists found that in the summer of 2022, Shell is supposed to have contacted Prime Minister Mark Rutte as they were at risk of missing out on a 150 million IPCEI subsidy for hydrogen production on EC technicalities (Schohaus et al., 2023). In response, Rutte’s ministry

contacted the responsible civil servants at EZK to inquire about the specific project and subsidy. While this process was entirely lawful, the incumbent access to the very top of the political pyramid receiving an immediate reaction within the bureaucracy illustrates that the legacy of NG does create a potential for influence on current policy formulation.

4.4. Actor analysis: political interests

The main actors seeking to influence decisions surrounding NG and hydrogen in the Netherlands are politicians, state and local level state actors, SOEs, private sector actors, and NGOs.

The current **ruling coalition** (VVD, CDA, CU, D66) firmly favors hydrogen development. The parliament broadly supported a motion in December 2022 to increase the domestic electrolyser production goal from 4GW to 8GW in 2030, showing how hydrogen does enjoy political support (Jetten & Adriaanse, 2023). This picture is more complicated for blue hydrogen, as CCS is often unpopular in the Netherlands [NGO_1, Branch_3, Prod_1, Jor_1]. CCS had significant opposition amongst progressive parties in the past (Akerboom et al., 2021).

EZK strongly supports hydrogen in the Netherlands, particularly renewable hydrogen. Blue hydrogen requires less support than renewable hydrogen as the ETS is making it commercially viable (Akerboom et al., 2021). Still, the technologically neutral and large SDE++ subsidy scheme does support CCS projects for existing SMR installations. For new ATR installations, no subsidies are available, as it does not involve direct CO₂ abatement. Meanwhile, EZK supports renewable hydrogen across the value chain (Jetten and Adriaanse, 2023). Still, EZK regularly pushes back against ‘the hype’ around hydrogen [Gov_1, Branch_2]. For instance, minister Jetten is cautious about the parliamentary request for increasing the electrolyser capacity goal in 2032 to 8GW, signaling that it could lead to shortages of available renewable electricity for direct electrification (Jetten & Adriaanse, 2023). Similarly, EZK pushed for a lower target for the industry of 35-40% in the REDIII compared to the proposed 50% by the EC [Gov_1].

However, it is important to stress that bureaucracies do not constitute unitary actors. As Trencher et al. (2020) argued, bureaucracies are often divided into ‘tribes,’ with different departments advocating different technological solutions for the energy supply. This involves significant internal debate and competition over resources. For example, the planned 21GW offshore wind in the Netherlands is the primary source of decarbonized energy, which means that the EZK policy of ‘direct electrification first’ results in competition from other groups in the bureaucracy for the scarce renewable energy supply [Gov_1].

The **Ministry of Infrastructure and Water Management (I&W)** favors the adoption of hydrogen to boost the transition in the mobility sector [Gov_1]. Like EZK, it is bound by the REDIII and the associated goals for RFNBO uptake in the mobility sector, as well as the ReFuelEU admixture target for Sustainable Aviation Fuels (SAF) of 6% in 2030 (Caroll, 2023).

Regional governments, particularly the provinces of Groningen and Zuid-Holland, actively promote hydrogen, seeing it as a way to decarbonize while also attracting business and employment opportunities [PGov_1].

The energy producers, including **utilities** and **NG producers**, have a strong interest in pushing the development of hydrogen through government policy, both on the supply and demand side. As discussed in the material analysis, this can be achieved through individual lobbying or lobby organizations. In particular, this group has a stake in production subsidies and high targets for hydrogen demand, which secures their offtake potential [Branch_2, Pri_1, Pri_3].

The chemical and high-temperature industry is supportive of blue and renewable hydrogen policies, as they are potential decarbonization options to avoid future ETS costs and retain their license to operate [Branch_1, Branch_2, Branch_3, NGO_1, Pri_1, Pri_2]. However, short-term policies that mandate renewable hydrogen use, such as the ‘consumption obligation’ mentioned in the last letter to parliament, are against their interest (Jetten & Adriaansens, 2023). The reason behind this is that the study by Leguijt et al. (2022) mentioned earlier in this paper, which was commissioned by the chemical lobby organization VNCI, signaled the potential damage to the competitiveness of specific Dutch industries like methanol and fertilizers. A hint that this skepticism is not abated is that industrial parties are currently funding a research paper specifically on this ‘consumption obligation,’ which runs parallel to an EZK-commissioned study on the effectiveness of these instruments.⁴

⁴The EZK study is discussed by (Jetten & Adriaanse, 2023). The industry study is based on knowledge gained through personal contact with the authors of the study.

The Ports play a prominent role in organizing common interests in industrial clusters, allowing production companies, industrial firms, and other firms in the large clusters to work together in influencing policy [Port_1, Branch_2, Prod_2].

SOEs like TSOs **Gasunie** and **TenneT** have a strong hand in government policy as their SOE status and their expertise regarding the energy system makes policymakers reliant on their knowledge and opinion [TSO_1, TSO_2, Branch_2, NGO_1]. **EBN** has a supportive position regarding blue hydrogen, seeing a possible role for itself in its facilitation, particularly for CCS [Jor_1, NGO_1, Prod_1, SOE_1]. Meanwhile, **GasTerra** has played a substantial role in promoting natural gas interests, with Oxenaar (2017, p. 68) concluding that “although partly government-owned itself, GasTerra is thus actively lobbying the government, also at the EU level, and acting as an industry partner.” Yet, as it has no apparent role for hydrogen, unsurprisingly this research finds no hints of GasTerra trying to influence hydrogen policy. Still, this research concurs with earlier conclusions by Oxenaar (2017) that SOEs can play a role in tying the state to NG interests. Yet, the decline of government dependence on revenues from NG production suggests these ties could weaken in the future.

Meanwhile, **DSOs** are speculated to have a relatively large hand in pushing for experiments for hydrogen in residential heating [NGO_1]. This seems unsurprising, as it is reconcilable with the economic interest of the actor group. However, firm evidence for policy influencing is lacking.

For civil society, it seems that in contrast to many other decentralized renewable energy projects, few ‘Not in My Backyard’ (**NIMBY**) dynamics are present [NGO_1, PGov_1]. This can be mainly attributable to future offshore wind parks being planned far from the coastline, as electrolyzers are mainly planned on current industrial sites. Therefore, local community actors are not as impacted, and as one respondent put it: “seagulls don’t vote” [Prod_2]. This might change in the future, as spatial implications for hydrogen production, storage, and infrastructure could take a more significant role. Some environmental **NGOs**, like Milieudefensie, oppose plans for blue hydrogen, fearing a lock-in from CCS [NGO_1, Prod_1]. Yet, this opposition seems minor, likely because the government’s main public efforts are concentrated on renewable hydrogen.

4.5 Socio-technical perspective: material analysis

In the Netherlands, the energy system is still dominated by a socio-technical regime based on fossil fuels, of which the NG regime is a part. Grey hydrogen is essentially part of the existing NG regime, while renewable hydrogen is still a technological niche in its infancy. Mirroring the assertions by Szabo (2021) and as discussed in the previous sections, the hydrogen niche seems to be dominated by incumbent firms that are part of the existing regime, which enthusiastically encourages policy support and innovation. Therefore, the typical dynamic in the socio-technical literature of the regime providing resistance towards introducing new technology seems to not be at play regarding the hydrogen niche (Geels, 2014).

4.6 Socio-technical perspective: actor analysis

The NG regime is influential in shaping public debate through connections in different sectors (production, transport, consumption) and the sheer range of actors involved with the NG niche (e.g., TSOs, DSOs, government, producers, and industry). Moreover, these interests are well organized through branch organizations or platforms like the CSWW. This also translates into high visibility through initiatives like ‘Mission H2,’ a public relations campaign with Olympic swimming gold medalist Ranomi Kromowidjojo as its ambassador. The campaign is aimed at creating more visibility for renewable hydrogen, but is also funded by private parties like Gasunie and Shell.

Yet, while the policy process is characterized by a high degree of access for incumbents, public discourse seems to be increasingly influenced by environmental concerns and NGOs, although these often cooperate with incumbents [Jor_1, Gov_1, Pri_3]. The debate around blue hydrogen can illustrate this. Many respondents signal that blue hydrogen was initially popular and meant to kick-start the hydrogen transition, with a significant share for CCS the national reduction plans formalized in the 2019 climate accord [NGO_1, Gov_1, Branch_1, Jor_1]. However, since then, the discourse surrounding blue hydrogen seemed to have been shelved in favor of the ‘hype’ around renewable hydrogen [Prod_1, NGO_1, Branch_3]. For instance, the ‘hydrogen pact’ presented by a broad coalition of NGOs and industry in 2021 to the current political coalition did not mention blue hydrogen (Veeger, 2021). Meanwhile, ‘new’ SMRs or ATRs seemingly disappeared from the discourse [Gov_1, Prod_1, NGO_1]. According to one respondent, this is because many incumbent industries considered the benefits of being on the podium with Greenpeace

as outweighing a public role for blue hydrogen [Jor_1]. This would be because they figured that blue hydrogen would come to fruition anyway, as efforts for CCS like the Porthos and Aramis are well underway. In essence, industries “have one project for the crowd, and another behind the scenes in the lobby circuit where they think they can fix it” [Jor_1]. The respondent does emphasize that the effectiveness of this tactic is on its way back: “I talk to a lot of public affairs people from large firms who are sitting with their hands in their hair, and that what used to work does not work anymore, largely due to the success of the environmental movement” [Jor_1]. Notably, some actors say that an inevitable role for blue hydrogen is re-emerging in discourse, with blue hydrogen being increasingly discussed as a building block for the transition in the electricity sector and hard-to-abate mobility and industry [Branch_1 Prod_1].

Meanwhile, renewable hydrogen may be used to greenwash NG infrastructure in public discourse, particularly for LNG terminals. As discussed in section 4.1, whether terminal infrastructure can be repurposed to liquefied hydrogen or ammonia is uncertain, while the to-be-expected volumes of hydrogen imports are equally uncertain (Schreiner et al., 2022). Yet, Gasunie publicly claims that the new LNG import terminal in the Eemshaven will be used “First for LNG, later for green hydrogen” (Gasunie, 2022). As the validity of such claims is questionable, it is arguable that hydrogen is used to legitimize LNG infrastructure, contributing to a possible NG lock-in.

The role of public opinion could change in the future, with one possible area for public attention being the safety issues surrounding ammonia imports [NGO_1, AC_2, Branch_3]. A recent news article picked up on warning signals from local safety authorities in the Rotterdam area, who signaled that safety limits could be significantly breached if ammonia imports spike (van Bokkum, 2023). While not yet sparking major controversy, 2023 news coverage about the current transport of other dangerous chemicals already speaks of “thousands of poison train carriages a year through residential areas” (NOS, 2023a). With a 2023 letter to parliament about ammonia imports possibly constituting ten thousand to hundreds of thousands of carriages a year, safety issues could attract significant public attention (Vijen & Jetten, 2023).

Still, competition within public discourse seemingly does not (yet) play a substantial role in the debate surrounding hydrogen. For many people working with hydrogen, their private life interlocutor’s first association with hydrogen that comes to mind is still the Hindenburg disaster and the notion of explosiveness [Branch_3, Gov_1, NGO_1]. In one instance, pressure from civil actors in the hydrogen sector can be identified. This is the FNV labor union putting significant pressure on the most prominent Dutch industrial firm, Tata Steel, to shelve its CCS plans in favor of reducing CO₂ emissions by producing steel with hydrogen via Direct Reduced Iron (DRI) (Ottens, 2022).

A last noteworthy observation is that hydrogen in the built environment could be associated with some behavioral lock-in, with some local governments and residents enthusiastic about using hydrogen for heating due to the lack of technical and behavioral change required [DSO_1]. Still, as hydrogen used for heating seems to have limited short-term application in the Netherlands, this does not seem an influential factor.

5. Discussion

This section will discuss the results from the previous section. Sections 5.1 and 5.2 will deduce causal mechanisms and link these to the two research questions posed in the introduction. Section 5.3 will place these findings in the broader literature, and juxtapose them in relation to previous research on NG lock-in and its interaction with the synthetic gas niche. Section 5.4 will discuss the limitations of the research.

5.1 Mechanisms concerning the legacy of NG on hydrogen production and use

In the introduction, this research posed the question: how do actors' perceptions and the interaction with material conditionalities regarding existing NG production and consumption influence the production and use of hydrogen? Based on the case study of the Netherlands, various mechanisms are deduced:

First, the availability of existing NG infrastructure facilitates hydrogen up-scaling due to lower costs for constructing hydrogen transport and distribution infrastructure (Techno-economic). Due to the historically vital role of NG use in the Netherlands, a sizeable infrastructural network has been constructed for NG. The initiation of the Gas Roundabout policy further expanded this. Previous academic research on NG lock-in questioned this assumption of convertibility of infrastructure (Szabo, 2021). In particular, terming NG infrastructure as 'hydrogen ready' was characterized by Brauers (2022, p. 13) as a "vague term" which would result in "mostly creating a further lock-in but no systemic changes." More recent evidence from the Netherlands suggests otherwise, at least for the national transport network. The existing network lowers cost due to convertibility and seemingly provides no lock-in effects due to the availability of parallel pipelines.

Second, existing NG-based hydrogen consumers provide a potential early offtake market for renewable hydrogen (Techno-economic). One significant issue concerning the use of hydrogen is a classic 'chicken-egg' problem for technological development, with a need for a simultaneous up-scaling of demand and supply of renewable hydrogen. The Netherlands has a proportionally sizeable hydrogen-consuming industry, primarily developed due to Dutch historically low-gas prices (Oxenaar, 2017). The presence of existing consumers provides an opportunity, as through regulation or subsidies, they can be pushed to offtake renewable hydrogen if the essential supply and infrastructure are present. While this does not lead to a net increase in the potential usage of hydrogen, it can help the renewable hydrogen niche to develop in the early years of upscaling.

Third, an institutional environment that empowers incumbent actors can strengthen fossil interests (Political). In the Netherlands, the ties between bureaucracy and politicians with the existing energy producers through a consultative but centralized policy process can lead to the prominence of vested interests. Connections arise between policymakers and vested interests due to institutional feedback. This is created when dominant private actors change institutional rules and policies to entrench themselves further and grant themselves more resources. This dynamic could be exacerbated when state capacity is insufficient, as this makes the state potentially vulnerable to reliance on the expertise of external actors. In the Netherlands, further research on this is necessary due to the possibly strong reliance of the bureaucracy on external resources and knowledge. Interestingly, the Dutch policy processes might be opening up, as discussed in section 4.6, which would mean policy is becoming less dependent on closed policy deliberations. This supports the idea suggested by Seto et al. (2016, p. 435) that "intentional efforts or propitious circumstances can create conditions of institutional plasticity," with concerted efforts forcing change in the institutional environment.

Fourth, due to the synergy between the hydrogen niche and the NG regime, regime resistance is partly replaced by a supportive drive from an incumbent coalition (Socio-technical). This contrasts the typical dynamic in socio-technical systems of prominent incumbent actors resisting technological change advocated by new entrants to the market. Instead, the production and consumption of hydrogen are driven primarily by incumbent actors. The fact that incumbent firms dominate this transition is partly due to the sheer size of necessary investments for offshore wind and electrolyzers, which carry financial risks that smaller firms cannot easily meet. Therefore, the results from the Netherlands contrast with Szabo's (2021, p. 104) results, who argued that the NG industry was set on perpetuating only blue hydrogen, arguing that "renewables and green hydrogen producers are both fairly small and convey fragmented interests." One explanation for the divergence in results could be that Szabo's research focuses on the EU as a whole. More likely, however, is that developments in the energy transition have caught up with the results, as respondents

have argued that while blue was popular in the past, attention has been increasingly focused on renewable hydrogen in recent years [Gov_1, Prod_2, Jor_1].

Fourth, the prominent role of SOEs in the NG sector can amplify the influence of NG interest when these actors internalize these interests (Political). Arguably, actors like Gasunie and EBN have a claim on an individual level in perpetuating their current mode of operation. One can argue that SOEs are, in a sense, without their own interests, as the state owns them and does not depend on profits (DSO_1). Yet, this seems to not comply with earlier literature. For instance, research on the phase-out of coal in Poland notes the strong lobby by SOEs in the coal sector, which focuses on self-preservation in the face of phase-out (Brauers & Oei, 2020; Szabo & Fabok, 2020; Żuk & Szulecki, 2020). With Oxenaar (2017) and Ahmadov and van der Borg (2019) noting the intense lobbying of SOEs in the Netherlands, it is reasonable to assume a certain degree of self-preservation in their behavior.

The influence of incumbents is thus amplified because SOEs like TSOs, DSOs, and Ports also subscribe to the notion of hydrogen development, meaning a strong **incumbent coalition** appears in the Netherlands. Considering the compatibility of the hydrogen niche with the NG regime, SOEs empowered by their role in the NG regime are likely to positively influence the developing hydrogen niche. This is perhaps most well illustrated by the 'Missie H2' initiative mentioned in section 4.6, which exemplifies the bundling of efforts by SOEs and firms along the renewable hydrogen value chain. This might lead to a push for higher targets for electrolysis capacity and offtake obligations, as well as a push for higher subsidy grants. This mirrors Smink et al.'s (2015, p. 39) findings, which show that in the Netherlands, "incumbents' institutional entrepreneurship activities to promote biomethane correspond with more substantial institutional change than new entrants' activities." Thus, while incumbents may resist transitions, once they are also onboard, they can be far more effective compared to new entrants in changing policy and regulations to support niche technologies.

5.2 The effect of hydrogen production and use on NG lock-in

As its second research question, this research posed the question: how do actors' perceptions and the interaction with material conditionalities regarding existing NG production and consumption influence the production and use of hydrogen? Based on the results, various mechanisms were deduced.

First, blue hydrogen can prolong NG use, as investments can either extend the lifetime of existing installations or create sunk costs for new installations (Techno-economic: Infrastructural lock-in). This mechanism might seem the most apparent lock-in mechanism, as Seto et al. (2016) describe how new investments can create lock-in effects via carbon-emitting assets. Whether there is a need to break this lock-in depends on assessing the long-term desirability of blue hydrogen, which falls outside the scope of this research. It is interesting to note that some behavioral lock-in might be created, as CCS allows existing modes of production to continue with lower CO₂ cost, extending the license to operate via public discourse effects. However, this is not a value judgment as the CO₂ reduction effects can contribute to fighting climate change, if these reduction effects are real. Hence, lock-in dynamics are not by definition negative. This shows the necessity of a nuanced approach regarding the role of fossil fuels until 2050.

Meanwhile, the question of how to break such a lock-in will likely be answered by government intervention, such as through a moratorium on CCS. This intervention is already present to an extent, as CCS short of 100% capture rates will be phased out by the ETS forbidding scope 1 and 2 emissions by 2040 (Rooijers et al., 2022). Therefore, the ETS partly creates a natural end date for some of these assets and thus for the lock-in [Gri_2]. Yet, if installations with a near 100% capture rate can be achieved, or if a small fraction of ETS rights is preserved, these installations could continue. Hence, an ETS revision or an EU or national directive is required for a complete phase-out. Whether this is desirable is debatable, as there is also potential to replace natural gas with biogas at some point, which would turn the installation into Bio-Energy with Carbon Capture and Storage (BECCS). Irrespective of these possibilities, out of the respondents, many see blue hydrogen as a temporary bridge option, with none noting it as a long-term solution [Branch_1, Branch_2, Gov_1, Gri_2, NGO_1, Pri_1, Pri_2, Pri_3].

Second, ambitious renewable hydrogen development can slow down the short-term phase-out of NG via an opportunity cost effect (Techno-economic). As argued in section 4.1.3, increased demand for electricity can cause a suboptimal allocation of renewable electricity if the short-term phase-out of NG and CO₂ reduction are prioritized. This dynamic can be ameliorated if true 'additionality' of renewable energy sources is ensured when these sources are only realizable via simultaneous development of electrolyser capacity.

Yet, while this may prolong NG use, there does not seem to be a precise ‘lock-in’ mechanism at hand to attribute to this effect. Instead, one could see it as an inefficiency in the broader energy transition regarding decarbonization. Given the extended time horizons associated with creating a mature market for new technological applications, short-term suboptimal solutions might be necessary to enable the future decarbonization of hard-to-abate sectors. Still, while renewable hydrogen production might lead to higher NG consumption in the short-term, long-term effects might differ. Initial investments in electrolyser capacity in the Netherlands may contribute to a decreased learning curve for the technology, higher efficiency, and a better base for the expansion of electrolyser capacity when renewable electricity becomes abundant [AC_1]. In the long-term, this could create the potential for decreasing the cost of the decarbonization of hard-to-abate sectors and allow this to be implemented faster [Pri_3].

Moreover, one can argue that rich countries like the Netherlands can play an important role in investing money into niche technologies to create long-term benefits for the worldwide energy transition. For example, the positive externalities of the Japanese (1990s) and German (2010s) expensive policies for creating demand for solar panels come to mind, which laid the foundation for the rise of solar panel production (Yu et al., 2016). Therefore, the question is whether the long-term need for up-scaling niche technologies outweighs short-term adverse effects.

Third, the creation of ‘hydrogen ready’ infrastructure could prolong the use of NG through public legitimizing its use (Socio-technical: Discursive lock-in). As discussed in section 4.1.3, there is a possibility that hydrogen is misappropriated to legitimize NG infrastructure, creating infrastructural lock-in. However, no such effects seemed apparent for national transportation in the Netherlands. This appears to depend on the opportunity of parallel running NG infrastructure that can be repurposed without extending the lifetime of NG pipelines. Nevertheless, such an effect seems possible for LNG terminals as the Dutch LNG terminal in the Eemshaven is claimed to be ‘hydrogen ready.’ This is also identified by Brauers et al. (2021), meaning it requires exploration in other contexts. This mechanism clearly demonstrates how lock-in mechanisms must be explored across realms. On the one hand, techno-economic dynamics are at play, with LNG terminals possibly creating sunk costs due to an inability for technical repurposing. At the same time, through public discourse, hydrogen can be used in the socio-technical realm to solidify the position of LNG terminals in the NG regime.

One other possible mechanism that should be further explored is the possibility of behavioral lock-in being created in heating if hydrogen is seriously considered as a replacement for NG in the long-term. This may delay the phasing-out of NG boilers if hydrogen is claimed to become widely available in the future. However, as discussed, in the Netherlands, hydrogen in heating seems essentially not cost-effective nor widely supported, which makes this risk small.

Regarding state goals, no clear mechanism can be deduced. While there could be possibilities to achieve sustainability, for energy security and affordability, there are no clear lock-in mechanisms or positive effects identified for NG lock-in.

Lastly, while this research looked primarily at causes of lock-in, it is important to repeat that hydrogen can also be used to phase out NG in hard-to-abate industries and adjustable power once renewable energy becomes widely available (Techno-economic).

5.3 Synergizing findings with the literature

The paper contributes to the literature on socio-technical transitions, specifically pertaining to the work on regime resistance pioneered by Geels (2014). Sections 5.1 and 5.2 identify mechanisms that support this contribution. Similar to the findings of Smink et al. (2015) regarding biogas, the compatibility of a niche technology with the existing regime in the energy transition upsets the dominant dynamic of the regime resisting new modes of energy production and use. Rather than opposing change, the adoption of the hydrogen regime by the NG regime serves as a catalyst for the integration of hydrogen in the energy transition. This aligns with the arguments put forward by Brauers et al. (2021) and Szabo (2021, p. 104), who argue that synergy exists between hydrogen and NG, as hydrogen essentially offers “the convenient solution of substituting a gas for another.”

However, contrary to Szabo’s conclusion, this research does not find evidence that the NG regime favors blue hydrogen over renewable hydrogen, finding the existing regime strongly supports the renewable hydrogen niche. Rather than being a zero-sum game, it appears that multiple technological solutions have a role to play, with renewable hydrogen being constrained less by regime resistance and more by cost developments and temporal limitations concerning the availability of renewable electricity. These findings highlight the value of the framework developed by Cherp et al. (2018), emphasizing the need for a

comprehensive approach that avoids oversimplifying energy transitions to conflicts between incumbents resisting change and new entrants seeking change.

5.4 Limitations

Naturally, this research is subject to certain limitations, which are described in the following paragraphs.

Firstly, it is important to acknowledge the dynamic nature of the research context. The analysis only provides snapshots of a rapidly evolving context, wherein positions and influence can swiftly change due to internal and external events. The evolving nature of the context may impact the validity and relevance of the findings over time.

Secondly, the lack of rigid structure in the interview process creates a variable questioning bias and hinders replicability, as there is no strict consistency maintained between interviews as in a survey. The absence of a standardized questionnaire and rigid questioning framework may lead to variations in the depth and focus of the interviews. However, this approach is justified given the exploratory nature of the research, which necessitates flexibility and the ability to explore further specific dynamics brought on by the respondents. Many questions would not be generalizable due to the diverse sectors and positions of the respondents. Moreover, rigidity would not be desirable, as leveraging the respondent's specific expertise allows for a deeper exploration of otherwise overlooked mechanisms. Nevertheless, this approach carries the risk that the researcher may ask questions and interpret data in a manner that supports their own ideas.

Thirdly, respondents may change positions, and responses ultimately reflect personal views that may differ from those held by others in their organization. Additionally, the subjective nature of self-reported data obtained through interviews raises concerns about social desirability bias and recall bias. Respondents may provide answers they perceive as favorable or aligned with the researcher's expectations, leading to an over- or underrepresentation of certain perceptions and arguments.

Fourthly, since this study follows an exploratory approach, the findings may not be externally valid and travel to other cases, especially considering the absence of a comparative research design. Nonetheless, these results will open up new avenues for research, enabling the testing of generated hypotheses in similar cases.

Fifthly, the research does not sufficiently consider variables related to *innovation systems* and *technological diffusion*, which implies the need for further research on these factors, particularly regarding lock-in.

Lastly, there is a potential bias on the part of the researcher, as they have become employed at the Dutch Ministry of Economic Affairs and Climate, working on hydrogen policy. Consequently, there is an inherent risk that the research may be influenced by the researcher's working environment, which could impact the interpretation of results. To mitigate bias, the findings are triangulated to the greatest extent possible, drawing upon academic and grey literature employed where possible to reinforce the interpretation of perceptions and phenomena.

These limitations should be considered when interpreting the results and conclusions of the research. In future studies, these limitations should be addressed, preferably through mixed-method approaches. In conclusion, recommendations for further avenues of research are made.

6. Conclusion

This research explored the interaction effects between NG lock-in and hydrogen, utilizing the Netherlands as a case study. Taking an explorative case study approach, it sought to discover causal mechanisms for further empirical investigation, guided by two research questions. To this end, it utilized the frameworks for integrating political, socio-technical, and techno-economic perspectives by Cherp et al. (2018) and the conceptualization of types of lock-in by Seto et al. (2016) while taking lessons from the approach by Brauers et al. (2021) and Brauers (2022) in integrating these two different frameworks.

First, it explored the legacy of NG, finding five significant mechanisms by which existing NG production and consumption influence the production and use of hydrogen in the Netherlands:

- 1) the widespread availability of NG infrastructure, which facilitates the hydrogen niche;
- 2) the historical abundance of NG that has created an economic structure that facilitates the hydrogen niche;
- 3) an institutional environment that empowers incumbent NG actors allows them to influence hydrogen policy excessively;
- 4) the strong synergy between the robust NG regime and the hydrogen niche largely avoids regime resistance to the hydrogen niche;
- 5) the strong integration of state-owned enterprises in the NG sector enhances incumbent support and influence on the hydrogen niche.

Second, it explored the effect of further production and use of hydrogen could lead to NG lock-in, with two concrete mechanisms that this research deems worthy of further investigation:

- 1) for blue hydrogen, a possible lock-in effect is found in the form of infrastructural lock-in when the addition of CCS can either prolong the lifetime of existing NG-based installations or create sunk costs when new facilities are built.
- 2) a discursive lock-in could be possible for legitimizing existing or new NG infrastructure. This could be a risk for building new LNG terminals and, to a lesser extent residential heating.

Additionally, the research finds a particularly interesting dynamic for renewable hydrogen, although it does not seem to constitute an actual lock-in mechanism. For renewable hydrogen to be a genuinely effective way to decarbonize, true additionality of renewable electricity needs to be ensured and other options for direct electrification would need to be exhausted. This mechanism requires further investigation, as the worldwide drive for renewable hydrogen production could lead to short-term inefficiencies in tackling climate change. This would be particularly relevant to research across cases. States that still have a high emission intensity on the grid require particular attention, such as due to the use of coal, like Poland or in emerging economies. This also questions the desirability of hydrogen imports from states that have not yet decarbonized the low-hanging fruit of their own energy transitions. GHG emission reduction from countries in the Global South is particularly at risk.

Meanwhile, renewable hydrogen can also be a tool to escape NG lock-in, but this depends on the state of the energy system and the remaining opportunity cost for renewable hydrogen production. As argued, both policies aimed at creating an increased demand for hydrogen and stimulus for blue or renewable hydrogen production may adversely affect phasing-out NG and reducing GHG emissions. The inefficiencies associated with renewable hydrogen production over other technological opportunities, including direct electrification, may create CO₂ opportunity costs as renewable electricity could be more efficiently employed. For blue hydrogen, CO₂ opportunity costs only occur when the reduction of CO₂ via CCS outweighs the increased methane emissions and conversion losses as opposed to direct use of NG or direct use of NG accompanied by CCS.

Because this is a single-country case study, the external validity of the results is relatively weak, although specific results mirror earlier research, as discussed in section 5.3. Still, the mechanisms uncovered contain promising avenues for further study and are directly relevant to policymakers. Considering the lock-in dynamics, qualitative research across cases would be warranted. This would preferably be in a comparative fashion for increased external validity. This could, for instance, take the form of content

analyses in response to the role of hydrogen in potentially legitimizing NG infrastructure within public discourse. Additional research should also look at the legitimization of new NG electricity generation facilities, which could also be claimed to be ‘hydrogen ready.’

Meanwhile, advanced energy system modeling presents a valuable avenue for further research into the dynamics surrounding the opportunity cost of hydrogen use and production. Such research endeavors could aim to identify an optimal equilibrium between scaling niche technologies for long-term emission reduction and the imperative to swiftly capitalize on low-hanging fruit pertaining to GHG emissions. Consequently, the findings can inform government policy into determining the optimal allocation of subsidies and regulations.

To conclude, the research described in this paper underscores the inherent complexity of the energy transition process. Clean energy technologies, including renewable hydrogen, will increasingly assume a systemic role. However, it is important to recognize that these technologies do not offer a panacea for resolving the climate crisis. Constructing a clean energy system is a time-consuming endeavor that necessitates a long-term perspective. Therefore, contrary to the assertion made by Howarth, NG does not function as a bridge to nowhere in practical terms, as it is poised to retain a role in numerous energy systems for the foreseeable future. Rather than dismissing it as a bridge or debating its desirability, the challenge for researchers lies in discerning how to expedite the journey to the opposite side. By studying lock-in and identifying potential roadblocks, the process of navigating this path can be accelerated.

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Appendix 1: Information- and consent form.

Introductie

Mijn naam is Douwe Roest en ik ben een masterstudent aan de Erasmus Mundus master *European Politics en Society*, aangeboden door de Karelsuniversiteit in Praag, de Universiteit Leiden, de Jagiellonische Universiteit Krakau en Pompeu Fabra Barcelona. Momenteel schrijf ik een masterscriptie over de mogelijke impact van de waterstoftransitie op een zogenoemde ‘lock-in’ van de rol van aardgas binnen de Nederlandse energietransitie.

Hoewel er al veel academisch onderzoek bestaat over ‘lock-ins’ bij de uitfasering van kolen, zoals door gezonken kosten of de politieke invloed van bedrijven en vakbonden, is de uitfasering van aardgas een vrijwel onbegrepen onderwerp binnen de academische literatuur. Deze masterscriptie dient daarom twee doelen die sterk met elkaar verbonden zijn. Ten eerste onderzoekt het welke factoren mogelijk kunnen bijdragen aan het verlengen van het gebruik van aardgas. Ten tweede is het doel kennis te vergaren over de nog onbegrepen consequenties van grootschalige waterstofproductie, zowel aan de technische als de politiek-economische kant.

Voor meer informatie over dit onderzoek ben ik per e-mail te bereiken via douwe.c.roest@gmail.com en telefonisch via +31 6 31 07 03 99.

Dataverzameling

Voor mijn onderzoek verzamel ik data via officiële beleidsdocumenten, bedrijfsrapporten, krantenartikelen en via interviews met individuen (personen) die een belangrijke rol spelen in de gas- en waterstofmarkt. Tijdens de interviews worden respondenten gericht gevraagd naar zowel feitelijke analyses van de manieren waarop waterstof en aardgas direct en indirect met elkaar interageren, als naar de percepties van deze dynamiek vanuit het oogpunt van hun organisatie. De resultaten uit deze interviews worden gebruikt om mogelijke causale mechanismes te identificeren over de impact van waterstof op het gebruik van aardgas binnen de Nederlandse energiecontext.

Interviews worden opgenomen zodat deze hierna getranscribeerd kunnen worden. Wanneer deze transcripties af zijn, worden audio opnames van het interview verwijderd. Citaten uit de interviews worden mogelijk gebruikt in de scriptie, maar deze zullen niet direct aan uw naam verbonden worden. Bijdrages worden geanonimiseerd: bijvoorbeeld “een beleidsmedewerker van het Ministerie van Economische Zaken” of “een adviseur duurzame energie bij een grote energieproducent”.

Potentiële ongemakken en risico’s

Er zijn geen fysieke, rechtelijke of economische risico’s verbonden aan uw deelname in dit onderzoek. U bent niet verplicht om alle vragen te beantwoorden. Uw deelname is vrijwillig en kan op ieder moment beëindigd worden.

Vergoeding

Er is geen vergoeding verbonden aan deelname aan dit onderzoek.

Vertrouwelijkheid en databescherming

De verzamelde data zullen alleen worden gebruikt voor een geaggregeerde data-analyse en vertrouwelijke informatie of persoonlijke gegevens zullen niet worden gebruikt in de uitkomsten van het onderzoek.

Het delen van data

Ik deel de data met mijn scriptiebegeleider Dr. Eliška Ulřichov en mogelijk andere examinatoren met als het reden het onderzoeken en schrijven van mijn masterscriptie, verplicht voor het voltooien van mijn studie, de ‘Vaclav Havel Joint Masters Degree: European Politics and Society’, geregistreerd aan de faculteit Sociale Wetenschappen van de Karelsuniversiteit Praag.

Vrijwillige deelname en individuele rechten

Uw deelname is vrijwillig en het is mogelijk om op ieder moment te stoppen. Tijdens uw deelname aan het onderzoek heeft u het recht om meer informatie over de dataverzameling en -analyse te vragen. Daarnaast heeft u het recht om uw toestemming in te trekken en te vragen naar verwijdering van uw data voordat de dataset is geanonimiseerd of het manuscript is ingeleverd om gepubliceerd te worden. U kunt dit bewerkstelligen door contact op te nemen met Douwe Roest.

Indien u klachten heeft aangaande het verwerken van persoonlijke gegevens in dit onderzoek, neem dan gerust contact op met Douwe Roest.

Toestemming

Door het tekenen van dit toestemmingsformulier bevestig ik dat:

- Ik geïnformeerd ben over het doel van het onderzoek, de dataverzameling en het opslaan van data zoals beschreven in het informatieformulier;
- Ik het informatieformulier heb gelezen;
- Ik toestemming geef tot deelname aan dit onderzoek;
- Ik begrijp dat er vertrouwelijk wordt omgegaan met de informatie;
- Ik begrijp dat ik de deelname op ieder moment kan beindigen of het beantwoorden van vragen kan weigeren zonder enige consequenties;
- Ik begrijp dat ik mijn toestemming kan intrekken voor de dataset.

	Ja	Nee
Ik geef toestemming om audio van het interview op te nemen		
Ik geef toestemming om citaten van mijn interview te gebruiken.		

Naam van de deelnemer aan het onderzoek: _____

Datum: _____

Handtekening onderzoeker: _____

Handtekening respondent: _____