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Emerging hydrogen future(s) - Mapping visions and expectations in national strategies

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List of Abbreviations

CCUS	Carbon Capture Utilization and Storage
CO_2	Carbon Dioxide
GHG	Greenhouse Gas
H	Hydrogen
R&D	Research and Development
SMR	Steam Methane Reforming

Abstract

In the past six years, a substantial number of new hydrogen strategies have emerged, driven by the increasing pressure to decarbonize our energy system and the expectations that hydrogen can play a pivotal role in facilitating this transition. Despite significant advancements, there remains a need for a comprehensive analysis of the main expectations and visions articulated in these contemporary strategies. Previous research primarily focused on legacy strategies, emphasizing implementation periods, target sectors, partnerships, and R&D initiatives. In this master thesis, the objective was to develop a typology of the strategies that is based on the societal hopes associated with hydrogen (so-called socio-technical metaframes), the envisioned supply structure, and preferred hydrogen sources.

To develop the typology, a qualitative content analysis was applied to 33 national strategies. For the identification of the metaframes, existing categories were taken from previous literature and refined on the basis of the inductively generated insights from the analyzed strategies. Thereby, seven metaframes were identified: (i) *Independence*, (ii) *Community Development*, (iii) *Leadership*, (iv) *Inevitability*, (v) *Economic prosperity*, (vi) *Decarbonization*, and (vii) *Sufficiency and Radical Change*. While all countries emphasized *Decarbonization* and *Economic Prosperity*, the prominence of other socio-technical metaframes varied significantly. These differences provided the basis for the subsequent typological analysis. Analyzing the prevalence of the frames and their linkages with the envisioned supply structures and production paths led to the identification of six different strategic types: (i) *Hydrogen Optimists*, (ii) *Hydrogen Economy Leaders*, (iii) *Justice Seekers*, (iv) *Opportunity Seekers*, (v) *Green Hydrogen Exporters*, and (vi) *Economic Value Creators*.

The identified typology highlights the diverse pathways and potential outcomes of hydrogen adoption, offering valuable insights into best practices and areas for improvement. Overall, the research underscores the multifaceted nature of national hydrogen strategies, emphasizing the interplay between technological aspirations and socio-political contexts. The identified socio-technical metaframes and associated typologies provide a comprehensive understanding of how countries envision their transition to a hydrogen economy, highlighting both common goals and distinctive national priorities. By illuminating these diverse strategic priorities, the study contributes to the broader discourse on global energy transitions and offers guidance for policymakers in designing effective hydrogen strategies.

Keywords: national hydrogen strategies; energy transition; socio-technical metaframes; type formation

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1 Introduction

This initial chapter introduces the master thesis, beginning with a description of the problem, the research objectives, and the research questions. It establishes the context by emphasizing the significance of the topic and the necessity of this study. Following this, an overview of the thesis structure is provided, outlining the organization of the subsequent chapters.

1.1 Problem description

The current climate predicament represents a major challenge to the stability of Earth's ecosystems, driven by human activities that have accelerated climate change (Weiskopf et al., 2020). This phenomenon has diverse and significant impacts, including unusual weather patterns, rising sea levels, and disruptions to biological systems (Bolan et al., 2024). Given these serious consequences, it is essential for the global community to implement and enforce measures to mitigate current climate predicaments (Bausch and Mehling, 2011). The Paris Agreement, in effect since 2016, stands as a key collective effort that symbolizes the global commitment to addressing climate change (Falkner, 2016). To realize the Paris Agreement's aspiration, there is a pressing need for a comprehensive transformation of the energy systems that underpin our economies (Gielen et al., 2019).

Hydrogen has emerged as a promising energy carrier to support this transition. Nations worldwide are paying increasing attention to the potential of green and blue hydrogen within the economy to reduce emissions and mitigate climate change (Lebrouhi et al., 2022). Green hydrogen offers the advantage of being an environmentally friendly fuel with no harmful emissions and exhibits higher energy efficiency compared to alternative energy sources (Reda et al., 2024). Notably, green hydrogen can decarbonize sectors that are hard-to-abate, such as heavy-duty transport, iron and steel production, and petrochemicals production, making it a versatile energy carrier (Jayachandran et al., 2024). Furthermore, green hydrogen can serve as a storage medium for surplus energy generated from renewable sources (Hassan et al., 2023). It can be transported over long distances, from regions abundant in renewable resources to those with high energy demand, positioning it as a key component in the global energy transition (Hassan et al., 2024).

In addition to these benefits, green hydrogen contributes to energy security by providing a reliable and consistent energy source. Its capacity to produce high-temperature heat for industrial processes without emissions is particularly significant, offering a pathway to reduce the carbon intensity of industrial manufacturing (Marouani et al., 2023). The strategic deployment of green hydrogen technologies also aligns with the objectives of the Paris Agreement, supporting global efforts to limit temperature rise and foster a low-carbon economy (Reigstad et al., 2022). In summary, green hydrogen is poised to play a pivotal role in the clean energy landscape, offering a multitude of environmental, economic, and social benefits that extend far beyond its role as a gas or fuel. Its integration into the energy system signifies a progressive step toward achieving a sustainable and resilient energy transition (Islam et al., 2024).

In contrast, blue hydrogen provides a transitional solution by leveraging existing natural gas infrastructure. It combines traditional hydrogen production methods, such as steam methane reforming (SMR), with carbon capture and storage (CCS) technology to reduce greenhouse gas emissions. While not entirely free from emissions, blue hydrogen can play a critical role in the short-to-medium term by bridging the gap until large-scale green hydrogen becomes economically viable. The success of blue hydrogen depends heavily on the effectiveness of CCS, which varies based on factors such as capture rates (typically ranging from 70% to 95%) and methane leakage during production. This pathway also faces challenges, including water consumption and the need for dedicated CO_2 infrastructure, which may increase costs (Noussan et al., 2020). In terms of scalability, both green and blue hydrogen offer advantages. Green hydrogen, while fully renewable, is currently limited by production costs and the availability of renewable energy (Panchenko et al., 2023). Blue hydrogen, on the other hand, is less expensive in the near term and can help scale hydrogen production, especially for countries rich in natural gas resources or export markets, such as Norway (Cheng and Lee, 2022).

However, the long-term goal remains the transition toward a fully renewable hydrogen economy, with blue hydrogen serving as an intermediary step. Both pathways highlight the need for strong government support, favorable policies, and robust infrastructure to facilitate hydrogen production, distribution, and consumption on a global scale (Lebrouhi et al., 2022). The recently published national hydrogen strategies of various countries include topics on how the government supports the transition to the hydrogen economy, how country-specific areas of interest are highlighted, provide information on regulatory barriers and market opportunities and offer a country-specific context for the transition (Somenzi et al., 2021).

As of July 1, 2023, 41 nations across the globe have released their national hydrogen strategies, including 9 countries released within the past 12 months. This widespread adoption of national hydrogen strategies underscores the global commitment and strong hopes for transitioning towards a hydrogen-based future (Cheekatamarla, 2024). By outlining clear plans and objectives, these nations are demonstrating their dedication to integrating hydrogen as a key component of their energy systems. This collective effort not only highlights the strategic importance of hydrogen in achieving climate goals but also reflects a coordinated approach to fostering technological innovation, economic growth, and energy security through the deployment of hydrogen technologies (Hassan et al., 2023).

1.2 Research objective & research question

While existing studies address technical aspects (Gerres et al., 2022; Somenzi et al., 2021; Albrecht et al., 2020), they frequently overlook the broader socio-technical narratives embedded in national hydrogen strategies. These narratives, which reflect a nation's social, ecological, and economic aspirations, remain underexplored, highlighting the need for a comprehensive examination of the socio-technical metaframes that shape hydrogen strategies globally. Socio-technical metaframes, as conceptualized in this research, correspond to institutional frames as described by Cornelissen and Werner (2014). These metaframes represent broad, overarching narratives that guide discourse across various domains, including national hydrogen policies. They encapsulate social, economic, and ecological aspirations, reflecting key societal values such as sustainability, economic growth, and energy security (Snow & Benford, 1992; Moernaut et al., 2018). In the context of hydrogen strategies, these metaframes function as stable, interpretive structures that align policy development with broader institutional norms and expectations. By doing so, they facilitate a consistent framework for understanding how nations prioritize hydrogen technologies within the global transition to cleaner energy systems.

Technological advancements in hydrogen-related fields, such as electrolysis and fuel cells, have led to significant reductions in production costs and broadened the range of potential applications (Squadrito et al., 2023; Younas et al., 2022). Furthermore, hydrogen's role in energy storage has become increasingly important, positioning it as a key component in energy security and decarbonization efforts (Hassan et al., 2023). These technological breakthroughs are well-documented, and many national strategies reflect this progress. However, existing literature, particularly studies of hydrogen strategies published before 2022, often fails to engage with the socio-technical narratives that reveal the broader aspirations driving hydrogen adoption. Since 2022, 23 additional national hydrogen strategies have been released, reflecting not only technological progress but also evolving priorities in the global clean energy transition. The strategic goals embedded in these newer strategies are shaped not only by technological readiness but also by deeper socio-economic and ecological considerations. Despite these developments, there has been little research that systematically analyzes the socio-technical metaframes embedded within these strategies. This study aims to address this gap by exploring the ways in which hydrogen strategies reflect a nation's broader aspirations and societal values, offering insights into the narratives that guide policy formulation and stakeholder engagement.

To address this gap, this research will conduct a comparative analysis of the 33 national hydrogen strategies published in English as of August 1, 2023. The focus will be on identifying the socio-technical metaframes embedded in these strategies, with the aim of uncovering the social, ecological, and economic aspirations that shape national approaches to hydrogen adoption. These metaframes will provide a foundation for cross-national comparisons, helping to identify common trends as well as country-specific priorities. By aligning socio-technical metaframes with national priorities, this study will provide a deeper understanding of how hydrogen strategies aim to contribute to long-term sustainability and resilience through the integration of social, ecological, and economic goals.

The research will be guided by the following research questions:

- *Which socio-technical metaframes are predominantly utilized in national hydrogen strategies to express social, ecological, and economic aspirations?*
- *How can national hydrogen strategies be systematically classified into distinct types based on their socio-technical metaframes, envisioned supply structure, and projected short- and medium-term hydrogen sources? What are the defining characteristics and implications of each identified type?*

By analyzing these socio-technical metaframes and associated metadata, the study seeks to offer a comprehensive understanding of the diverse social, economic, and environmental dimensions embedded within national hydrogen strategies. The study explores each nation's unique vision for a hydrogen economy, aiming to identify strategic patterns and typologies shaping the global shift toward hydrogen-based societies.

1.3 Structure of the thesis

This master thesis is structured to provide a comprehensive exploration of the socio-technical metaframes in national hydrogen strategies. It begins with an establishment of the theoretical background and an overview of the current state of research, offering a global perspective on national hydrogen strategies through the lens of socio-technical theory and the theoretical framework of socio-technical metaframes. The methodology section details the research design, data collection methods, and the qualitative content analysis process using MaxQDA. It includes a thorough description of the coding process and the steps involved in identifying socio-technical metaframes and types of hydrogen strategies. In the findings section, the thesis presents the results of the analysis, starting with an overview of the analyzed national hydrogen strategies. It then identifies the prevalent socio-technical metaframes within these strategies. Additionally, this section includes the development of a typology, presenting criteria for classification and country types based on socio-technical metaframes. The discussion section provides an in-depth interpretation of the findings, drawing insights and implications from the identified socio-technical metaframes. It also addresses the limitations of the study and discusses their impact on the interpretation of results. Finally, the conclusion section summarizes the main findings and offers recommendations for future research. By following this structured approach, the thesis offers a systematic exploration and analysis of national hydrogen strategies and socio-technical metaframes, yielding valuable insights for both theory and practice.

2 Theoretical background and current state of research

This thesis aims to delineate the broad social, economic, and environmental aspirations that countries associate with the development and implementation of hydrogen technologies. To achieve this, it begins with a brief overview of hydrogen as an energy carrier, followed by a theoretical explanation of metaframes in policy analysis. Additionally, it provides an overview of the current literature on these topics.

2.1 Theoretical foundation: hydrogen as an energy carrier

Hydrogen has attracted significant attention for its potential as a clean and versatile energy source (Hassan et al., 2024). Hydrogen (H), with the atomic number 1, is the simplest and lightest element in the universe (Cruz Gómez et al., 2021). Under standard conditions, it exists as a colorless, odorless, tasteless, and flammable gas (Najjar, 2013). The hydrogen molecule (H_2) is diatomic, meaning it consists of two hydrogen atoms. Hydrogen is notable for its reactivity and its ability to form compounds with almost all other elements. Its most significant chemical property is its ability to combine with oxygen to form water (H_2O) (Cruz Gómez et al., 2021). Hydrogen possesses the highest energy content per unit mass (120 MJ/kg) of any chemical fuel, making it an attractive option for various energy applications (Yu et al., 2020). Hydrogen has the potential to address several challenges in the climate transition. It can decarbonize hard-to-abate sectors, such as heavy-duty transport and steelmaking, which require high temperatures (Jayachandran, 2024). Additionally, hydrogen can integrate renewable energy and provide long-duration energy storage solutions to enhance power system flexibility. Furthermore, it can replace fossil fuels as a zero-carbon feedstock in chemical and fuel production (Cheng and Lee, 2022).

However, achieving a hydrogen-based economy requires careful consideration, as hydrogen's carbon emissions depend on the production method itself as well as from the feedstock or electricity supply (Albrecht et al., 2020). Hydrogen can be climate-neutral, low-carbon, or have a significant carbon footprint depending on the production process and the scope of emissions calculations. A color-coded terminology distinguishes different types of hydrogen based on their production methods. Currently, there are eight recognized types of hydrogen, as illustrated in Figure 1. Green hydrogen, produced by electrolysis using renewable energies (e.g., wind, solar, water, geothermal, or tidal), is considered climate neutral. Pink hydrogen (from nuclear energy) and yellow hydrogen (from the current grid energy mix) are also produced by electrolysis. Blue hydrogen is produced by steam methane reforming (SMR) with carbon capture utilization and storage (CCUS) (World Energy Council, 2021).

	Terminology	Technology	Feedstock/ Electricity source	GHG footprint*
PRODUCTION VIA ELECTRICITY	Green Hydrogen	Electrolysis	Wind, Solar, Hydro, Geothermal, Tidal	Minimal
	Purple/Pink Hydrogen		Nuclear	
	Yellow Hydrogen		Mixed-origin grid energy	Medium
PRODUCTION VIA FOSSIL FUELS	Blue Hydrogen	Natural gas reforming + CCUS gasification + CCUS	Natural gas, coal	Low
	Turquoise Hydrogen	Pyrolysis	Natural gas	Solid carbon (by-product)
	Grey Hydrogen	Natural gas reforming		Medium
	Brown Hydrogen	Gasification	Brown coal (lignite)	High
	Black Hydrogen		Black coal	

Figure 1: Different Types of Hydrogen and their GHG footprint (World Energy Council, 2021)

National hydrogen strategies outline the anticipated importance of various hydrogen production technologies. Green hydrogen is prominently mentioned in all national publications, although some countries prioritize blue hydrogen in the early phases of the hydrogen economy transition (Yap and McLellan, 2024). In scientific discourse, the color-coded hydrogen terminologies based on production methods are often treated as fact rather than commitment implemented through stringent regulation (Cheng and Lee, 2022). While only renewable energy-based green hydrogen is universally considered climate-neutral, blue hydrogen remains crucial for transitional pathways due to its ability to be produced in large quantities at a low cost. This is particularly relevant for countries like Norway, which plan to export substantial quantities of hydrogen (Espegren et al., 2021).

Despite its potential, hydrogen technology faces several challenges. The production, storage, transport, and utilization of hydrogen must be managed safely and efficiently. Given hydrogen's flammability, comprehensive risk assessments are necessary to address safety concerns (Calabrese et al., 2024). The high costs associated with green hydrogen production, primarily due to the expense of renewable energy and electrolysis equipment, pose significant challenges (Jovan and Dolanc, 2020). Additionally, the variable and intermittent nature of renewable resources used in hydrogen production requires technical solutions to balance energy supply and demand (Maggio et al., 2019). Hydrogen holds promise as a clean and sustainable energy source. However, realizing its full potential will require overcoming the existing technical, economic, and safety challenges (Yusaf et al., 2024).

2.2 National hydrogen strategies

To transform hydrogen from a niche technology into a widespread energy carrier, an integrated policy approach is essential to overcome initial resistance and achieve a minimum threshold for market penetration (IRENA, 2020). According to IRENA (2020), the formulation of a hydrogen strategy involves four key steps (see Figure 2). The recently published hydrogen strategies represent the beginning of a new wave of measures. The strategy process begins with establishing R&D programs to create a knowledge base. Subsequently, a vision document is created to articulate the country's rationale for adopting hydrogen. This is followed by the development of a roadmap, an integrated plan outlining the activities required to better assess hydrogen's potential. The roadmap also identifies the necessary measures to facilitate hydrogen's introduction and defines research areas and applications.

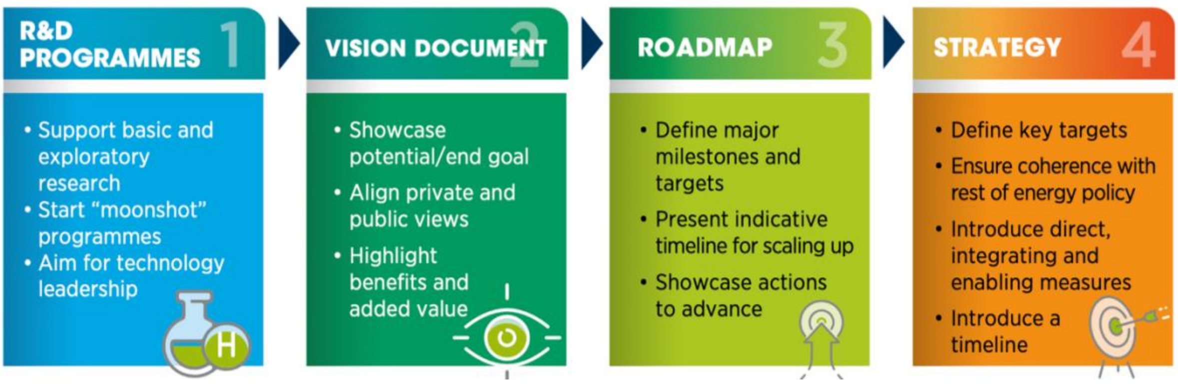

Figure 2: Steps to formulate a national hydrogen strategy (IRENA,2020)

The strategy itself then sets targets, addresses specific policy measures, and assesses the adaptability of existing energy policies. This strategy is typically based on extensive scenario modeling, often co-designed by academia and industry (IRENA, 2020). Generally, national strategies provide information on how governments plan to support the transition to a hydrogen economy. They highlight country-specific areas of interest, identify regulatory barriers and market opportunities and provide a context specific to each country's transition (Gerres et al., 2022).

2.2.1 Key components of national hydrogen strategies

In developing a comprehensive national hydrogen strategy, various critical topics must be addressed to ensure a clear and actionable plan (World Energy Council, 2021):

- Firstly, the strategy must delineate a time horizon which defines the timeframe within which the goals and objectives of the hydrogen strategy are to be achieved. Typically, this period extends to 2030, 2040, or 2050, with specific milestones for short-term, medium-term, and long-term targets. Such a roadmap facilitates gradual and systematic progress.
- Furthermore, the national strategy should specify the type of hydrogen to be prioritized, indicating the planned methods for hydrogen production. Identifying primary hydrogen sources is fundamental to aligning the strategy with national energy policies and sustainability goals.
- A clear vision and mission are also crucial components. The vision articulates the long-term aspirational role of the hydrogen economy within the country's energy landscape, while the mission details the specific objectives and actions required to achieve this vision.
- Moreover, the strategy should state its value chain focus. This outlines the segments of the hydrogen supply chain that will receive particular attention, including production, storage, transportation, distribution, and utilization. A holistic approach that considers the entire value chain ensures the development of a robust and integrated hydrogen economy.
- The supply structure of hydrogen must be detailed, explaining how the country plans to meet its hydrogen demand. This includes whether the country intends to import hydrogen, export it, or rely on domestic production to satisfy its needs. Understanding the supply structure is vital for planning the necessary infrastructure and for developing policies that ensure a stable and reliable hydrogen supply.
- Main target sectors should be identified to prioritize areas where hydrogen can have the most significant impact. These sectors often include transportation, industrial processes, power generation, and residential heating. Highlighting these sectors helps focus efforts on areas with the highest potential for decarbonization and economic benefits.
- Research and development (R&D) initiatives are critical for advancing hydrogen technologies and reducing costs. The strategy should outline key R&D priorities,

funding mechanisms, and collaboration opportunities with academic and industrial partners. Investing in R&D is essential for overcoming technical barriers and fostering innovation.

- Partnership strategies are also fundamental. Successful implementation of a hydrogen strategy requires collaboration among government entities, private companies, research institutions, and international partners. The strategy should outline potential funding sources, including public funding, private investments, and international grants.

These topics are essential for outlining the strategic framework, setting realistic goals, and identifying key areas for implementation and collaboration. Incorporating these topics into a national hydrogen strategy provides a comprehensive framework that addresses all critical aspects of hydrogen deployment. By clearly defining goals, priorities, and collaborative efforts, the strategy can effectively guide the transition toward a sustainable and resilient hydrogen economy (De-León Almaraz et al., 2023).

2.3 Socio-technical theory

The socio-technical theory encompasses the social, political, and economic factors that influence the development and implementation of a technology (Cherp et al., 2018). Socio-technical systems represent complex interactions between ecological, social, and economic systems and humans (Ahlborg et al., 2019). The impacts of these systems over their life cycles can be characterized as positive, negative, or neutral in terms of their contribution to sustainable development, depending on the design and operation of the system (De-León Almaraz et al., 2023). The socio-technical theory rests on two core principles: the success of a system is shaped by the dynamics between its social and technical components and achieving an optimal state for the overarching system requires a harmonious alignment or "goodness of fit" between these social and technical factors. This theory emphasizes that technology cannot be understood or developed in isolation from the social context within which it operates (Abbas and Michael, 2023).

2.3.1 Socio-technical measures of hydrogen

The transition to a hydrogen economy is not merely a technological shift but a complex socio-technical process. Socio-technical measures are crucial in shaping hydrogen strategies, providing a comprehensive understanding of the dynamics involved in the transition to a hydrogen economy (McDowall, 2014). Supportive policies and regulations are vital socio-technical measures that can facilitate the development and deployment of hydrogen technologies (Gordon et al., 2023). For instance, government incentives and clear regulatory frameworks can lower barriers to entry for hydrogen technologies, encouraging investment and innovation (Bleischwitz and Bader, 2010). Similarly, positive public perception and acceptance are essential for driving demand for hydrogen technologies. Public awareness campaigns and education can address safety concerns and highlight the environmental benefits of hydrogen, fostering a supportive social environment (Stalker et al., 2022).

The development of robust hydrogen infrastructure is another critical socio-technical measure. Ensuring the availability and accessibility of hydrogen through comprehensive infrastructure planning can promote its use across various sectors (Gordon et al., 2023). Additionally, the economic viability of hydrogen technologies influences their competitiveness in the energy market, affecting their adoption and use. Economic measures such as subsidies, research funding, and market incentives play a significant role in making hydrogen technologies more economically attractive (Tseng et al., 2005). In conclusion, socio-technical measures provide a comprehensive framework for understanding and addressing the challenges involved in the transition to a hydrogen economy (McDowall, 2014). These measures are instrumental in shaping effective and sustainable hydrogen strategies, ensuring that the technological transition is supported by a conducive social, political, and economic environment (Bleischwitz and Bader, 2010).

2.4 Metaframes in framing theory

In the context of framing theory, socio-technical metaframes—also referred to as master frames or overarching frames—are pivotal in shaping discourse across multiple domains. These frames provide broad, overarching narratives that influence the interpretation of social, political, or technological phenomena, grounded in underlying values, beliefs, and ideologies (Snow & Benford, 1992). Unlike issue-specific frames, socio-technical metaframes remain relatively stable across different topics, ensuring consistency in interpretation (De Vreese, 2005). As cognitive structures, they help individuals organize and understand complex information, serving as templates for interpreting various phenomena (Vollmer, 2014).

2.4.1 Socio-technical metaframes

In this research, the concept of socio-technical metaframes corresponds directly to what Cornelissen and Werner (2014) term the institutional frame. While the terminology differs, both frames function similarly in shaping organizational and policy responses to broader institutional contexts such as norms, values, and regulations. The socio-technical metaframe, like the institutional frame, provides a cognitive framework that helps align strategies and behaviors with external expectations, particularly in the context of hydrogen strategies. The institutional frame, or socio-technical metaframe in this thesis, emerges through a process of gradual evolution. It begins as localized or provisional framing within specific contexts, evolves into "field-level frames" shared among actors within a particular sector, and eventually becomes naturalized as an institutional frame or overarching metaframe that is widely accepted and taken for granted. This mirrors how socio-technical metaframes shape discourse in multiple policy areas, including hydrogen (Cornelissen and Werner, 2014).

Institutional and socio-technical metaframes alike structure expectations within broader societal contexts, enabling alignment of strategic priorities with overarching social, ecological, and economic goals. In this research, socio-technical metaframes in national hydrogen strategies mirror institutional frames, as they similarly encapsulate the normative aspirations that shape strategic decisions regarding hydrogen adoption. Moreover, institutional change is significantly influenced by both socio-technical metaframes and institutional frames. These frames not only legitimize new ideas and practices but can also reinforce existing structures, making them resistant to change. This function is crucial for understanding how socio-technical metaframes in hydrogen strategies guide policy development while simultaneously reflecting the entrenched socio-technical systems they operate (Cornelissen and Werner, 2014).

In the context of national hydrogen strategies, metaframes refer to overarching themes or frames that shape and guide the discourse, policies, and narratives surrounding hydrogen energy. When applied to national hydrogen strategies, metaframes articulate the key motivations and objectives driving a country's approach to the deployment of hydrogen as an energy carrier. They clarify the anticipated social, economic, and environmental benefits that a country aims to achieve through the transition to hydrogen. These socio-technical metaframes encapsulate the broader social, economic, and environmental aspirations, values, and priorities that countries associate with the development and implementation of hydrogen technologies. By providing a unified perspective, socio-technical metaframes allow for the comparison of different national strategies, highlighting common themes and approaches that reflect each country's priorities.

Eames et al. (2006) investigate the hydrogen economy's role as a guiding vision encompassing multiple contested technological futures, value judgments, and problem framings. The authors identify six overarching and competing narrative themes within hydrogen visions: power and independence, community empowerment and democratization, ecotopia, technical fix, inevitability and progress, and "staying in the race." These themes underscore the interpretive flexibility of the hydrogen economy, which is central to its rhetorical power. This flexibility enables the hydrogen economy to serve as a platform for promoting divergent interests and agendas. The case study of London demonstrates how the open and flexible vision of a hydrogen economy must be reimagined and anchored in local agendas and contexts to fulfill its potential. This case highlights the necessity of negotiating contested visions and managing place-specific expectations during the transition toward a hydrogen economy. The study underscores the importance of integrating diverse perspectives and aligning them with local contexts to facilitate the effective implementation of hydrogen technologies.

Similar to the report by Eames et al. (2006), a few years later Sovacool and Brossmann (2010) looked further into the topic. In their study Symbolic Convergence and the Hydrogen Economy, they analyzed the symbolic narratives underlying the concept of the hydrogen economy. They discuss the fantasy theme of hydrogen, interwoven with rhetorical visions that captivate both politicians and scientists. The rhetorical visions they identify in their study include independence, patriotism, progress, democracy, and inevitability. The case study of London demonstrates how the open and flexible vision of a hydrogen economy must be reimagined and anchored in local agendas and contexts to fulfill its potential. It is important to note that in the context of national hydrogen strategies, these socio-technical metaframes are similar to the rhetorical fantasies and visions of the hydrogen economy described by Sovacool and Brossmann (2010) and the rhetorical themes connected to hydrogen characterized by Eames et al. (2006). These narratives build broad public appeal, reinforcing hydrogen's symbolic potential and promise of hydrogen technologies, shaping public perception and policy direction.

In essence, the successful deployment of hydrogen as an energy carrier hinges on the harmonization of socio-technical measures and metaframes. When national hydrogen strategies are aligned with broader narratives of environmental sustainability, economic potential, and energy security, they foster a comprehensive and consistent approach that accelerates the acceptance and integration of hydrogen technologies (Reigstad et al., 2022). This holistic framework ensures that hydrogen strategies are not only technically feasible and economically viable but also align with societal values and priorities (De-León Almaraz et al., 2023). By doing so, it lays the foundation for a sustainable and resilient energy future, underlining the importance of connecting socio-technical measures and metaframes in the context of national hydrogen strategies. In summary, socio-technical metaframes are crucial in the context of national hydrogen strategies for articulating the broader social, economic, and environmental rationale behind the push towards hydrogen energy. They offer a coherent framework that guides policy development, stakeholder engagement, and comparative analyses, ultimately influencing the deployment of hydrogen at both national and global levels (Hamza and Mellouli, 2018).

2.5 Previous analyses of national hydrogen strategies

In order to gain a more comprehensive insight into global trends, it is imperative to scrutinize the frameworks of these strategies and pinpoint shared architectural elements. Currently, there is a dearth of literature dedicated to the comparative analysis of national hydrogen strategies. In their working paper, Gerres et al. (2022) analyze twelve national hydrogen strategies, identifying common design elements and global trends. They offer recommendations on the most effective hydrogen production methods, essential applications, strategies to balance supply and demand, and policy measures to advance the development of a hydrogen economy. Their findings highlight that hydrogen production is closely tied to a country's energy resources. However, the projected demand for hydrogen by 2030 is expected to remain relatively low, predominantly serving the industrial and transport sectors. A significant common element among the national strategies is the anticipation of a future global hydrogen market, especially pertinent for potential hydrogen-exporting countries. This includes an analysis of long-distance hydrogen transportation possibilities. Despite these insights, national hydrogen strategies, motivated by long-term climate policy goals, still leave several questions regarding the emergence of a hydrogen economy unanswered.

In 2021, the World Energy Council published a working paper in which 13 hydrogen strategies were analyzed. This publication provides an overview of the strategies and analyzes the areas to which they relate and the policy tools mentioned in these strategies. In their report "A Critical Assessment of national hydrogen strategies", Somenzi et al. (2021) analyzed 26 strategies, the highest number of hydrogen strategies (both national and regional) to date. The research focus of this report was on the measures and policies to promote hydrogen, taking into account the objectives of the respective countries. Through the analysis, it was found that the strategies show a desire for international cooperation. Furthermore, the strategies avoid setting clear numerical targets and more than half of them focus on the export of hydrogen.

Albrecht et al. (2020) have published a report in which the government measures for hydrogen in 16 countries (UK, Japan, South Korea, Australia, the Netherlands, France, Italy, Spain, China, Ukraine, Germany, Switzerland, Morocco, California (United States of America), Russia, and Norway) and the European Union. The focus here is on the respective national objectives, the target sectors, the infrastructure, the support measures and the requirements for the hydrogen used. The study revealed that the primary motivators for the authorities include the goal of minimizing greenhouse gas emissions, the incorporation of renewable energies and the prospect of fostering economic growth. Significant national disparities exist among the strategies, yet there is widespread international acknowledgment that hydrogen plays an essential and indispensable role in the decarbonization of the energy system. Consequently, the central focus of many strategies is on green hydrogen.

3 Methodology

The following chapter introduces the methodology employed in this master thesis. It begins by providing an overview of the research design, offering insights into the structured approach adopted for data collection. Followed by the explanation of the conducted qualitative content analysis according to Kuckartz and the formation of types according to Kelle and Kluge.

3.1 Research design

This research is situated within the domain of social research, a critical tool for generating new knowledge and enhancing the understanding of contemporary society. Social research investigates the dynamics of human interactions and provides insights into how individuals navigate their environments. Its significance extends beyond academia, informing governmental policies, assisting businesses in understanding consumer behavior, and helping communities address pressing social issues (Clark et al., 2021, p.4). This master's thesis aims to contribute to social research by analyzing the country-specific social, economic, and ecological aspirations associated with a hydrogen economy. The focus is on national hydrogen strategies published by various countries, reflecting their visions for a hydrogen-based future.

In addressing the research questions, an inductive research approach was adopted, utilizing a qualitative research design. This design allows for a comprehensive exploration of the diverse and context-specific aspects of national hydrogen strategies (Döring and Bortz, 2016, p.184, 222, 223). It captures the depth and complexity of the topic, including the underlying socio-technical metaframes. By employing qualitative methods, a holistic understanding of the strategies and the broader socio-political landscape in which these strategies exist can be achieved (Döring and Bortz, 2016, p.184). This study is explanatory, aiming to provide a detailed account of the subject matter. The primary focus is on uncovering the commonalities, variations, overarching socio-technical metaframes, and the economic, social, and environmental aspirations embedded within national hydrogen strategies. An initial analysis of the 33 published national hydrogen strategies will be performed (Döring and Bortz, 2016, p.191). This exploratory study is designed to meticulously investigate and elucidate the subject, formulating scientific research questions, hypotheses, and theories (Döring and Bortz, 2016, pp.192-193).

3.2 Data collection

The data for this analysis was derived from the national hydrogen strategies published by the respective governments. Notably, the analysis extends beyond documents explicitly labeled as "strategies" to include English summaries and roadmaps that meet the key content criteria of hydrogen strategies. This inclusive approach is justified, as roadmaps constitute a fundamental phase of strategy development. They provide crucial information, such as defining key milestones and targets for hydrogen, establishing a timeline for program expansion, outlining support measures, and specifying areas of application. Subsequently, the formal hydrogen strategies delineate the main objectives while ensuring alignment with the overarching energy policy. These strategies play a pivotal role in facilitating the comprehensive implementation of the entire hydrogen system (IRENA, 2020). The inclusion of roadmaps from certain countries is also appropriate for this study. As of August 1, 2023, the hydrogen strategies and roadmaps from 33 countries meet these criteria and are available in English (see Table 1).

Table 1: Countries with a hydrogen strategy or roadmap

Country	**Publication date**	**Ministry/ Institution responsible**	**Typology of document**
Australia	July 2019	COAG Energy Council Hydrogen Working Group	Strategy
Austria	June 2020	Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology	Strategy
Belgium	October 2022		Strategy
Brazil	February 2021	Federal Government Ministry of Mines and Energy NME	Strategy
Canada	December 2020	Zen and the Art of Clean Energy Solutions and Institute for Breakthrough Energy + Emission Technologies	Strategy
Chile	November 2020	Ministry of Energy, Government of Chile	Strategy
Colombia	September 2021		Roadmap
Croatia	March 2022	Ministry of Economy and Sustainable Development	Strategy
Czech Republic	July 2021	Ministry of Industry and Trade of the Czech Republic	Strategy
Denmark	December 2021	Danish Ministry of Climate, Energy and Utilities	Strategy
European Union	July 2020	European Commission	Strategy
Finland	November 2020	Business Finland	Roadmap
France	September 2020	Ministry for the Ecological Transition and Ministry of the Economy, Finance and the Recovery	Strategy (English draft)
Germany	June 2020	Federal Ministry for Economic Affairs and Energy	Strategy
Hungary	May 2021		Strategy
India	January 2023	Ministry of new and renewable energy	Strategy
Japan	March 2019 (updated June 2023)	Hydrogen and Fuel Cell Strategy Council	Strategic Roadmap
Namibia	November 2022	Ministry of Mines and Energy Namibia	Strategy
Netherland	April 2020		Strategy
New Zealand	September 2019/ August 2023	Ministry of Business, Innovation and Employment	Roadmap
Norway	August 2020	Norwegian Ministry of Petroleum and Energy Norwegian Ministry of Climate and Environment	Strategy
Poland	November 2021	Ministry of Climate and Environment	Strategy (English summary)
Singapore	October 2022	Ministry of Trade and Industry Singapore	Strategy
Slovakia	August 2022	Ministry of Economy	Strategy
South Africa	October 2021	Department of Science and Innovation	Roadmap
South Korea	January 2019	Government of Korea	Roadmap
Sweden	December 2021	Fossil free Sweden	Strategy
Trinidad and Tobago	November 2022	Inter-American Development Bank and National Energy Corporation of Trinidad and Tobago	Roadmap
Turkey	January 2023	Republic of Turkey and Ministry of Energy and Natural Resources	Strategy and Roadmap
Ukraine	March 2021	UNECE Sustainable Energy Division and Federal Ministry for the Environment, Nature Conservation and Nuclear	Draft Roadmap
United Kingdom	August 2021	Secretary of State for Business, Energy & Industrial Strategy and Command of Her Majesty	Strategy
United States	June 2023	U.S. Department of Energy	Draft Strategy and Roadmap
Uruguay	June 2022	Ministerio de Industria, Energía y Minería	Roadmap

3.3 Qualitative content analysis

Content analysis, a research method used to systematically examine textual, visual, or audio data, aims to identify patterns, themes, and meanings. This method involves coding and categorizing content based on predetermined criteria or emergent themes, enabling researchers to derive insights and interpretations about the phenomenon under study (Clark et al., 2021). Content analysis provides a structured and systematic approach to analyzing large volumes of data, ensuring consistency throughout the research process. Its versatility permits the examination of various data types, making it adaptable to diverse research contexts (Mayring, 2010, pp. 11-13). Content analysis facilitates objective evaluation, minimizing subjective bias. The replicability of findings enhances the credibility and reliability of research outcomes. Through meticulous analysis, researchers can uncover rich insights into underlying themes, discourses, and trends within the data (Mayring, 2010, pp. 11-13). Selection criteria must be rigorously and consistently applied to account for variations in message content, ensuring reliable and valid results (Lombard, 2002). Despite its strengths, content analysis can be resource-intensive, particularly when dealing with extensive datasets, requiring substantial time and effort. Standardizing coding procedures can be challenging and the inherent subjectivity in coding may introduce potential biases. While content analysis provides valuable insights, it may sometimes offer only surface-level understanding, lacking the depth and nuance of other qualitative methods, such as interviews or ethnography. Nevertheless, when applied judiciously, content analysis remains a powerful tool for uncovering meaningful insights from complex datasets (Mayring, 2010, pp. 11-13).

3.3.1 Qualitative content analysis according to Kuckartz

To examine national hydrogen strategies, a qualitative content analysis was conducted, following the methodological framework developed by Udo Kuckartz (2018, pp. 16-29). Kuckartz (2018) distinguishes various qualitative content analysis techniques, which he characterizes as foundational methods. In this study, the foundational method of content-structuring qualitative content analysis was employed. This method proves particularly advantageous when the research inquiry necessitates nuanced comprehension of the textual content. The content-structuring qualitative content analysis was utilized to analyze and identify the underlying social, environmental, and economic metaframes, as well as the similarities and differences in the application areas, production processes, and projected development paths of national hydrogen strategies. This method facilitates the exploration of various types of hydrogen strategies based on their socio-technical metaframes, hydrogen sources, and supply structures. Additionally, it enables the investigation of the economic, social, and environmental aspirations associated with the increased use of hydrogen within these strategies (Kuckartz, 2018, pp. 13-16). Content-structuring qualitative content analysis dissects the strategies into smaller units of meaning, subsequently organizing these units into themes or codes. This approach unveils underlying patterns and themes in the strategies that may not be immediately evident. Moreover, it represents a versatile and adaptable research methodology suitable for the analysis of a wide array of data types (Kuckartz, 2018, pp. 16-29). Given the scarcity of literature in the field of hydrogen strategies, the decision to employ qualitative content analysis according to Kuckartz is motivated by its stronger focus on material-oriented analysis when compared to the qualitative content analysis method by Mayring (Kuckartz, 2019).

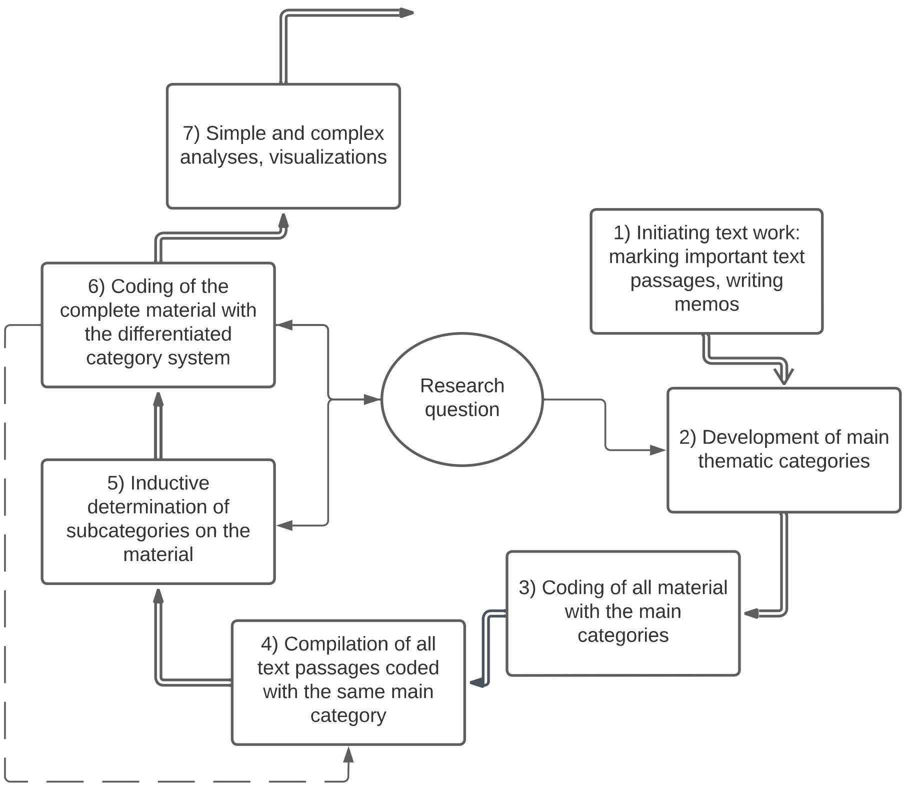

Figure 3: Flowchart of a content-structuring content analysis (based on Kuckartz, 2018, p. 100, figure 16)

The content-structuring qualitative content analysis framework by Kuckartz, encompassing the phases depicted in Figure 3, is utilized in this study. It is important to note that this analysis is non-linear, allowing for the flexibility to transition between phases at any point during the data analysis process (Kuckartz, 2018, pp. 100-110):

1) *Initiating text work, marking important text passages in the national hydrogen strategies and writing memos.*
2) *Developing main thematic categories*: this step is explained in detail in the following paragraphs
3) *Coding the entire material (available up to that point) with the main categories*: the national hydrogen strategies are processed sequentially, i.e., line by line from the beginning to the end and then assigned to the text sections of the categories.
4) *Compiling all text passages coded with the same category.*
5) *Inductive determination of subcategories on the material*: after the first coding process, a differentiation of the initially still relatively general categories was made.
6) *Subsequent Coding Stage*: Application of nuanced categories to the entire dataset.
7) *Simple and complex analyses and visualizations.*

Qualitative content analysis, in contrast to traditional content analysis, does not adhere to a rigid phased model. Instead, it consistently integrates iterative and feedback loops, the extent of which can vary. This approach is open-ended, with a general absence of preformulated hypotheses. Furthermore, the distinct phases of analysis are not strictly delineated; the assessment and development phases may occur concurrently, often involving feedback loops (Kuckartz, 2018, p.100-110). The categorization process addresses the time-consuming nature of content analysis through the establishment of categories. There are two primary approaches to categorization: deductive and inductive. Deductive categorization (a priori categories) relies on theoretical frameworks to guide the development of categories based on preconceived ideas or concepts. In contrast, inductive category formation derives categories directly from the analyzed material. Often, research projects utilizing qualitative content analysis adopt a mixed approach, referred to as deductive-inductive category formation (Kuckartz, 2018, pp. 95-96).

Initially, a comprehensive review of all extant national hydrogen strategies was undertaken with the objective of collating and summarizing the critical metadata associated with each strategy into a tabulated format. The metadata was meticulously extracted from a variety of credible sources, including but not limited to, seminal works by Cheng and Lee (2022), the World Energy Council (2021), and Gerres et al. (2022). The categories of metadata that were considered in this review encompassed: year of publication, typology, type of hydrogen, and supply structure. Each category was carefully analyzed to provide a holistic understanding of the various facets of the national hydrogen strategies.

3.3.1.1 Identification of socio-technical metaframes

Socio-technical metaframes, often referred to as overarching narratives, are pivotal in shaping social discourse. In the context of national hydrogen strategies, several key socio-technical metaframes have been identified that are integral to the narratives surrounding these strategies. Sovacool and Brossmann (2010) highlight the following rhetorical visions: inevitability, energy independence, patriotism (national leadership and competitiveness), progress (economic growth), and democratization (decentralized energy production). These rhetorical visions were further refined and developed, resulting in the socio-technical metaframes presented in Figure 4.

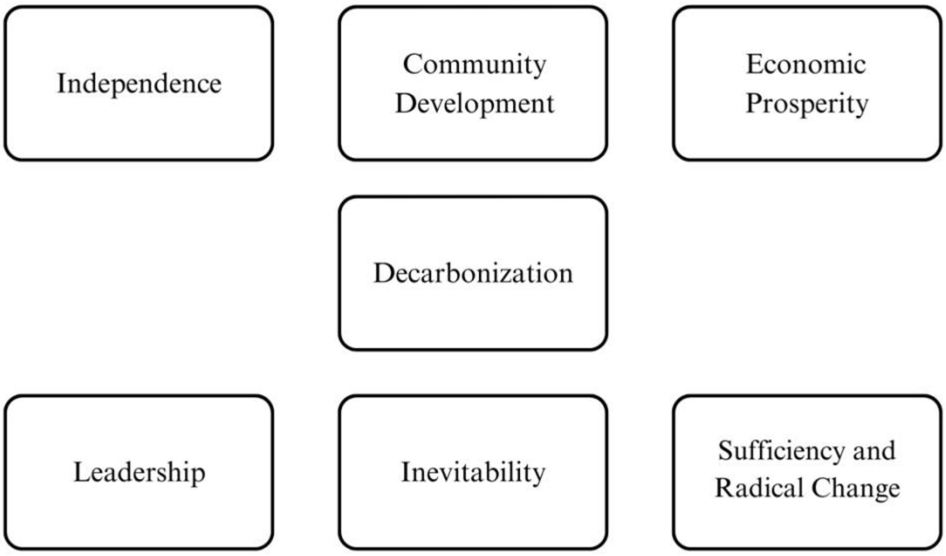

Figure 4: Socio-technical metaframes of national hydrogen strategies

The *Inevitability* metaframe was retained in its original form. The metaframe energy independence was retained in its original form with the new name *Independence*. The democratization metaframe evolved into the *Community Development* metaframe, while the patriotism metaframe was transformed into the *Leadership* (Industrial and Technological) metaframe. The progress metaframe was renamed *Economic Prosperity*. In addition, two new inductive socio-technical metaframes were created: *Decarbonization* and *Sufficiency and Radical Change*. However, during the coding process of the national hydrogen strategies, it was found that the metaframe *Sufficiency and Radical Change* appeared exclusively in the South African strategy and was only mentioned in the context of declining economic growth (Department of Science and Innovation, 2021, p.19). Consequently, this metaframe was excluded from the final analysis.

3.3.1.2 Coding and categorization process

The qualitative content analysis employed a mixed approach. Initially, a priori categories were drawn from the paper "Symbolic Convergence and the Hydrogen Economy" by Sovacool and Brossmann (2010). The identified rhetorical visions included: inevitability, energy independence, patriotism (national leadership and competitiveness), progress (economic growth), and democratization (decentralized energy production). These categories served as the foundation for subsequent inductive categorization. The material was systematically searched for these categories and categorized accordingly. In the next step, additional subcategories were inductively formed from the national hydrogen strategies (Kuckartz, 2018, pp. 95-96).

The analysis was conducted using content-structuring qualitative content analysis with MaxQDA software (Döring and Bortz, 2016, p. 608). This software facilitated the categorization of strategies, enabling the identification of socio-technical metaframes within the national hydrogen strategies. Additionally, MaxQDA simplified the management of extensive datasets and supported systematic, rule-based data evaluation, category system development, result evaluation, and the clear presentation of the analysis process and findings (Kuckartz, 2010, pp. 12-15). To enhance reliability, a detailed category description of the various socio-technical metaframes has been written and the entire coding process was repeated four weeks after the initial coding. This double coding allowed for the verification and adjustment of categories, ensuring the consistency and robustness of the analysis.

In conclusion, the socio-technical metaframes corresponding to each country were systematically cataloged in a tabular format to enhance comprehensibility. The socio-technical metaframes were subjected to a hierarchical classification ranging from 'very low' to 'very strong'. This hierarchical structure was established based on two primary factors: the quantity of elements encoded with the respective code and the substantive content of these encoded elements. This classification served as the foundational framework for the identification of the prevailing socio-technical metaframes within each country.

3.4 Formation of types

The foundation for constructing multidimensional types was established through Kuckartz's categorization using qualitative content analysis. A typology results from a grouping process in which an object area is categorized into groups or types based on one or more characteristics. Elements within a type should exhibit high internal homogeneity, while types should exhibit high external heterogeneity from each other. The term "type" refers to subgroups with common characteristics, which can be described and characterized based on their specific constellation of these characteristics (Kelle and Kluge, 2010, pp. 83-85). Büschges (1989) defines this as "summarizing those objects into types that are more similar than others in terms of certain characteristics".

3.4.1 Multidimensional typology

In this master's thesis, typologies are formed as multidimensional typologies through the combination of characteristics. Relevant research categories are combined according to their dimensions, and the resulting feature space is reconstructed (Kelle and Kluge, 2010, pp. 87-89). Categorizing cases into different groups aids in understanding and explaining the content-related orders leading to these groupings. The type formation process aims to grasp the meaning and significance of these combinations of characteristics, with typologies serving a heuristic function and referring to contextual contexts.

The following steps were undertaken to form the typology of national hydrogen strategies:

1) *Development of Relevant Comparative Dimensions*: The relevant categories and characteristics—namely socio-technical metaframes, source of hydrogen, and supply structure—were identified and defined through prior qualitative content analysis. The socio-technical metaframes were further divided into subcategories through qualitative content analysis and only the categories that provided the most value for the type formation were used. The identified socio-technical metaframes are *Independence*, *Community Development*, *Leadership*, *Inevitability* and *Economic Prosperity*. The metaframe *Sufficiency and Radical Change* was excluded due to an insufficient number of codes. Additionally, the metaframe *Decarbonization* was not utilized, as every strategy among the 33 countries contained codes corresponding to *Decarbonization*.

2) *Grouping of Cases and Analysis of Empirical Regularities*: The national hydrogen strategies were grouped according to the relevant comparative dimensions and characteristics. These groups were then analyzed for empirical regularities. A cross-tabulation of categories was performed to provide an overview of all potential combinations and the empirical distribution of cases across these combinations. Internal homogeneity was ensured by comparing strategies assigned to specific combinations of characteristics.

3) *Analysis of Contextual Contexts*: The contextual contexts of the empirical combinations of characteristics found were analyzed.

4) *Characterization of the Formed Types*: The constructed types were comprehensively characterized based on their feature combinations and contextual contexts of meaning.

These steps were iteratively applied, as new abductive conclusions were drawn during the analysis, leading to the identification of new relevant characteristics (Kelle and Kluge, 2010, pp. 87-93). At the conclusion of the type formation process, the types were characterized as comprehensively and precisely as possible based on the relevant comparison dimensions and combinations of characteristics (Kelle and Kluge, 2010, p. 105).

4 Findings

This section displays the outcome of the content analysis. Firstly, an overarching summary of the analyzed Strategies is provided. Subsequently, a detailed examination of findings relating to the research questions from the qualitative content analysis is presented. The socio-technical metaframes and type development are also discussed in detail. This systematic approach aims to illuminate the key findings from the analyzed national hydrogen strategies and contribute to a deeper understanding of the research area.

4.1 Overview of analyzed strategies

Figure 5 displays the countries that have published a national hydrogen strategy in English by August 1, 2023, marked in turquoise. Additionally, countries that have published a roadmap or a hydrogen strategy under a different title are marked in blue. Countries with hydrogen strategies not available in English are marked in gray and were excluded from this analysis.

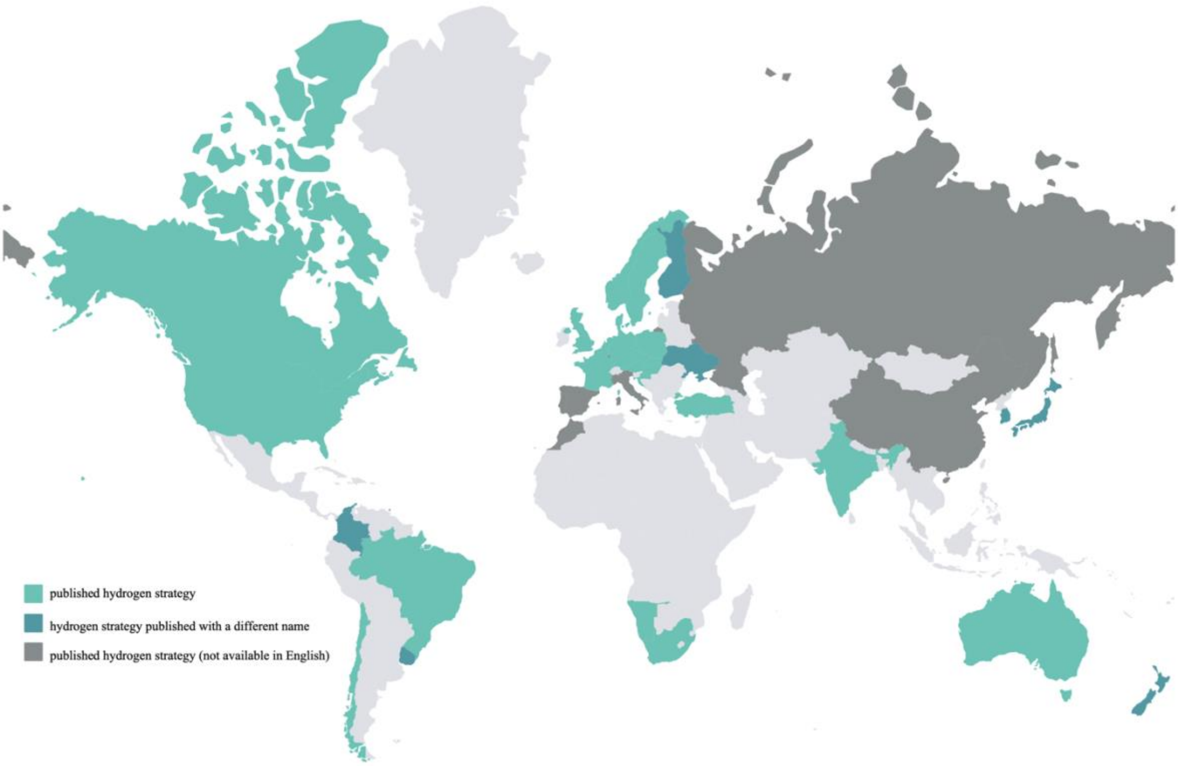

Figure 5: Overview world map of countries with a national hydrogen strategy

The analysis spans national hydrogen strategies released between January 2019 and January 2023. In 2019, only four countries published a hydrogen strategy. From 2020 onwards, there was a notable increase in the number of countries releasing hydrogen strategies, as illustrated in Figure 6. Japan stands out as the only country to have revised its hydrogen strategy, with the updated version from June 2023 included in this analysis. The varied publication dates and the evolving research landscape are evident in the strategies, particularly in areas such as hydrogen production and international partnerships.

*Figure 6: Timeline of publication dates of national hydrogen strategies (*not considered for the analysis, **first published draft)*

Analyzing the metadata shows a consensus among countries on the direction of development of a hydrogen economy in the long term, albeit with some differences in detail. Most countries prioritize green hydrogen in the long term, with some also considering blue hydrogen. In the short to medium term, countries such as Austria, Chile, Denmark, Germany and Uruguay are focusing on pure green hydrogen. Most strategies focus on low carbon (blue hydrogen) as a target source, such as Australia, Columbia, Norway and Turkey. Some countries want to use turquoise, pink, gray and brown hydrogen (classified as all sources). Countries such as Croatia, the Czech Republic and Hungary are planning to use Turkish hydrogen, which is produced by pyrolysis with natural gas. Countries such as South Africa, South Korea and Trinidad and Tobago currently rely on gray hydrogen produced by natural gas reforming until they can develop capacities for green and blue hydrogen. Table 2 provides a detailed overview of each country's short- and medium-term hydrogen sources.

Table 2: Short- and medium-term hydrogen sources and supply structure mentioned in the respective national hydrogen strategy

Country	Sources of hydrogen by 2030	Supply structure
Australia	blue and green	export
Austria	green	import
Belgium	blue and green	import
Brazil	green	export
Canada	blue and green	export
Chile	green	export
Columbia	blue and green	export
Croatia	blue and green	export
Czech Republic	blue and green	import
Denmark	green	export
European Union	green	domestic and import
Finland	blue and green	domestic
France	blue and green	domestic and import
Germany	green	import
Hungary	blue and turquoise	domestic
India	green	export
Japan	blue and green	import
Namibia	green	export
Netherlands	blue and green	import
New Zealand	green, blue, gray and brown	export
Norway	blue and green	domestic
Poland	blue and green	domestic
Singapore	blue and green	import
Slovakia	blue and green	domestic
South Africa	blue, green and gray	export
South Korea	gray	import
Sweden	blue and green	domestic
Trinidad and Tobago	blue, green and gray	export
Turkey	blue, turquoise and green	export
Ukraine	blue and green	export
United Kingdom	blue and green	export
United States	blue and green	domestic
Uruguay	green	export

The supply structure adopted by countries depends on their resource capacities. Nations with abundant natural resources (e.g., hydropower, wind power, solar energy, geothermal energy, and tidal power) can potentially meet their own hydrogen needs and export surplus hydrogen. Table 2 lists potential export countries, import countries, and those aiming for domestic production and use. The EU and Finland, for instance, aim to meet their hydrogen demand domestically but will consider imports if necessary. Tables 2 also show that Brazil, Chile, Croatia, Denmark, India and Uruguay are developing into green export countries.

4.2 Description of the socio-technical metaframes

The following seven socio-technical metaframes of national hydrogen strategies were identified and defined through the conducted qualitative content analysis:

Independence

The metaframe *Independence* encapsulates the strategic aspirations of nations to achieve a stable, resilient, and self-sufficient energy future through the adoption of hydrogen. This socio-technical metaframe underscores the ambitions of national hydrogen strategies to ensure a continuous, dependable, and robust energy supply while reducing dependency on external fossil fuels and gas. It encompasses visions for enhancing energy security, ensuring reliable system performance, maintaining energy availability, fortifying energy resilience, improving energy efficiency, and securing an uninterrupted energy supply, all while fostering domestic energy capabilities to gain political and economic independence. Within the metaframe *Independence*, national strategies often articulate measures and policies designed to protect the nation's energy supply from potential threats or disruptions and to ensure self-sufficiency. For instance, Australia's national hydrogen strategy emphasizes that "the development of our hydrogen resources could enhance Australia's energy security" (COAG Energy Council Hydrogen Working Group, 2019, p.5). This vision extends to ensuring that hydrogen resources are accessible and sufficient to meet current and future demands, thereby maintaining or enhancing the availability of hydrogen as an energy carrier.

Similarly, Germany's national hydrogen strategy highlights the critical role of hydrogen in the energy transition, stating, "The energy transition – which represents the efforts undertaken and results achieved on renewable energy expansion and energy efficiency – is our basis for a clean, secure and affordable energy supply, which is essential for all our lives" (Federal Ministry for Economic Affairs and Energy, 2020, p.2). This statement underscores the ambition to create a reliable energy infrastructure that focuses on the consistent performance and dependability of hydrogen production, storage, and distribution systems. Strategies aimed at fortifying the energy system's capacity to withstand and quickly recover from adverse events, such as natural disasters, technical failures, or geopolitical conflicts, are integral to this metaframe, ensuring minimal disruption to the energy supply.

In addition to energy security, the metaframe *Independence* also highlights the strategic goals of nations to achieve greater self-sufficiency and autonomy in their energy systems through hydrogen adoption. Croatia's hydrogen strategy presents a framework for hydrogen production and utilization, emphasizing renewable hydrogen as a fossil fuel alternative to enhance the stability of the renewable energy-based electricity system and promote energy self-sufficiency: "The Strategy provides a framework for hydrogen production and use with a focus on renewable hydrogen as a substitute for fossil fuels and increasing the stability of the RES-based electricity system for energy self-sufficiency and clean energy transition and sustainable mobility" (Ministry of Economy and Sustainable Development, 2022, p.5). Strategies that focus on this socio-technical metaframe, collectively emphasize the aspiration for energy autonomy, where hydrogen production, storage, and utilization are largely independent of external influences, thereby reducing the risks associated with geopolitical and market fluctuations. The pursuit of independence through hydrogen underscores the commitment to creating a resilient, self-reliant energy infrastructure that not only secures the energy supply but also enhances national sovereignty and economic stability.

Community Development

The metaframe *Community Development* embodies the strategic aspirations of nations regarding the role of hydrogen in fostering vibrant, inclusive, and empowered local communities. This socio-technical metaframe reflects the ambitions of national hydrogen strategies to promote social equity, enhance local empowerment, and ensure a fair and inclusive transition to a hydrogen-based economy. National strategies often articulate visions for supporting local communities through decentralized energy production and distribution, thereby increasing local control and benefits. For example, South Africa's Hydrogen Society Roadmap emphasizes the importance of gender, equality and social inclusion (GESI) in the transition to a low carbon economy to tackle the triple challenges of poverty, unemployment and inequality: "Ensure that Gender, Equality and Social Inclusion (GESI) are at the core of the transition to a low carbon economy to tackle the triple challenges of poverty, inequality and unemployment" (Department of Science and Innovation, 2021, p. 12).

Similarly, New Zealand's vision for hydrogen emphasizes a 'just transition' that is fair, equitable, and inclusive: "The Government has committed to making this process a ’just transition’– one that is fair, equitable and inclusive" (Ministry of Business, Innovation & Employment, 2019, p.4). This vision includes fostering active participation of local populations in the energy transition, ensuring that community voices are heard and valued. The aspiration for gender equality highlights the commitment to ensuring equal opportunities for all genders within the hydrogen economy, while the notion of a localized world emphasizes the importance of developing hydrogen initiatives tailored to the unique needs and contexts of local communities. Diversity, equity, accessibility, and inclusion are integral to this vision, ensuring that the benefits of the hydrogen transition are shared equitably across all segments of society, including marginalized and underserved groups. The concept of a "Just Transition" underlines the commitment to a fair and equitable shift to a hydrogen-based economy, ensuring that no community is left behind and that the transition supports sustainable development and social justice.

Leadership

The metaframe *Leadership* captures the strategic ambitions of nations to position themselves as global frontrunners in the hydrogen economy. This socio-technical metaframe reflects the desire for national hydrogen strategies to achieve prominence and competitive advantage in various aspects of hydrogen technology, production, usage, and export, thereby solidifying their status as industrialized, innovative, and influential countries. National hydrogen strategies often articulate visions for achieving leadership and pioneering the best hydrogen technologies to gain a competitive edge. For instance, the UK's hydrogen strategy states: "Our vision is that by 2030, the UK is a global leader on hydrogen" (Department for Energy Security and Net Zero, 2021, p. 14). This vision emphasizes the strategic importance of hydrogen in maintaining and enhancing the nation's industrial capabilities and economic strength. The aspiration to be a leading country encompasses the ambition to excel in hydrogen production, use, and export, positioning the nation as a key player in the global hydrogen landscape. Similarly, Chile's national hydrogen strategy outlines the ambition to become the world's leading producer of green copper, leveraging hydrogen technologies: "A concrete opportunity, for example, would be to become the world's leading producer of green copper" (Ministry of Energy, 2020, p.4). This statement highlights the commitment to becoming a leading global hydrogen player, exporting hydrogen and related technologies to other countries and establishing the nation as one of the world's greatest players in the hydrogen economy.

Inevitability

The metaframe *Inevitability* captures the strategic recognition that transitioning to a hydrogen-based economy is an unavoidable and essential development for nations. This socio-technical metaframe reflects the understanding within national hydrogen strategies that participation in the global hydrogen market and maintaining competitiveness are imperative for future economic and technological progress. National strategies often articulate visions for maintaining competitiveness, recognizing the necessity of adopting hydrogen technologies and participating in the hydrogen economy to remain economically viable and technologically advanced. For example, Slovakia's national hydrogen strategy highlights the long-term importance of hydrogen technologies for transforming industrial processes to carbon-neutral ones and maintaining competitiveness: "In the long-term, hydrogen technologies are one of the means of how to transform industrial processes to carbon-neutral ones and to maintain the competitiveness of the Slovak industry" (Sinay et al., 2021, p. 20).

Similarly, Brazil's baseline for the national hydrogen strategy emphasizes the need for competitiveness levels with other energy sources through cost reduction: "The main challenge for the development of the energy use of hydrogen is to achieve competitiveness levels with other sources through cost reduction, according to the projections of the studies mentioned above" (Ministry of Mines and Energy, 2021, p. 16). This recognition underscores the inevitability of hydrogen adoption for staying relevant and competitive in the evolving energy landscape, highlighting the importance of international cooperation and integration into global supply chains.

Economic Prosperity

The metaframe *Economic Prosperity* embodies the strategic aspirations of nations regarding the transformative role of hydrogen in driving new economic growth and maintaining existing economic stability. This socio-technical metaframe reflects the dual ambitions of national hydrogen strategies: to leverage hydrogen technologies and infrastructure for economic advancement and to secure current economic during the transition to a hydrogen-based economy. National strategies often articulate visions for economic growth, recognizing hydrogen's potential to boost GDP, create jobs, attract investments, develop industries, and enhance export potential. For instance, Canada's hydrogen strategy outlines the economic and environmental opportunities associated with hydrogen, including job creation and expanding exports: "It will position Canada to seize economic and environmental opportunities that exist coast to coast. Expanding our exports. Creating as many as 350,000 good, green jobs over the next three decades" (Natural Resources Canada, 2020, p. 1).

Similarly, the U.S. National Clean Hydrogen Strategy and Roadmap emphasizes the potential of hydrogen to support a skilled workforce and union jobs, highlighting opportunities for workers transitioning from fossil energy employment: "Hydrogen is an opportunity to support a skilled workforce and union jobs across a range of sectors, including new opportunities for workers transitioning from fossil energy employment and for individuals denied access to high-quality employment" (U.S. Department of Energy, 2023, p. 6). This vision includes strategic initiatives aimed at fostering innovation, attracting domestic and international investments, and supporting the development of new technologies, while also ensuring that the economic transition is inclusive and equitable.

Decarbonization

The metaframe *Decarbonization* embodies the strategic objectives of nations to reduce carbon emissions, mitigate climate change, and achieve environmental sustainability through the adoption of hydrogen as a clean energy carrier. This socio-technical metaframe reflects the ambitions of national hydrogen strategies to transition away from carbon-intensive fuels and technologies towards low-carbon or carbon-neutral alternatives, thus contributing to global climate goals and improving environmental health. National strategies often articulate visions for climate change mitigation, recognizing the essential role of hydrogen in achieving carbon reduction targets. For example, Uruguay's National Hydrogen Strategy outlines the role of hydrogen in decarbonizing industrial sectors and contributing to climate neutrality: " Green hydrogen is key to achieving ambitious global decarbonization goals, particularly for those sectors where it is most difficult to reduce greenhouse gas emissions." (Ministry of Industry, Energy and Mining, 2022, p. 14).

Similarly, Japan's Basic Hydrogen Strategy emphasizes the potential of hydrogen to achieve significant reductions in CO_2 emissions, thus contributing to climate goals: "Hydrogen, which can be used as a clean energy without emitting CO_2 when consumed, is expected to play a central role in achieving significant CO_2 reductions" (Ministerial Council on Renewable Energy, Hydrogen and Related Issues, 2023, p. 1). This vision includes strategic initiatives to develop and deploy hydrogen technologies that can significantly reduce carbon emissions in various sectors, including energy, industry, and transportation. The aspiration to mitigate climate change through hydrogen adoption highlights the commitment to environmental sustainability and the global effort to combat climate change. In summary, these socio-technical metaframes collectively encapsulate the comprehensive and multifaceted ambitions embedded within national hydrogen strategies. They reflect the diverse, yet interconnected goals of energy security, autonomy, community development, leadership, inevitability, economic prosperity, and decarbonization, which together drive the global hydrogen transition.

4.2.1 Predominant socio-technical metaframes in national hydrogen strategies

Figure 7 illustrates the predominant socio-technical metaframe for each country, representing the primary societal aspiration driving the transition to a hydrogen-based economy. During the coding process, it was evident that all countries aim for the decarbonization of society and the economy through the adoption of hydrogen. Consequently, the metaframe *Decarbonization* was excluded from determining the predominant socio-technical metaframes. Similarly, the *Economic Prosperity* metaframe was omitted because it would dominate more than half of the analyzed strategies and is present in nearly all countries, except Hungary, Poland, and Singapore. These two socio-technical metaframes— *Decarbonization* and *Economic Prosperity*—are the fundamental societal visions in the strategies published by 1 July 2023. Therefore, Figure 7 focuses on more specific predominant socio-technical metaframes, reflecting the distinct primary societal visions of the respective countries.

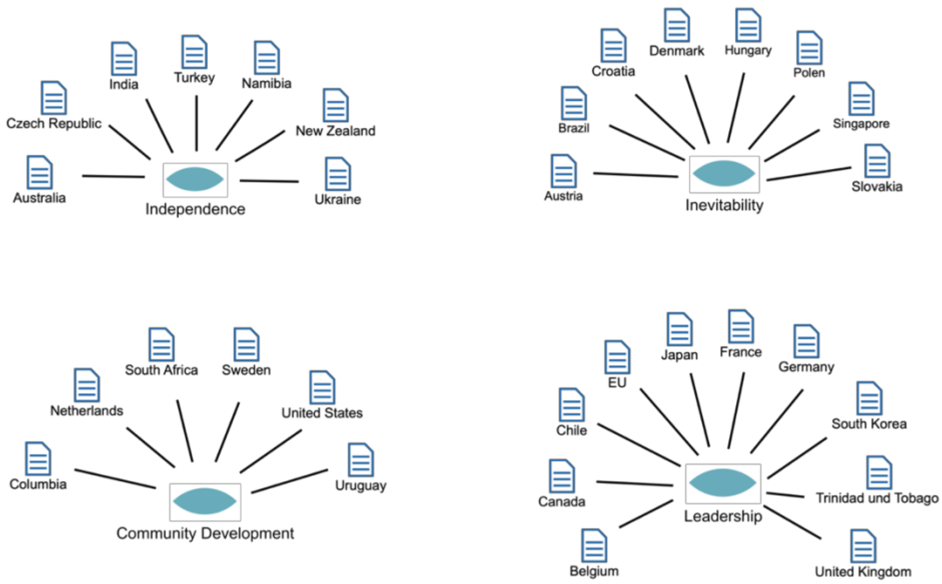

Figure 7: Predominant Socio-technical metaframes of national hydrogen strategies

Independence

Australia, the Czech Republic, India, Turkey, Namibia, New Zealand, and Ukraine identify *Independence* as their predominant metaframe. These countries aspire to achieve energy security and enhance the reliability of their energy systems through the utilization of hydrogen as an energy source and in transportation and the economy. Their strategies emphasize increasing energy efficiency, ensuring supply chain resilience, and guaranteeing a stable energy supply. Additionally, these nations aim to attain political independence from traditional fossil fuel exporters such as oil and gas-producing countries.

Community Development

In Colombia, South Africa, Sweden, the United States, and Uruguay, the metaframe *Community Development* serves as the primary societal vision for transitioning to a hydrogen-based economy. Central to this socio-technical metaframe is the principle of Just Transition, which promotes equality, diversity, inclusion, and accessibility. These countries strive to ensure that the benefits of the transition are equitably distributed among their populations. Their strategies focus on supporting regional communities through decentralized energy production, developing systems that address local energy needs, and fostering inclusive development. Additionally, there is a strong emphasis on achieving gender equality and social justice through the energy transition.

Leadership

Countries such as Belgium, Canada, Chile, the EU, Japan, France, Germany, South Korea, Trinidad & Tobago, and the United Kingdom aim for *Leadership* in the hydrogen sector. Their strategies are geared towards becoming global leaders in the emerging hydrogen market, excelling in the development and production of low-carbon hydrogen technologies. These nations aspire to lead in the new energy sector and achieve international competitiveness for their industries. Some have set goals to become top exporters of clean hydrogen or innovative hydrogen and fuel cell technologies. Overall, these countries strive to become global champions in the field of hydrogen.

Inevitability

The metaframe *Inevitability* is prominent in the national hydrogen strategies of Austria, Brazil, Croatia, Denmark, Hungary, Poland, Singapore, and Slovakia. These countries recognize the inevitable nature of the energy transition but do not seek a leading role. Their primary objective is to maintain economic competitiveness while acknowledging the unavoidable shift to hydrogen in various sectors, including industry and transportation.

Undefined Leading Metaframe

No leading metaframe could be defined for Norway and Finland, as their national strategies focus exclusively on *Decarbonization* and *Economic Prosperity*. These countries have not articulated a distinct primary societal hope beyond these fundamental aspirations.

4.3 Types of hydrogen strategies

Using Kelle and Kluge's (2010) methodology, the 33 national hydrogen strategies are grouped into six categories, each reflecting different priorities and approaches within hydrogen development. A detailed description of each type is provided in the subsequent tables 3 to 8.

Table 3: Type description Hydrogen Optimists

Hydrogen Optimists	
The *Hydrogen Optimists* type emphasizes a comprehensive strategy focused on *Independence*, *Community Development*, *Leadership*, and *Economic Prosperity*. Central to this approach is the use of diverse hydrogen sources, including green, blue, grey, and brown hydrogen, with a significant emphasis on exporting hydrogen to international markets. This type prioritizes ensuring the reliability of the energy system, reducing dependence on imported fuels, and achieving energy self-sufficiency through decentralized hydrogen production. By diversifying hydrogen sources and promoting exports, countries in this group aim to strengthen their economic position while ensuring energy security. In addition, the *Hydrogen Optimists* seek to create a more inclusive economy by benefiting communities, particularly indigenous and remote areas, and promoting gender equality and social inclusion. Empowering women and fostering social equity are key components of this strategy, reflecting the commitment to a just transition that transforms the economy to be more equitable and inclusive. The *Hydrogen Optimists* also focus on establishing themselves as global leaders in the hydrogen industry, driving economic growth, job creation, and workforce reskilling, while fostering robust domestic markets. Their emphasis on resilience, community engagement, and promoting equity, diversity, and inclusion supports their continued leadership in hydrogen fuel cells and the clean hydrogen sector.	
Metaframes	*Leadership, Independence, Community Development and Economic Prosperity*
Hydrogen Sources	Diverse (green, blue, and others)
Supply structure	Export
Priorities	• Energy system reliability and self-sufficiency. • Decentralized hydrogen production for community benefits. • Inclusive economic growth, gender equality, and social equity. • Global leadership in clean hydrogen technologies. • Economic growth, job creation, and workforce reskilling
Countries	Australia, Canada, New Zealand, South Africa and United Kingdom

Table 4: Type description Hydrogen Economy Leaders

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Hydrogen Economy Leaders

The *Hydrogen Economy Leaders* type emphasizes achieving political independence by reducing reliance on fossil fuel and gas imports while promoting leadership in hydrogen technologies. This type plans to both produce hydrogen domestically and import hydrogen to ensure a diverse and resilient hydrogen supply. It aims to utilize a variety of hydrogen sources, including green, blue, pink, grey, and brown hydrogen, as part of its strategic approach. A core goal of this type is to champion the production and use of decarbonized hydrogen, fostering the creation of new "green" jobs and ensuring energy security through a resilient supply chain. By leveraging both domestic production and imports, this type seeks to enhance energy self-sufficiency and stability. Decentralization of hydrogen production is another key focus, intending to promote local and self-sustaining energy systems that reduce dependence on centralized fuel supplies. Ultimately, the *Hydrogen Economy Leaders* type strives to position nations as leaders in the global hydrogen economy, driving industrial competitiveness and economic growth through cutting-edge hydrogen technologies.

</td></tr>
<tr><td>Metaframes</td><td>Economic Prosperity, Leadership and Independence</td></tr>
<tr><td>Hydrogen Sources</td><td>Diverse (green, blue, and others)</td></tr>
<tr><td>Supply structure</td><td>Domestic use and imports</td></tr>
<tr><td>Priorities</td><td>• Achieving political independence from fossil fuel and gas imports.
• Leading in hydrogen technologies and decarbonized hydrogen.
• Ensuring energy security and supply chain resilience.
• Promoting decentralized and local hydrogen production.
• Driving economic growth and job creation.</td></tr>
<tr><td>Countries</td><td>Belgium, France, Germany, Japan, South Korea and the United States</td></tr>
<tr><td>Deviations</td><td>Unlike the Hydrogen Economy Leaders, Japan and the US place a strong focus on Community Development. Additionally, Germany differs from the Hydrogen Economy Leaders as it plans to use only green hydrogen.</td></tr>
</table>

Table 5: Type description Justice Seekers

Justice Seekers *Justice Seekers* champion a just transition, prioritizing equity, decentralized energy, and broad community participation. This type prioritizes the creation of an inclusive energy transition that ensures broad participation and shared benefits. In addition to community aspirations, the *Justice Seekers* also focuses on *Economic Prosperity*, aiming to drive economic growth, create new job opportunities, and maximize wealth. Countries of this type seek to support economic development by leveraging hydrogen to stimulate growth and offer new opportunities for businesses and workers alike. Furthermore, this type is characterized by its commitment to independence, particularly through enhancing the efficiency and reliability of the energy system. By reducing dependence on imported fossil fuels and focusing on energy self-sufficiency, countries within this group aim to strengthen their energy security and achieve long-term energy independence. The *Justice Seekers* type also aspires to achieve leadership in the global hydrogen market. Countries in this group seek to be market leaders in green hydrogen technologies and aim for regional leadership in the hydrogen transition, positioning themselves as strong players in the emerging hydrogen economy. Within the *Justice Seekers* type, there are two sub-types: **1. *The Diverse Justice Seekers* (Columbia, Trinidad & Tobago, Turkey, and Ukraine):** This sub-group focuses on using diverse hydrogen sources, including green, blue, turquoise, and grey hydrogen, to support their energy and economic goals. **2. *The Green Justice Seekers* (India, Namibia, and Uruguay):** This sub-group prioritizes the use of only green hydrogen and seeks to export it as part of their strategy.	
Metaframes	*Community Development, Economic Prosperity, Independence and Leadership*
Hydrogen Sources	Green and Diverse (green, blue, and others)
Supply structure	Export
Priorities	• Promoting a just transition with equal opportunities. • Supporting decentralized energy systems to meet local energy needs. • Driving economic growth, creating new jobs, and maximizing economic value. • Achieving energy independence and self-sufficiency by reducing reliance on imported fossil fuels. • Leading in the production and use of hydrogen technologies, establishing regional and global leadership.
Countries	Columbia, India, Namibia, Trinidad & Tobago, Turkey and Ukraine and Uruguay
Deviations	Turkey does not prioritize *Community Development,* and Trinidad & Tobago does not focus on I*ndependence*. Namibia and Uruguay, within the Green *Justice Seekers* sub-group, do not emphasize *Leadership*.

Table 6: Type description Opportunity Seekers

Opportunity Seekers The *Opportunity Seekers* type underscores the inevitability of a hydrogen transition, with a balanced approach to decentralized production. This type focuses on the long-term potential of decentralized hydrogen production to empower local communities and reduce dependency on imported fossil fuels and gas. By prioritizing autonomy and self-reliance, *Opportunity Seekers* promotes a resilient and self-sustaining energy system that leverages domestic resources while also planning to import hydrogen when needed. This type plans to use a mix of green, blue, and turquoise hydrogen, ensuring a diverse and sustainable energy base. The emphasis on *Community Development* ensures that local benefits are maximized, supporting regional economies and fostering inclusive growth. Furthermore, this type underscores the importance of achieving energy independence by developing a hydrogen infrastructure that minimizes reliance on external energy sources.	
Metaframes	*Inevitability, Independence and Community Development*
Hydrogen Sources	Diverse (green, blue, and others)
Supply structure	Domestic use and imports
Priorities	• Emphasizing the inevitability of the hydrogen transition. • Balancing decentralized and centralized hydrogen production. • Reducing dependency on imported fossil fuels and gas. • Empowering local communities through decentralized energy production.
Countries	Austria, Hungary, Poland, Singapore, Slovakia and Sweden
Deviations	Slovakia and Sweden also focus on *Economic Prosperity*, while Austria focuses exclusively on green hydrogen.

Table 7: Type description Green Hydrogen Exporters

Green Hydrogen Exporters	
The *Green Hydrogen Exporter* type emphasizes the strategic role of green hydrogen in driving economic prosperity through international trade. This type exclusively utilizes green hydrogen as its hydrogen source and focuses on the export of this renewable energy resource, positioning itself as a key player in the global hydrogen market. By leveraging the transition to green hydrogen, countries in this type view it as an opportunity for sustainable economic growth, job creation, and long-term competitiveness. A central tenet of this type is the recognition of the inevitability of the global shift towards a hydrogen-based economy. These nations are committed to being at the forefront of this transition, ensuring they capitalize on the economic potential of green hydrogen exports while maintaining their competitive edge in the evolving global energy landscape. Countries in the Green Hydrogen Exporter group see green hydrogen as a fundamental component of their future energy strategies. They aim to establish themselves as leading exporters of green hydrogen, benefiting from the economic opportunities associated with production, innovation, and trade in green hydrogen, and enhancing their role in the global energy transition.	
Metaframes	*Economic Prosperity and Inevitability*
Hydrogen Sources	Green
Supply structure	Export
Priorities	• *Economic Prosperity,* with a strong emphasis on economic growth and job creation • Commitment to the inevitability of the transition to a hydrogen-based economy • Emphasis on the inevitability of the transition to a hydrogen-based economy
Countries	Brazil, Chile, and Denmark
Deviations	While the *Green Hydrogen Exporter* generally emphasizes *Economic Prosperity* and the *Inevitability* of the hydrogen transition, Brazil does not focus on *Economic Prosperity*, instead prioritizing social aspects. Chile differs by focusing on *Leadership* rather than *Inevitability*.

Table 8: Type description Economic Value Creators

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Economic Value Creators

The *Economic Value Creators* type is characterized by a singular focus on *Economic Prosperity*, relying primarily on green and blue hydrogen sources. This type integrates both domestic hydrogen production and imports, aiming to generate significant economic value and create new business opportunities. By balancing local production with imported hydrogen, the *Economic Value Creators* ensures a stable and diverse supply to support the growth of the hydrogen economy. This approach is designed to foster economic growth through the hydrogen sector, enhancing overall economic development while promoting the adoption of green and blue hydrogen technologies. The emphasis is on developing a sustainable and prosperous economic environment that leverages the potential of hydrogen to drive business innovation and long-term prosperity.

</td></tr>
<tr><td>Metaframes</td><td>Economic Prosperity</td></tr>
<tr><td>Hydrogen Sources</td><td>Diverse (green, blue, and others)</td></tr>
<tr><td>Supply structure</td><td>Domestic use and imports</td></tr>
<tr><td>Priorities</td><td>• Driving economic growth and creating economic value.
• Supporting business opportunities through green hydrogen.</td></tr>
<tr><td>Countries</td><td>Czech Republic, Finland, Netherlands and Norway</td></tr>
<tr><td>Deviations</td><td>Unlike the Economic Value Creators, the Czech Republic also focuses on Independence, while the Netherlands emphasizes Community Development.</td></tr>
</table>

5 Discussion

This section provides an in-depth reflection on the outcomes of the content analysis, accompanied by an interpretation of the socio-technical metaframes and the resultant types. Initially, a holistic review of the qualitative content analysis and type formation is presented. Following this reflection, the study's limitations, as well as potential areas for improvement, are discussed.

5.1 Reflection on findings

Analyzing national hydrogen strategies provides valuable insights into the planned development of countries towards a hydrogen economy. These strategies outline the goals and visions that nations aim to achieve through hydrogen utilization. The overarching narrative consistently employs positive language, emphasizing societal benefits, economic advantages, and contributions to a climate-neutral society. However, it is important to note that the published hydrogen strategies and roadmaps are designed with a multi-faceted use of hydrogen across various sectors, such as industry, transport and power generation, as the ultimate goal. Consequently, these documents primarily focus on the benefits and opportunities that hydrogen offers, often neglecting to question hydrogen as the definitive solution. Few documents address the limitations associated with this type of energy production.

Sovacool and Brossmann (2010), in their foundational work on the rhetorical visions used in this study, highlight that experts are skeptical about the widespread commercial use of hydrogen. This skepticism is attributed to the inherent dangers and safety concerns associated with hydrogen, similar to petrol and natural gas, and the costly, energy-intensive nature of its production process. The commercial adoption of hydrogen would require trillions of dollars in investment and significant technological advancements. Despite these challenges, a considerable number of politicians, entrepreneurs, the public, and academics remain intrigued by the potential of hydrogen. Sovacool and Brossmann (2010) explain this allure using symbolic convergence theory, which describes how fantasy themes coalesce into shared rhetorical visions. Proponents of a hydrogen economy are driven by a vision steeped in idealism, envisioning an independent energy sector, revitalized national strength, accelerated technological progress, and a decentralized energy supply. The prevalence of these fantasy themes suggests that energy policy decisions are not solely based on rationality. It is important to note that the presence of a mass fantasy around the hydrogen economy does not imply homogeneity of opinion or delusion among its proponents. Some actors view hydrogen more as a short-term, niche application rather than a catalyst for radical transformation.

This divergence is evident in national hydrogen strategies. Countries like Australia, Japan, South Africa, and the United Kingdom have high aspirations for a hydrogen-based society, aiming to decarbonize their economies, gain economic advantages, achieve energy independence, and establish secure energy grids, with hydrogen as a key energy source across various sectors. In contrast, countries such as Austria, Finland, and Poland adopted a more cautious approach, focusing primarily on decarbonization and economic growth, considering other societal benefits as secondary. Therefore, the publication of a national hydrogen strategy does not necessarily indicate strong support for a hydrogen economy. It may also reflect an acknowledgment of international developments and the global trend towards hydrogen. This is exemplified by the *Inevitability* metaframe, which suggests that the transition to a hydrogen economy is perceived as both inevitable and crucial for societal progress.

Mcdowall and Eames (2006) also address the disadvantages and uncertainties of a hydrogen economy, citing significant uncertainties regarding future costs, technological performance, and sustainability impacts. Over the past 14 years, substantial research has been conducted, resulting in technological, economic, and social advancements. Yue et al. (2021) indicate that larger installations of electrolysers for renewable hydrogen are achievable in the coming years with technological improvements. However, they also note that hydrogen's introduction into industry remains non-competitive. National hydrogen strategies and pilot projects, such as the "Western Sydney Green Gas Project" in Australia and the "Three Hydrogen Valley" projects in Namibia, illustrate that nearly a third of the world's countries recognize the future relevance of hydrogen as an energy carrier. These countries have developed financing plans and research and development strategies for the advancement and implementation of a hydrogen economy. Thus, it is expected that significant progress will continue in this field over the coming years. However, it remains uncertain whether all countries will achieve the ambitious visions, goals, missions, and hopes articulated in their hydrogen strategies.

5.1.1 Socio-technical metaframes

This thesis examines socio-technical metaframes as visions for the future of technological change. Similar concepts have been described in the literature as rhetorical fantasies or rhetorical visions (Sovacool and Brossmann, 2010) and rhetorical themes connected to hydrogen (Eames et al., 2006). Essentially, these terms refer to the same underlying idea. Due to the commonality of fantasy themes within groups, combined with dramatis personae and symbolic references, individual themes often merge into a larger narrative or discourse, which Sovacool and Brossmann (2010) refer to as rhetorical visions. McDowall and Eames (2006) argue that such visions of the future help create a shared awareness of priorities and policies. These descriptions form one of the foundations for the socio-technical metaframes utilized in this thesis.

Sovacool and Brossmann (2010) based their rhetorical structure on Eames et al. (2006). This is why the structure of Sovacool and Brossmann (2010) has been employed in the development of the socio-technical metaframes. Consequently, there are similarities and differences between the rhetorical visions and socio-technical metaframes. The primary difference between Sovacool and Brossmann and the present study lies in the underlying documents used to define the rhetorical visions and metaframes. Sovacool and Brossmann used articles articulating a positive vision of the hydrogen economy to form their theoretical visions, whereas this study bases its visions on published national hydrogen strategies. The differences and similarities between the socio-technical metaframes and rhetorical visions are explored in detail below:

***Inevitability* of the Hydrogen Economy**

Both Sovacool and Brossmann and this study underscore the inevitability of transitioning to a hydrogen-based economy. Sovacool and Brossmann describe this inevitability through the lenses of historical progression, environmental necessity, and technological advancement. They argue that the shift away from fossil fuels towards hydrogen is essential, driven by the impending scarcity of conventional fuels and the pressing need for clean energy alternatives. This theme posits that since the hydrogen economy is unavoidable, efforts should focus on expediting the transition. Similarly, the current study emphasizes that adopting hydrogen technology is crucial for national competitiveness and future economic and technological advancement. This perspective is framed within national hydrogen strategies, which articulate the imperative to engage in the global hydrogen market to maintain economic viability. Thus, both sources converge on the notion that hydrogen adoption is a necessary evolution in the energy landscape, though they highlight slightly different driving factors.

Independence

Energy independence and security emerge as dominant themes in both analyses. Sovacool and Brossmann highlight the potential of hydrogen to reduce dependence on foreign fuels, thereby enhancing national security and economic stability. They cite political endorsements and literature that depict hydrogen as a means to achieve energy self-sufficiency and mitigate the economic risks associated with fuel imports. This study echoes this sentiment, framing energy independence as a strategic goal within national hydrogen strategies. These strategies advocate for a stable, resilient energy future through hydrogen adoption, emphasizing the reduction of reliance on external fossil fuels. This investigation also highlights measures to ensure a robust and uninterrupted energy supply, reinforcing the theme of energy security.

Leadership **in the Hydrogen Economy**

The theme of leadership is articulated differently in the two sources. Sovacool and Brossmann discuss hydrogen as a patriotic endeavor, particularly within the context of the United States. They draw parallels to the Apollo program, suggesting that a similar national commitment could drive technological and economic leadership in the hydrogen economy. This theme extends to other countries, emphasizing the competitive advantage of being early adopters. Conversely, the current research focuses on strategic ambitions to position nations as global leaders in hydrogen technology. National hydrogen strategies outline visions for achieving prominence in hydrogen production, usage, and export. This narrative underscores the desire to be at the forefront of the hydrogen economy, leveraging technological innovation to gain a competitive edge internationally.

Economic Prosperity

Economic prosperity is another critical theme explored in both studies. Sovacool and Brossmann discuss the potential of hydrogen to sustain economic growth and reduce environmental degradation. They highlight the promises of unlimited growth and environmental benefits, framing hydrogen as a solution to the limitations of fossil fuels. Similarly, this research emphasizes hydrogen's role in driving new economic growth and maintaining existing stability. National strategies often articulate the economic benefits of hydrogen, such as job creation, investment attraction, and industry development. This study also stresses the importance of an inclusive economic transition, ensuring opportunities for workers transitioning from fossil fuel industries.

Community Development

A unique theme in Sovacool and Brossmann's work is the idea of decentralization and community empowerment through hydrogen. They envision a decentralized energy system, akin to the World Wide Web, promoting participatory and community-owned energy production. This vision aims to fundamentally alter ecological values and the relationship between humanity and energy technologies. While the current analysis does not explicitly focus on this theme, it touches upon aspects of decentralization in the context of ensuring a resilient and self-sufficient energy supply. The emphasis is more on strategic policies to protect national energy interests, but also includes community development, ensuring equity, gender inclusivity, and equal rights. This is to ensure that local communities benefit from the transformation to a hydrogen-based economy, particularly through decentralized energy supply.

Additional socio-technical metaframes

This research identifies two additional socio-technical metaframes not mentioned by Sovacool and Brossmann: *Decarbonization* and *Sufficiency and Radical Change*. *Decarbonization* emerges as the core socio-technical metaframe on which all countries agree without exception, highlighting the global consensus on the need to reduce carbon emissions through the adoption of hydrogen technologies. In contrast, *Sufficiency and Radical Change* is only briefly mentioned in one national hydrogen strategy. However, this socio-technical metaframe should be considered for future research, as upcoming national hydrogen strategies might integrate this socio-technical metaframe. A concept similar to *Sufficiency and Radical Change* is discussed by Eames et al. (2006) as ecotopia, which refers to an ideal, sustainable society that harmoniously integrates ecological principles within the social and economic system. Unlike the notion of sufficiency and radical system change, ecotopia emphasizes a utopian vision of a society built on ecological harmony, signaling the transformative potential of embedding ecological ideals at the foundation of social and economic structures. In summary, both Sovacool and Brossmann and this research present compelling arguments for the transition to a hydrogen economy, framed through themes of inevitability, energy independence, leadership, economic prosperity, and, to some extent, decentralization. While there are overlaps in these themes, each source brings its unique perspective, reflecting different priorities and strategic aspirations in the global discourse on hydrogen energy. These narratives collectively underline the transformative potential of hydrogen, advocating for comprehensive strategies to realize a sustainable and secure energy future.

5.1.2 Local contextualization of hydrogen economy visions

Eames et al. (2006) show that visions of a hydrogen economy can support a variety of agendas and expectations. They argue that different visions need to be negotiated and anchored in local contexts to realize the promise of a hydrogen economy. This perspective is also evident in the current research, which examines different predominant socio-technical metaframes across countries. The respective nations focus on specific socio-technical metaframes, with only complete agreement on the topic of *Decarbonization* through a hydrogen economy and nearly complete agreement on *Economic Prosperity*. Other socio-technical metaframes reveal clear differences between countries. For example, *Leadership* and *Inevitability* illustrate this divergence. Countries such as Canada, Trinidad & Tobago, and the UK prioritize *Leadership*, aiming to be leaders in the new hydrogen economy and to develop hydrogen technologies for export. In contrast, countries like Singapore, Poland, and Hungary recognize the inevitability of a hydrogen economy but lack a deeper commitment to this transition. The predominant socio-technical metaframes clearly show that visions around hydrogen are also controversial and that there is no uniform vision of a sustainable hydrogen economy worldwide.

5.1.3 Typologies of hydrogen strategies

Currently, there is a lack of research that categorizes hydrogen strategies based on socio-technical metaframes, supply structures, and hydrogen sources. This subchapter aims to examine the unique characteristics and shared traits of various hydrogen strategy types among various hydrogen strategy types and discuss the added value that typology creation brings to the field. Given the increasing number of hydrogen strategies, the creation of types according to Kelle and Kluge (2010) presented significant challenges, particularly due to the diversity of strategies and the complexity involved in categorizing them effectively. To facilitate the formation of types, hydrogen resources were categorized into "green only" or "diverse (green, blue, and others)," and the supply structure was divided into "export" or "import/domestic use." These initial categories served as a foundation for forming types, which were then further differentiated using the socio-technical metaframes.

The *Hydrogen Optimists* can be described as an exemplary type. This type addresses all socio-technical metaframes comprehensively, demonstrating to other countries the potential of transitioning to a hydrogen-based society. Economically viable hydrogen production is prioritized in the short term, with a long-term goal of transitioning to green hydrogen for export. The *Hydrogen Optimists* combine technological leadership with a commitment to social inclusion, gender equality, and an inclusive energy transition, offering a balanced approach that prioritizes economic, environmental, and social goals. This type exemplifies the potential for hydrogen to transform national energy landscapes and the global energy market. In contrast to the *Hydrogen Economy Leaders*, which emphasize both domestic production and import of hydrogen, with a strong focus on the *Leadership* metaframe, aiming to lead in decarbonized hydrogen technologies, the *Justice Seekers* place their primary emphasis on *Community Development*, with a focus on equality, inclusive development, and equal opportunities. This distinction highlights a difference in priorities: while *Hydrogen Economy Leaders* seek to dominate the global hydrogen landscape through technological leadership, *Justice Seekers* prioritize social equity and the inclusive growth of their societies.

Within the *Justice Seekers* type, there are two distinct subtypes. The first, Green *Justice Seekers* (India, Namibia, and Uruguay), focuses exclusively on the use of green hydrogen and plans to export it. This subtype is driven by a vision of sustainability and global environmental leadership, positioning itself as a key player in the transition towards green hydrogen economies. In contrast, the second subtype, Inclusive *Justice Seekers* (Colombia, Turkey, Trinidad & Tobago, and Ukraine), employs a more diversified approach, utilizing a mix of green, blue, turquoise, and grey hydrogen, with a strong emphasis on domestic production and regional energy independence. For this group, the priority is to create an equitable energy system that supports community empowerment and fosters regional stability.

The *Opportunity Seekers* type diverges from both the *Hydrogen Economy Leaders* and *Justice Seekers* by acknowledging the necessity of hydrogen as part of the future energy mix but acknowledging hydrogen's importance in energy but adopting a localized approach without pursuing global leadership. Instead, this type focuses on decentralized production to empower local communities and reduce dependency on imported energy, but without an ambition to lead the global hydrogen transition. The *Green Hydrogen Exporters*, in contrast, are fully committed to the exclusive use of green hydrogen, primarily for export. This type is further divided into two subgroups, with one prioritizing the *Inevitability* metaframe, acknowledging the global shift towards hydrogen, and the other emphasizing *Independence* through a focus on self-sufficient production of green hydrogen for export.

Lastly, the *Economic Value Creators* stand apart from the other types with their singular focus on *Economic Prosperity*. Relying on green and blue hydrogen sources, this type integrates both domestic production and imports to maximize economic value, create new business opportunities, and drive economic growth. Unlike types such as the *Hydrogen Optimists* and *Justice Seekers*, the *Economic Value Creators* are predominantly concerned with the economic benefits of hydrogen rather than broader social, environmental, or leadership goals. This focus on economic gain distinguishes them from the more multifaceted hydrogen strategies observed in other types.

The formation of these hydrogen strategy types is critical for several reasons. Firstly, it allows for a structured comparison of different national approaches, enabling the identification of best practices and areas for improvement. Secondly, these types provide a framework for policymakers to design more targeted and effective hydrogen strategies that align with their specific national priorities and capabilities. Lastly, the typology highlights the diverse pathways and potential outcomes of hydrogen adoption, fostering a deeper understanding of how different socio-technical, economic, and political contexts influence the development and implementation of hydrogen strategies. The added value of creating these types lies in their ability to guide countries in formulating their hydrogen policies. By understanding the various types and their associated socio-technical metaframes, countries can better navigate the complexities of the hydrogen transition and leverage the full spectrum of opportunities provided by a hydrogen economy. This approach ensures that hydrogen strategies are not only technically and economically viable but also socially inclusive and environmentally sustainable.

5.2 Limitations of the study

This master's thesis acknowledges several limitations that must be considered when interpreting the findings. One limitation concerns the study's sample, which is restricted to national hydrogen strategies published in English. This language restriction may affect the generalizability of the findings, as non-English publications that could provide additional insights into the socio-technical metaframes guiding hydrogen strategies were excluded. Including a broader linguistic range of strategies would allow for a more comprehensive analysis and could yield a richer understanding of the diverse aspirations and priorities shaping the hydrogen economy. Moreover, the selection of strategies is limited to those countries that have officially published their hydrogen strategies as of August 1, 2023. This selection bias may lead to an overrepresentation of early-adopting nations, as some countries may still be developing their hydrogen policies or have delayed formal publication. Consequently, the findings may not fully capture the complete global picture of perspectives on the hydrogen economy.

The content-structuring qualitative content analysis approach used in this thesis, which combines predefined categories with inductive categorization, may also constrain the discovery of emergent themes outside the initial coding categories. While this structured approach enables systematic categorization, expanding the methodological framework to include other qualitative techniques, such as grounded theory or thematic analysis, could yield additional insights into emergent socio-technical metaframes within hydrogen strategies. The inherent subjectivity in this content analysis methodology may further influence data interpretation. This subjectivity, shaped by the researcher's perspective, has implications for the reliability and validity of the findings. Efforts to mitigate this issue included re-coding the data at a later stage as a consistency check, yet the absence of intercoder reliability checks remains a limitation. Involving multiple coders and calculating intercoder reliability could enhance the objectivity of the categorization, thereby strengthening the robustness of the analysis.

The rapidly evolving nature of hydrogen strategies and hydrogen technology also presents a temporal limitation. The strategies analyzed were current as of August 1, 2023, meaning that subsequent developments or updates to these strategies are not reflected in the findings. Given the swift pace of technological advancements and policy shifts in the hydrogen sector, ongoing research is crucial for capturing the most recent trends and shifts in national priorities. Additionally, the analysis is limited to government-authored strategies, excluding input from other key stakeholders, such as industry leaders, academic institutions, and civil society organizations. These groups can contribute valuable insights, particularly in relation to technical feasibility, economic considerations, and social impacts. Including perspectives from these additional stakeholders could lead to a more holistic understanding of the factors driving or potentially hindering the hydrogen transition.

Furthermore, the type formation process, based on Kelle and Kluge's (2010) method, adds a further layer of complexity due to the challenge of categorizing a diverse set of countries across multiple socio-technical categories. Constructing types required subjective judgments to align each country's strategy with specific criteria, which may have influenced the types that emerged. Alternative analytical approaches might yield distinct categorizations, as type formation could feasibly be conducted in other ways. Collaborative typology construction with multiple researchers would likely enhance the validity and reliability of the types identified. A team-based approach could reduce individual biases and strengthen the robustness of the derived types by incorporating diverse perspectives. Future studies may benefit from interdisciplinary collaboration in type formation to refine the classification of national hydrogen strategies, potentially capturing a broader range of socio-technical perspectives and increasing the accuracy of the typological framework.

6 Conclusion

In the concluding chapter of this thesis, the research questions are addressed, providing a comprehensive understanding of the study's findings. Finally, a forward-looking perspective is offered, outlining potential directions for future studies.

6.1 Main findings

This study underscores the importance of aligning national hydrogen strategies with specific socio-technical contexts. The diversity of socio-technical metaframes across countries indicates that there is no one-size-fits-all approach to hydrogen adoption. Each nation tailors its strategy to its unique economic, social, and environmental circumstances, reflecting different priorities and capabilities. This research highlights the multifaceted nature of national hydrogen strategies, emphasizing the interplay between technological aspirations and socio-political contexts. The identified socio-technical metaframes provide a comprehensive understanding of how countries envision their transition to a hydrogen economy, highlighting both common goals and distinctive national priorities.

6.1.1 Socio-technical metaframes

The content-structuring qualitative content analysis of national hydrogen strategies revealed seven distinct socio-technical metaframes: *Independence, Community Development, Leadership, Inevitability, Economic Prosperity, Decarbonization and Sufficiency and Radical Change*. These socio-technical metaframes reflect the strategic aspirations and priorities of different nations regarding hydrogen adoption. The study found that while all countries emphasize *Decarbonization* and *Economic Prosperity*, the prominence of other socio-technical metaframes varies significantly. Furthermore, the metaframe *Sufficiency and Radical Change* is not considered relevant for all national hydrogen strategies published in English by 1 July 2023. The 6 relevant socio-technical metaframes are briefly described below:

The metaframe ***Independence*** highlights the ambition of nations to achieve a stable and self-sufficient energy future by for example reducing dependency on external fossil fuels. This socio-technical metaframe underscores the importance of energy security and resilience, with countries aiming to create robust energy infrastructures that enhance national sovereignty and economic stability. ***Community Development*** focuses on the role of hydrogen in fostering vibrant, inclusive, and empowered local communities. National hydrogen strategies under this frame emphasize social equity, local empowerment, and ensuring a fair transition to a hydrogen-based economy. This includes addressing issues of social justice, gender inclusivity, and equal opportunities for all. The ***Leadership*** metaframe captures the strategic ambitions of nations to position themselves as global frontrunners in the hydrogen economy. This socio-technical metaframe reflects the desire to achieve competitive advantages in hydrogen technology, production, usage, and export. It highlights the importance of innovation and industrial leadership in the global hydrogen market. ***Inevitability*** reflects the recognition that transitioning to a hydrogen-based economy is seen as an unavoidable and essential development for future economic and technological progress. National strategies framed in this context stress the imperative to engage in the global hydrogen market to maintain economic viability and competitiveness. ***Economic Prosperity*** embodies the dual ambitions of leveraging hydrogen technologies for economic advancement while securing current economic and social values. This socio-technical metaframe underscores the potential of hydrogen to drive new economic growth, create jobs, attract investments, and sustain existing economic stability. The final metaframe ***Decarbonization*** emphasizes the strategic objectives of reducing carbon emissions, mitigating climate change, and achieving environmental sustainability through hydrogen adoption. This socio-technical metaframe reflects the commitment to transitioning away from carbon-intensive fuels and technologies towards low-carbon or carbon-neutral alternatives, contributing to global climate goals and improving environmental health.

This study provides a comprehensive analysis of national hydrogen strategies, revealing the diverse socio-technical narratives and priorities driving the global transition to a hydrogen economy. These strategies, while emphasizing the benefits of hydrogen across various sectors, often overlook its limitations and the significant investments required for widespread adoption. Despite skepticism about hydrogen's commercial viability due to safety and cost concerns, the symbolic convergence theory explains the collective allure of hydrogen, driven by visions of energy independence, technological progress, and decentralized energy supply.

6.1.2 Predominant socio-technical metaframes

This thesis identifies the predominant socio-technical metaframes driving national hydrogen strategies. By excluding the metaframes *Decarbonization* and *Economic Prosperity*, which are fundamental to all strategies, the focus shifts to more specific societal aspirations. These prevalent socio-technical metaframes reflect the overarching priorities and strategic objectives of each nation, aligning their hydrogen strategies with broader national goals:

Countries such as Australia, Czech Republic, India, Turkey, Namibia, New Zealand, and Ukraine prioritize ***Independence***, aiming for energy security and political autonomy by enhancing energy efficiency and supply chain resilience through hydrogen utilization. In

Colombia, the Netherlands, South Africa, Sweden, the United States, and Uruguay, the primary focus is on ***Community Development***. These nations emphasize a Just Transition, ensuring equitable distribution of benefits, promoting regional development through decentralized energy production, and fostering social justice and gender equality. ***Leadership*** is the main goal for Belgium, Canada, Chile, the EU, Japan, France, Germany, South Korea, Trinidad & Tobago, and the United Kingdom. These countries strive to lead in the global hydrogen market by developing advanced hydrogen technologies and achieving international competitiveness, with some aiming to become top exporters of clean hydrogen. Austria, Brazil, Croatia, Denmark, Hungary, Poland, Singapore and Slovakia acknowledge the ***Inevitability*** of the hydrogen transition. Their strategies focus on maintaining economic competitiveness while accepting the unavoidable shift to hydrogen in various sectors. Norway and Finland do not articulate a distinct primary societal hope beyond *Decarbonization* and *Economic Prosperity*.

This research highlights the diverse strategic priorities and unique societal aspirations driving the global transition to a hydrogen-based economy. Each country's approach reflects its specific goals, whether it is achieving independence, fostering community development, leading the market, or adapting to inevitable changes. These predominant socio-technical metaframes encapsulate the broader national objectives, demonstrating how hydrogen strategies are integrated into each nation's vision for its future energy landscape.

6.1.3 Typology of hydrogen strategies

The formation of hydrogen strategy types according to Kelle and Kluge (2010) based on socio-technical metaframes, supply structure and hydrogen source provided valuable insights into the diverse approaches taken by different countries. The types, such as the *Hydrogen Optimists*, *Hydrogen Economy Leaders*, and *Green Hydrogen Exporters*, highlight the varied pathways and potential outcomes of hydrogen adoption. These typologies allow for a structured comparison of national approaches, enabling the identification of best practices and areas for improvement. This research identified six types from 33 national hydrogen strategies. These types are as follows:

The *Hydrogen Optimists* focus on diverse hydrogen sources (green, blue and others) for export. Priorities include energy reliability, decentralized production, inclusive economic growth, gender equality, social equity, and global leadership in hydrogen technologies. The *Hydrogen Economy Leaders* reduce reliance on fossil fuels to strengthen energy sovereignty, energy security, and decentralized production. Their strategy combines domestic use and imports from diverse hydrogen sources, promoting industrial competitiveness and economic growth. The

Justice Seekers emphasizes community development, equity, decentralized energy systems, domestic production, and regional leadership in hydrogen. Their export-focused strategy aims to create jobs and economic opportunities while fostering inclusive growth. Furthermore, their major focus lies on advancing the just transition. The *Pragmatic Implementer* highlights the inevitability of hydrogen transition, balancing decentralized and centralized production and reducing fossil fuel dependency. Their approach integrates domestic use and imports of diverse hydrogen sources, promoting a resilient, self-sustaining energy system and local community empowerment. The *Green Hydrogen Exporters* focus on exporting green hydrogen to drive economic growth, create jobs, and establish a robust green hydrogen economy. Some sub-groups of this type emphasize *Leadership*, *Independence*, and *Community Development*. The *Economic Value Creators* prioritize *Economic Prosperity* by using diverse hydrogen sources (green, blue, and others) for domestic use and imports. Priorities include driving economic growth, creating economic value, and supporting business opportunities through green hydrogen. This strategy promotes a sustainable and prosperous economic environment.

These typologies, based on socio-technical metaframes, supply structures, and hydrogen sources, offer a structured framework for comparing national approaches and guiding policymakers in designing effective hydrogen strategies. The study underscores the importance of aligning hydrogen strategies with national priorities and capabilities to realize the full spectrum of opportunities provided by a hydrogen economy, thereby empowering policymakers to leverage unique national strengths for more efficient and inclusive energy transitions.

6.2 Recommendations for future research

Future research should aim to address the limitations identified in this study. Expanding the sample to include non-English national hydrogen strategies would provide a more comprehensive global perspective on the socio-technical metaframes. Further research could also explore the dynamic nature of hydrogen strategies by including recent updates and developments. During the analysis process and the writing process of this paper, eight new strategies and three updated strategies were published (as of May 2024). Longitudinal studies that track changes in national hydrogen strategies over time would provide valuable insights into the evolving landscape of hydrogen adoption and the impact of technological advancements and policy shifts. Additionally, incorporating multiple coders and conducting intercoder reliability checks would enhance the reliability and validity of the qualitative content analysis.

Moreover, employing a mixed-methods approach that combines qualitative content analysis with quantitative techniques, such as surveys or statistical analysis of published scientific papers, could provide a more holistic understanding of the factors influencing national hydrogen strategies. This approach would allow for a deeper exploration of the relationships between socio-technical metaframes and specific policy outcomes. Additionally, comparative studies that analyze the differences and similarities between hydrogen strategies in various regions or economic contexts could provide valuable insights into the global hydrogen landscape. Such studies would enhance our understanding of how different socio-economic and political environments shape hydrogen adoption and the effectiveness of various strategic approaches.

References

Abbas, R. and Michael, K., 2023. Socio-Technical Theory: A review. In: S. Papagiannidis, ed. TheoryHub Book. ISBN 9781739604400.

Ahlborg, H., Ruiz-Mercado, I., Molander, S., Masera, O., 2019. Bringing Technology into Social-Ecological Systems Research—Motivations for a Socio-Technical-Ecological Systems Approach. Sustainability 11, 2009. https://doi.org/10.3390/su11072009

Albrecht, U., Bünger, U., Michalski, J., Raksha, T., Wurster, R., & Zerhusen, J., 2020. INTERNATIONAL HYDROGEN STRATEGIES A study commissioned by and in cooperation with the World Energy Council Germany. Final report. Ludwig-Bölkow-Systemtechnik GmbH

Bausch, C. and Mehling, M., 2011. Addressing the challenge of global climate mitigation: an assessment of existing venues and institutions. ISBN 978-3-86872-867-5

Bleischwitz, R. and Bader, N., 2010. Policies for the transition towards a hydrogen economy: the EU case. Energy Policy 38, 5388–5398. https://doi.org/10.1016/j.enpol.2009.03.041

Bolan, S., Padhye, L.P., Jasemizad, T., Govarthanan, M., Karmegam, N., Wijesekara, H., Amarasiri, D., Hou, D., Zhou, P., Biswal, B.K., Balasubramanian, R., Wang, H., Siddique, K.H.M., Rinklebe, J., Kirkham, M.B., Bolan, N., 2024. Impacts of climate change on the fate of contaminants through extreme weather events. Sci. Total Environ. 909, 168388. https://doi.org/10.1016/j.scitotenv.2023.168388

Büschges, G., 1989. Gesellschaft. In: G. Endruweit and G. Trommsdorff, eds. 1989. Wörterbuch der Soziologie. Bd. 1: Abhängigkeit-Hypothese. Stuttgart: Enke. ISBN 3-8252-0172-5

Calabrese, M., Portarapillo, M., Di Nardo, A., Venezia, V., Turco, M., Luciani, G., Di Benedetto, A., 2024. Hydrogen Safety Challenges: A Comprehensive Review on Production, Storage, Transport, Utilization, and CFD-Based Consequence and Risk Assessment. Energies 17, 1350. https://doi.org/10.3390/en17061350

Cheekatamarla, P., 2024. Hydrogen and the Global Energy Transition—Path to Sustainability and Adoption across All Economic Sectors. Energies 17, 807. https://doi.org/10.3390/en17040807

Cheng, W. and Lee, S., 2022. How Green Are the National Hydrogen Strategies? Sustainability 14, 1930. https://doi.org/10.3390/su14031930

Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E., Sovacool, B., 2018. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. Energy Res. Soc. Sci. 37, 175–190. https://doi.org/10.1016/j.erss.2017.09.015

Clark, T., Foster, L., Sloan, L., Bryman, A., 2021. Bryman's Social Research Methods. 6th ed. Oxford: Oxford University Press. ISBN 9780198796053

COAG Energy Council Hydrogen Working Group, 2019. Australia's National Hydrogen Strategy. [online] Available at: https://www.dcceew.gov.au/sites/default/files/documents/australias-national-hydrogen-strategy.pdf [Accessed 6 Aug. 2024]

Cornelissen, J.P., Werner, M.D., 2014. Putting Framing in Perspective: A Review of Framing and Frame Analysis across the Management and Organizational Literature. Acad. Manag. Ann. 8, 181–235. https://doi.org/10.5465/19416520.2014.875669

Cruz Gómez, M.J., Galindo Uribarri, S., Benítez López, O.B., 2021. The Astrophysical Processes of Cosmological Hydrogen that Generate the Chemical Elements that Make up the Universe. Nat. Sci. 13, 103–116. https://doi.org/10.4236/ns.2021.133010

De-León Almaraz, S., Kocsis, T., Azzaro-Pantel, C., Szántó, Z.O., 2023. Identifying social aspects related to the hydrogen economy: Review, synthesis, and research perspectives. Int. J. Hydrog. Energy 49, 601–618. https://doi.org/10.1016/j.ijhydene.2023.10.043

Department for Energy Security and Net Zero, 2021. UK Hydrogen Strategy. [Online] London: Presented to Parliament by the Secretary of State for Business, Energy & Industrial Strategy by Command of Her Majesty. Available at: https://www.gov.uk/government/publications/uk-hydrogen-strategy [Accessed 6 Aug 2024]

Department of Science and Innovation, 2021. Hydrogen Society Roadmap for South Africa 2021. [Online] Pretoria. Available at: https://www.dst.gov.za/index.php/resource-center/strategies-and-reports/3574-hydrogen-society-roadmap-for-south-africa-2021 [Accessed 6 Aug 2024]

De Vreese, C.H., 2005. News framing. Information Design Journal, 13(1),51–62. https://doi.org/10.1075/idjdd.13.1.06vre

Döring, N. and Bortz, J., 2016. Forschungsmethoden und Evaluation in den Sozial- und Humanwissenschaften, 5. vollständig überarbeitete, aktualisierte und erweiterte Auflage. ed, Springer-Lehrbuch. Springer, Berlin Heidelberg. ISBN 978-3-642-41088-8

Eames, M., McDowall, W., Hodson, M., Marvin, S., 2006. Negotiating contested visions and place-specific expectations of the hydrogen economy. Technology Analysis & Strategic Management, 18, 361-374. https://doi.org/10.1080/09537320600777127.

Espegren, K., Damman, S., Pisciella, P., Graabak, I., Tomasgard, A., 2021. The role of hydrogen in the transition from a petroleum economy to a low-carbon society. Int. J. Hydrog. Energy 46, 23125–23138. https://doi.org/10.1016/j.ijhydene.2021.04.143

Falkner, R., 2016. The Paris Agreement and the new logic of international climate politics, International Affairs, Volume 92, Issue 5, 1107–1125, https://doi.org/10.1111/1468-2346.12708

Federal Ministry for Economic Affairs and Energy, 2020. The National Hydrogen Strategy. [Online] Berlin: Public Relations Division. Available at: https://www.bmbf.de/SharedDocs/Downloads/files/bmwi_nationale-wasserstoffstrategie_eng_s01.pdf?__blob=publicationFile&v=2 [Accessed 6 Aug. 2024]

Gerres, T., Serna Zuluaga, S., Cossent, R., 2022. National Hydrogen Strategies in a Global Context: Common Design Elements Across Country-Specific Visions. SSRN Electron. J. https://doi.org/10.2139/ssrn.4203346

Gielen, D., Boshell, F., Saygin, D., Bazilian, M.D., Wagner, N., Gorini, R., 2019. The role of renewable energy in the global energy transformation. Energy Strategy Rev. 24, 38–50. https://doi.org/10.1016/j.esr.2019.01.006

Gordon, J.A., Balta-Ozkan, N., Nabavi, S.A., 2023. Socio-technical barriers to domestic hydrogen futures: Repurposing pipelines, policies, and public perceptions. Appl. Energy 336, 120850. https://doi.org/10.1016/j.apenergy.2023.120850

Hamza, K. and Mellouli, S., 2018. Background on Frameworks for Policy Analytics. In: J. Gil-Garcia, T. Pardo and L. Luna-Reyes, eds. Policy Analytics, Modelling, and Informatics. Springer, 19-37. Public Administration and Information Technology, vol 25. https://doi.org/10.1007/978-3-319-61762-6_2

Hassan, Q., Algburi, S., Jaszczur, M., Al-Jiboory, A. K., Al Musawi, T. J., Ali, B. M., Viktor, P., Fodor, M., Ahsan, M., Salman, H. M., & Sameen, A. Z., 2024. Hydrogen role in energy transition: A comparative review. Process Safety and Environmental Protection, 184, 1069-1093. https://doi.org/10.1016/j.psep.2024.02.030.

Hassan, Q., Sameen, A.Z., Salman, H.M., Jaszczur, M., Al-Jiboory, A.K., 2023. Hydrogen energy future: Advancements in storage technologies and implications for sustainability. Journal of Energy Storage, 72, Part B, p.108404. Available at: https://doi.org/10.1016/j.est.2023.108404.

IRENA, 2020. Green Hydrogen: A guide to policy making. Abu Dhabi: International Renewable Energy Agency. ISBN 978-92-9260-286-4.

Islam, A., Islam, T., Mahmud, H., Raihan, O., Islam, Md.S., Marwani, H.M., Rahman, M.M., Asiri, A.M., Hasan, Md.M., Hasan, Md.N., Salman, Md.S., Kubra, K.T., Shenashen, M.A., Sheikh, Md.C., Awual, Md.R., 2024. Accelerating the green hydrogen revolution: A comprehensive analysis of technological advancements and policy interventions. Int. J. Hydrog. Energy 67, 458–486.

Jayachandran, M., Gatla, R.K., Flah, A., Milyani, A.H., Milyani, H.M., Blazek, V., Prokop, L., Kraiem, H., 2024. Challenges and Opportunities in Green Hydrogen Adoption for Decarbonizing Hard-to-Abate Industries: A Comprehensive Review. IEEE Access 12, 23363–23388. https://doi.org/10.1109/ACCESS.2024.3363869

Jovan, D.J. and Dolanc, G., 2020. Can Green Hydrogen Production Be Economically Viable under Current Market Conditions. Energies 13, 6599. https://doi.org/10.3390/en13246599

Kelle, U. and Kluge, S., 2010. Vom Einzelfall zum Typus: Fallvergleich und Fallkontrastierung in der qualitativen Sozialforschung, 2., überarbeitete Auflage. ed, Qualitative Sozialforschung. VS Verlag, Wiesbaden. ISBN 978-3-531-14704-8

Kuckartz, U., 2019. Qualitative Inhaltsanalyse: von Kracauers Anfängen zu heutigen Herausforderungen. Forum Qual. Sozialforschung Forum Qual. Soc. Res. Vol 20, No 3 (2019): Qualitative Content Analysis I. ISBN 9783779946830

Kuckartz, U., 2018. Qualitative Inhaltsanalyse: Methoden, Praxis, Computerunterstützung, 4. Auflage. ed, Grundlagentexte Methoden. Beltz Juventa, Weinheim Basel. ISBN 978-3-7799-3682-4

Kuckartz, U., 2010. Einführung in die computergestützte Analyse qualitativer Daten (German Edition). VS Verlag für Sozialwissenschaften. ISBN 978-3531166612

Lebrouhi, B.E., Djoupo, J.J., Lamrani, B., Benabdelaziz, K., Kousksou, T., 2022. Global hydrogen development - A technological and geopolitical overview. International Journal of Hydrogen Energy, Volume 47, Issue 11, 7016-7048, https://doi.org/10.1016/j.ijhydene.2021.12.076

Lombard, M., Snyder-Duch, J., Bracken, C.C., 2002. Content analysis in mass communication: Assessment and reporting of intercoder reliability. Human Communication Research, 28(4), 587 604. https://doi.org/10.1111/j.1468-2958.2002.tb00826.x.

Maggio, G., Nicita, A., Squadrito, G., 2019. How the hydrogen production from RES could change energy and fuel markets: A review of recent literature. International Journal of Hydrogen Energy, 44(23), 11371-11384. https://doi.org/10.1016/j.ijhydene.2019.03.121.

Marouani, I., Guesmi, T., Alshammari, B.M., Alqunun, K., Alzamil, A., Alturki, M., Hadj Abdallah, H., 2023. Integration of Renewable-Energy-Based Green Hydrogen into the Energy Future. Processes 11, 2685. https://doi.org/10.3390/pr11092685

Maurer, M., 2017. Agenda-Setting. 2nd ed. Baden-Baden: Nomos, Reihe: Konzepte. Ansätze der Medien- und Kommunikationswissenschaft, Band 1. ISBN 978-3-8487-4022-2.

Mayring, P., 2010. Qualitative Inhaltsanalyse: Grundlagen und Techniken. 12th ed. Weinheim Basel: Beltz Verlag. ISBN 978-3-407-25730-7.

McDowall, W., 2014. Exploring possible transition pathways for hydrogen energy: A hybrid approach using socio-technical scenarios and energy system modelling. Futures 63, 1–14. https://doi.org/10.1016/j.futures.2014.07.004

McDowall and W., Eames, D.M., 2006. A multi-criteria mapping of the UKSHEC hydrogen futures. International Journal of Hydrogen Energy, Volume 32, Issue 18, 2007, 4611-4626, https://doi.org/10.1016/j.ijhydene.2007.06.020.

Ministerial Council on Renewable Energy, Hydrogen and Related Issues, 2023. Basic Hydrogen Strategy. [online] Available at: https://www.meti.go.jp/shingikai/enecho/shoene_shinene/suiso_seisaku/pdf/20230606_5.pdf [Accessed 6 Aug 2024]

Ministry of Business, Innovation & Employment, 2019. A Vision for Hydrogen in New Zealand: Green Paper. [Online] Wellington. Available at: https://www.mbie.govt.nz/dmsdocument/6798-a-vision-for-hydrogen-in-new-zealand-green-paper [Accessed 6 Aug 2024]

Ministry of Economy and Sustainable Development, 2022. Hydrogen Strategy of the Republic of Croatia until 2050. [Online] Zagreb. Available at: https://mingo.gov.hr/UserDocsImages/UPRAVA%20ZA%20ENERGETIKU/Croatian%20Hydrogen%20Strategy%20ENG%20FIN%2022%208.pdf [Accessed 6 Aug 2024]

Ministry of Energy, 2020. National Green Hydrogen Strategy. [Online] Santiago. Available at: https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf [Accessed 6 Aug 2024]

Ministry of Industry, Energy and Mining, 2022. Green Hydrogen Roadmap in Uruguay. [Online] Available at: https://www.gub.uy/ministerio-industria-energia-mineria/comunicacion/noticias/green-hydrogen-roadmap-in-uruguay [Accessed 6 Aug 2024]

Ministry of Mines and Energy, 2021. Baseline to Support the Brazilian Hydrogen Strategy. [Online] Brasília: Energy Research Office (EPE). Available at: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-569/NT_Hidroge%CC%82nio_EN_revMAE%20(1).pdf [Accessed 6 Aug 2024]

Moernaut, R., Mast, J., Pauwels, L., 2018. Framing Climate Change: A Multi-level Model, in: Leal Filho, W., Manolas, E., Azul, A.M., Azeiteiro, U.M., McGhie, H. (Eds.), Handbook of Climate Change Communication: Vol. 1, Climate Change Management. Springer International Publishing, Cham, 215–271. https://doi.org/10.1007/978-3-319-69838-0_14

Najjar, Y.S.H., 2013. Hydrogen safety: The road toward green technology. International Journal of Hydrogen Energy, 38(25), 10716-10728. https://doi.org/10.1016/j.ijhydene.2013.05.126.

Natural Resources Canada, 2020. Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen - A Call to Action. [Online] Ottawa. Available at: https://publications.gc.ca/collections/collection_2021/rncan-nrcan/M134-65-2020-eng.pdf [Accessed 6 Aug 2024]

Noussan, M., Raimondi, P.P., Scita, R., Hafner, M., 2020. The Role of Green and Blue Hydrogen in the Energy Transition—A Technological and Geopolitical Perspective. Sustainability 13, 298. https://doi.org/10.3390/su13010298

Panchenko, V., Daus, Y., Kovalev, A., Yudaev, I. & Litti, Y., 2023. Prospects for the production of green hydrogen: Review of countries with high potential. International Journal of Hydrogen Energy, 48(12), 4551-4571. https://doi.org/10.1016/j.ijhydene.2022.10.084

Reda, B., Elzamar, A.A., AlFazzani, S., Ezzat, S.M., 2024. Green hydrogen as a source of renewable energy: a step towards sustainability, an overview. Environ. Dev. Sustain. https://doi.org/10.1007/s10668-024-04892-z

Reigstad, G.A., Roussanaly, S., Straus, J., Anantharaman, R., De Kler, R., Akhurst, M., Sunny, N., Goldthorpe, W., Avignon, L., Pearce, J., Flamme, S., Guidati, G., Panos, E., Bauer, C., 2022. Moving toward the low-carbon hydrogen economy: Experiences and key learnings from national case studies. Adv. Appl. Energy 8, 100108. https://doi.org/10.1016/j.adapen.2022.100108

Sinay, J., Weiterschütz, J., Jesný, M., Blaškovitš, P., & Sulík, R., 2021. National Hydrogen Strategy: Ready for the Future. [Online] Available at: https://nvas.sk/NVS_EN.pdf [Accessed 6 Aug 2024]

Snow, D. A., and Benford, R. D., 1992. Master frames and cycles of protest. In Frontiers in Social Movement Theory. Yale University Press.

Somenzi, E., Del Grosso, F., Pontoni, F., and Vaglietti, G., 2021. A Critical Assessment of National Hydrogen Strategies. FEEM Report no. 4 - 2021. ISBN 9791280348111

Sovacool, B.K. and Brossmann, B., 2010. Symbolic convergence and the hydrogen economy. Energy Policy 38, 1999–2012. https://doi.org/10.1016/j.enpol.2009.11.081

Squadrito, G., Maggio, G., Nicita, A., 2023. The green hydrogen revolution. Renew. Energy 216, 119041. https://doi.org/10.1016/j.renene.2023.119041

Stalker, L., Roberts, J.J., Mabon, L., Hartley, P.G., 2022. Communicating leakage risk in the hydrogen economy: Lessons already learned from geoenergy industries. Front. Energy Res. 10, 869264. https://doi.org/10.3389/fenrg.2022.869264.

Tseng, P., Lee, J., Friley, P., 2005. A hydrogen economy: opportunities and challenges. Energy, 30(14), 2703-2720. https://doi.org/10.1016/j.energy.2004.07.015.

U.S. Department of Energy, 2023. U.S. National Clean Hydrogen Strategy and Roadmap. [Online] Available at: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf?sfvrsn=c425b44f_5 [Accessed 6 Aug 2024]

Vollmer, B.A., 2014. Policy Discourses, Frames, Methods. In: Policy Discourses on Irregular Migration in Germany and the United Kingdom. New Perspectives in German Political Studies. Palgrave Macmillan, London. https://doi.org/10.1057/9781137307545_2

Weiskopf, S.R., Rubenstein, M.A., Crozier, L.G., Gaichas, S., Griffis, R., Halofsky, J.E., Hyde, K.J.W., Morelli, T.L., Morisette, J.T., Muñoz, R.C., Pershing, A.J., Peterson, D.L., Poudel, R., Staudinger, M.D., Sutton-Grier, A.E., Thompson, L., Vose, J., Weltzin, J.F., Whyte, K.P., 2020. Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. Sci. Total Environ. 733, 137782. https://doi.org/10.1016/j.scitotenv.2020.137782.

World Energy Council, 2021. WORKING PAPER | NATIONAL HYDROGEN STRATEGIES. [online] Available at: https://www.worldenergy.org/assets/downloads/Working_Paper_-National_Hydrogen_Strategies-_September_2021.pdf [Accessed 6 Aug. 2024]

Yap, J. and McLellan, B., 2024. Exploring transitions to a hydrogen economy: Quantitative insights from an expert survey. International Journal of Hydrogen Energy, 66, 371-386. https://doi.org/10.1016/j.ijhydene.2024.03.213.

Younas, M., Shafique, S., Hafeez, A., Javed, F., Rehman, F., 2022. An Overview of Hydrogen Production: Current Status, Potential, and Challenges. Fuel 316, 123317. https://doi.org/10.1016/j.fuel.2022.123317

Yu, X., Sandhu, N.S., Yang, Z., Zheng, M., 2020. Suitability of energy sources for automotive application – A review. Applied Energy, 271, 115169. https://doi.org/10.1016/j.apenergy.2020.115169.

Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., Hissel, D., 2021. Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. Renew. Sustain. Energy Rev. 146, 111180. https://doi.org/10.1016/j.rser.2021.111180.

Yusaf, T., Faisal Mahamude, A.S., Kadirgama, K., Ramasamy, D., Farhana, K., A. Dhahad, H., Abu Talib, A.R., 2024. Sustainable hydrogen energy in aviation – A narrative review. Int. J. Hydrog. Energy 52, 1026–1045. https://doi.org/10.1016/j.ijhydene.2023.02.086.