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Forecasting Technological Diffusion through Analogies:

Examining Historical Technologies to Assess the Future Growth of Green Hydrogen Electrolysis and Pipeline Network as Climate Mitigation Technologies

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Abstract

Green hydrogen is an advantageous clean energy carrier that enables the decarbonization of hard-to-abate sectors and addresses the intermittency of renewables. However, its global production is currently constrained by inadequate infrastructure, high investment risks, and relatively technological infancy. Failure to scale green hydrogen could hinder decarbonization efforts and climate goals. Recognizing these issues, this thesis examines the future growth of green hydrogen electrolysis in the EU and hydrogen pipelines in Europe using reference cases or historical technologies. Represented in feasibility spaces – multiparameter spaces for visualizing and assessing climate solutions to represent their likelihood of materializing – the maximum growth rates of the reference cases were evaluated against the required growth rates to achieve the future targets of the REPowerEU Plan, the EU's Hydrogen Roadmap, and the European Hydrogen Backbone. The results indicate that certain historical technologies, such as French nuclear power, Danish wind power, and German solar power, have surpassed the required growth rates for green hydrogen electrolysis, suggesting precedents that the required growth for green hydrogen electrolysis is within reach. However, solar and wind power in the EU fall short by 25% of achieving the necessary growth rates. For hydrogen pipelines, the study shows that the maximum growth rate of natural gas pipelines in Europe fails to reach pipeline addition targets by 15-30%. However, it may still be achievable with increased investment and accelerated growth. It is essential to consider the limitations and differences between the reference cases and target cases and tailor policy and technological diffusion insights from the selected reference cases to the unique geopolitical and socioeconomic landscape of the EU and Europe. Unlike previous studies focusing on engineering aspects, this thesis contributes to technology forecasting literature, particularly in formulating an analytical framework for reference case selection and using reference cases to assess the future growth of green hydrogen electrolysis and hydrogen pipelines. Scaling green hydrogen electrolysis and pipeline networks poses complex challenges but using established technologies as reference cases can inform methodologies and policies in the context of the EU.

Keywords: Technology diffusion, green hydrogen, electrolyze, pipeline, feasibility spaces, reference case forecasting

Executive Summary

Green hydrogen refers to hydrogen produced through electrolysis using renewable energy sources, which involves splitting water into its molecular components. This form of hydrogen is viewed highly for its advantageous characteristics, including its ability to store energy, mitigate the intermittency of renewables, and its versatility in decarbonizing hard-to-abate sectors like aviation and industry, where direct electrification is limited. Despite its energy security and sustainability potential, the global production of green hydrogen is currently constrained by factors such as inadequate infrastructure, high investment risks, and its early stage of development. Failure to scale green hydrogen at the required pace risks decarbonization efforts of the energy sector and, subsequently, the global climate agenda.

To support the advancement of this innovation, examining the diffusion and growth of historical technologies can provide valuable precedents for assessing the feasibility of green hydrogen growth and surface policy insights to replicate examples of successful energy technologies. Characterized as a technology forecasting study, this study employed valid historical technologies as reference cases in assessing the future growth of green hydrogen electrolysis and hydrogen pipelines – two of the most critical technological components of the hydrogen economy. Guided by an analytical framework comprised of four selection parameters, namely social function, granular-lumpy scale, technology readiness level, and growth rate/extent, the study identified eight energy generation technologies at varying scales as reference cases for assessing the future growth of green hydrogen electrolysis. Meanwhile, only natural gas pipelines have been identified to evaluate the feasibility of hydrogen pipelines' future expansion due to data limitations. This analytical framework substantiates the logical relationship between the historical technology (reference case) and the future technology (target case), thus, supporting further quantitative analysis.

To test the robustness of the identified reference cases, their maximum growth rates were calculated, normalized to their corresponding total electricity supply (TWh), and compared with the normalized growth rates required to reach future green hydrogen electrolysis targets. Such targets are captured in relevant policies relevant to green hydrogen electrolysis namely the REPowerEU Plan which sets to develop 100 GW of capacity by 2030, and the EU Hydrogen Roadmap for a Climate-Neutral Europe which aims at 500 GW capacity. The availability of quantitative targets enshrined in policies, as well as its front runner position in terms of existing capacity and leadership, made the EU as the backdrop for the assessment of the future growth of green hydrogen electrolysis. On the other hand, the growth rates of natural gas pipelines in Europe have been calculated and compared with the required growth rates to achieve the future targets of the European Hydrogen Backbone Initiative, which envisions the construction of 28,000 KM of hydrogen pipelines by 2030, and 54,000 KM by 2050, across Europe.

The two sets of maximum growth rates for the reference cases and the two sets of required growth rates for the target cases have been plotted in feasibility space to represent the implementation levels for technological growth that have been demonstrated historically. Feasibility spaces are multiparameter spaces that visualize climate solutions of interest in a matrix to represent their likelihood of materializing, depending on predefined parameters.

The results indicated that the maximum normalized growth rates of the country-level reference cases (French nuclear power, Danish wind power, and German solar power) significantly surpassed the necessary growth rates for green hydrogen electrolysis to meet future targets. French nuclear power exhibited the highest maximum normalized growth rate, exceeding the required targets for 2030 and 2050 by 264% and 243%, respectively. Overall, these country-scale examples of rapid technological diffusion surface valuable policy principles and insights

that can be replicated to reproduce the same level of success in the context of green hydrogen electrolysis in the EU.

Whereas the country-level reference cases exhibited rapid technological growth rates, the maximum normalized growth rates for solar power and wind power in the EU fell short by approximately 25% of achieving the growth rates required for the targets for green hydrogen electrolysis in 2030 and 2050. This would suggest that to achieve the EU's future targets for green hydrogen electrolysis, unprecedented effort, investment, and policy coordination are crucial, more than what has been exerted for solar and wind power in the EU. And lastly, the maximum normalized growth rates of the global level reference cases fail to reach the 2030 and 2050 targets by approximately 40%.

In terms of pipelines, the study showed that the maximum growth rate of natural gas pipelines in Europe (26,153 km) falls short by 31% and 15% of reaching the EHB's hydrogen pipeline addition targets by 2030 and 2040, respectively. However, applying a +20% threshold for 26,153 km to account for data uncertainties would suggest that the 2040 target can still be within reach, subject to increased investment and accelerated growth observed for natural gas pipelines between 1991 and 2001.

While there are technology growth insights that can be surfaced from reference cases and applied to target cases, precaution must be taken, given three things. First, reference cases provide some level of abstraction but are limited by what they can explain and, thus, what can be applied and relevant to target cases. Second, there are inherent differences between the country-scale reference cases and the EU-level green hydrogen electrolysis targets, such as GDP and size of energy systems – factors that could have influenced the difference in their growth rates. And third, applying other scales (national or global) of policy insights into the level of the EU requires tailoring to the region's unique geopolitical and socioeconomic landscape.

Whereas the study's findings have important practical and policy propositions, the thesis contributes significantly to the literature on technology forecasting study on three grounds. First, the covered literature does not employ frameworks for selecting reference cases except Jewell and Cherp's (2023) framework on constructing feasibility spaces. Second, this study contributes to the limited literature on assessing the future growth of green hydrogen electrolysis using reference cases. Using a combination of historical technologies at various scales, the study expands the approach by Odenweller et al. (2022), who used solar and wind as reference cases for forecasting green hydrogen production. And lastly, the thesis contributes to technology forecasting and the use of reference cases for assessing the future growth of hydrogen pipelines. Most hydrogen pipeline studies pursue an engineering angle and examine fuel mixing with natural gas or the conversion of natural gas pipelines into hydrogen-ready transport infrastructure. Unlike most studies that primarily focus on the engineering aspects and the integration of hydrogen with natural gas pipelines, this thesis used natural gas pipelines as a reference to examine the future growth of hydrogen pipeline targets of the EHB.

In conclusion, the study recognizes the complex technological and infrastructure challenge of scaling green hydrogen electrolysis and pipeline network in relevant jurisdictions. Using established technologies as reference cases provides a valuable point of comparison, which have important methodological and policy implications.

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Abbreviations

AR – Assessment Report

BAU – Business as Usual

BECCS – Bioenergy with Capture and Storage

CCS – Carbon Capture and Storage

CCUS – Carbon Capture Utilization and Storage

EU – European Union

EC – European Commission

ETP – Energy Technology Perspective

IAM – Integrated Assessment Model

IEA – International Energy Agency

IPCC – Intergovernmental Panel on Climate Change

PEM – Polymer Electrolyte Membrane

RES – Renewable Energy Source

SDG – Sustainable Development Goal

SDS – Sustainable Development Scenario

SPS – Stated Policies Scenario

TRL – Technology Readiness Level

UNFCCC – United Nations Framework Convention on Climate Change

1 Introduction: Energy Technologies and Climate Change

The Paris Agreement is a groundbreaking step by the global community to tackle climate change, aiming to hold global mean temperature beyond 1.5°C above the pre-industrial era through reinforced measures (The Paris Agreement, 2015). Turning 1.5°C-compatible climate pathways into a reality hinges on the decarbonization of the energy sector, which entails the extensive rollout of various technologies (IEA, 2020). Together with the continued uptake of renewables and energy efficiency, decarbonizing the energy sector depends on the accelerated deployment of four low-carbon and net-emission technologies namely end-use electrification, carbon capture utilization and storage (CCUS) systems, hydrogen and hydrogen-derived fuels, and bioenergy (*Ibid.*). Bringing these future technologies to the needed scale persists as a challenge and could undermine the targets of the Paris Accords and the Sustainable Development Goals (SDG) if not overcome.

Investigating historical examples can provide valuable insights into the diffusion of the aforementioned low-carbon and net-emission technologies. Historical technologies have achieved widespread and ubiquitous use and studying them can reveal patterns and lessons for assessing the feasibility of future technological growth (van Sluisveld et al., 2015). This presents opportunities to understand the drivers and barriers to technological growth, which have significant implications for policy design and financial investments. Overall, technology forecasting, defined as an intentional and systematic effort to predict and understand the possible trajectory, pace, attributes, and impacts of technological advancements, particularly innovations (Firat et al. 2008), plays a crucial role in understanding the pathways of energy and climate innovations, and in decarbonizing today's economy.

1.1 Green Hydrogen and climate neutrality

Green hydrogen is a form of hydrogen derived from electrolysis powered by renewables (Ueckerdt et al., 2021), and is considered to play a key role to help achieve net-zero emissions by 2050 due to its capacity to be stored and transported in high volumes over long distances (Hydrogen Council & McKinsey & Company, 2022). Its versatility makes it an attractive option to decarbonize hard-to-abate sectors like industry and aviation, where direct electrification is not technically viable to date (IEA, 2022a).

However, unlocking hydrogen in the global agenda for clean energy transition is subject to continued innovation, reduction in costs, and enhancement of the performance of commercially available technologies, which would allow the diffusion of next-generation hydrogen technology IEA (2022). According to the Hydrogen Council and McKinsey & Company (2022), achieving net zero requires global production of more than 660 million tons (Mt) of hydrogen. The challenge for governments and investors is to orchestrate resources to scale such production given that green hydrogen for industrial and clean energy vector purposes remains at an early stage of technological growth (IEA, 2020). For instance, electrolysis, or the process of splitting water molecules into its two components H_2 and O using renewable electricity is commercially available and operational in specific countries but needs incremental development to stay economical (IEA, 2020). To date, global electrolyzer capacity is around 8 gigawatts (GW) per annum, and can achieve 60 GW annually by 2030 according to industry forecasts (IEA, 2022a).

In 2022, the European Commission (EC) put forward the REPowerEU Plan to accelerate the EU Green Deal, cut off the bloc from Russian fossil fuel imports before 2030, and help ensure energy security (IEA, 2022a). This plan envisions the production of 10 Mt of green hydrogen by 2030 – which is approximately equivalent to 100 GW electrolysis capacity – and importing the same volume from other countries (EC, 2020). Further, the EU Hydrogen Strategy aims for 500 GW of such capacity by 2050 (*Ibid.*).

In terms of infrastructure, hydrogen pipelines require further integration for them to attain commercial and viable levels (IEA, 2022b). The European Hydrogen Backbone (EHB) is a consortium of 31 European gas infrastructure companies from 25 EU Member States (MS), Norway, and the United Kingdom, which committed to building hydrogen supply corridors across the continent and eventually with neighboring countries (van Rossum et al., 2022). The initiative aspires to develop a 28,000 km pipeline network of low-emission hydrogen supply by 2030 to connect hydrogen valleys in the continent.

By 2040, the network shall expand beyond the region and cover a pan-European network of around 53,000 km, 60% of which is converted natural gas pipelines and 40% new and dedicated hydrogen pipelines. To date, the total length of hydrogen pipelines in Europe is roughly 1,600 km (H2Tools, 2021), which pales in comparison to existing natural gas transmission and distribution pipelines at approximately 1.2 million km (CEER, 2016; as cited by Lambert & Schulte, 2021). At a more global level, the fulfillment of successful hydrogen trade hinges on the development of hydrogen pipeline infrastructure with the capacity to transport 200 MT per annum by 2050, to connect key markets like the EU, the United States, and China (Hydrogen Council & McKinsey & Company, 2022).

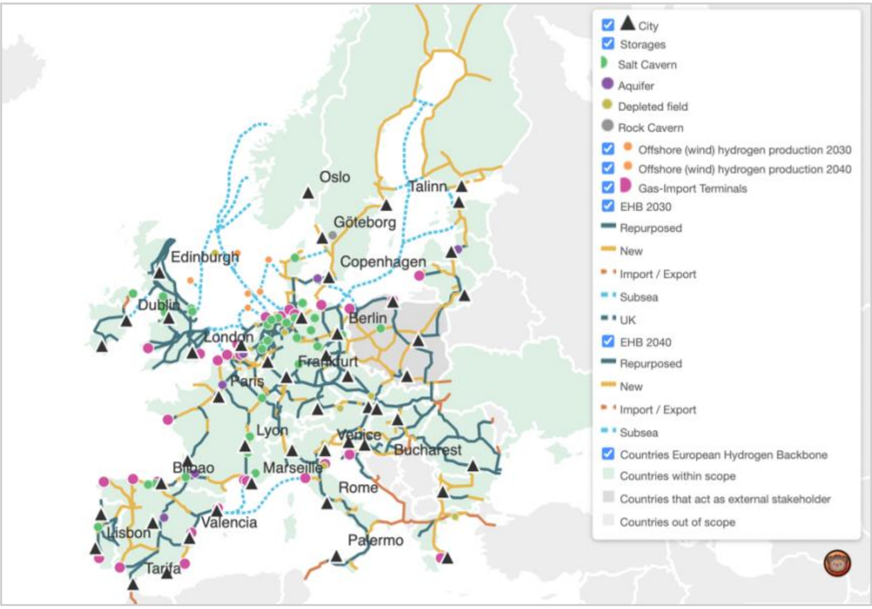

Figure 1: Map of the European Hydrogen Backbone and the envisioned infrastructure up to 2040[1]

Overall, given the current status of both technologies, and tightening policy ambitions, climate commitments, and implementation timelines, governments and industry need to ensure hydrogen electrolysis capacity and the pipeline network infrastructure grow consistently and rapidly while minimizing investment risks along the way. In the context of this study, investigating historical examples of energy and climate technologies can provide valuable insights into assessing the feasibility of their future growth, and understanding the broad policy landscape that can help promote their rapid deployment by leveraging historical experience.

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[1] Map directly lifted from the interactive site/report of the European Hydrogen Backbone Initiative (van Rossum et al., 2022).

1.2 A new approach to forecasting technology diffusion

The literature on technology forecasting is well covered, either when forecasting the future growth of energy pathways or technologies using their own historical data under different climate or growth constraints (Chen et al., 2010; Cherp et al., 2021; Grübler, 1999; Iyer et al., 2015; Kramer & Haigh, 2009; van Sluisveld et al., 2015), or using references cases, where the historical data or experience of a different technology is used as benchmarks to predict the future growth patterns of another (Höök et al., 2012; Odenweller et al., 2022; van Ewijk & McDowall, 2020). There are also several studies that use a combination of both categories of technology forecasting (Lund, 2006; Wilson, 2012; Wilson et al., 2013a).

Falling under the first category, Iyer et al. (2015) used the historical average annual growth rates of bioenergy, nuclear, CCS, and renewables, and examined how they would grow in the future if capped at a maximum growth rate of 5%, 10%, and 15% a year. They found that factors related to organizations, human actions, and societal norms and values can significantly affect both the feasibility and costs of attaining carbon budget targets, which can be impeded by delays in climate policies. Broadly, delaying the deployment of CCS and renewables only increases their costs dramatically, to nuclear or bioenergy (Iyer et al., 2015).

On the other hand, and classified under the second category of technology forecasting studies, Odenweller et al. (2022) used historical growth data of solar PV and wind power and assessed the feasible deployment trajectories of electrolysis capacity – a key component for green hydrogen production. Using the unique growth rates of the two renewables as reference cases to test the feasibility of green hydrogen production, they found out that hydrogen will stay insufficient in the short term and uncertain in the long run.

This thesis brings a new approach to studying the technological diffusion of future technologies following two stages. The first stage involves a broad, qualitative analysis that examines the feasible growth of hydrogen electrolysis and pipelines as climate mitigation technologies at the European Union level. The analysis is extended by diving deeper into a more specific quantitative analysis where the feasibility of the future growth of hydrogen electrolysis and pipeline network is assessed using the historical experiences of the identified reference cases.

The combined approach of macro and micro analyses can yield insights into how robust and applicable historical evidence can be applied to assess the future growth of technologies. The findings of this thesis can have important contributions to the literature on both categories of technology forecasting in terms of the methodological approach.

At a practical and policy level, empirical analyses of historical technological growths can help reveal historical precedents, which can be applied to forecasting future technological diffusion under stringent and ambitious climate scenarios. Further, the study can help point to important barriers and success factors like government regulations, financial investments, and research and development (R&D), among others, in terms of promoting the future growth of hydrogen electrolysis production and pipeline network.

Ultimately, these insights can be useful to support the decarbonization of the energy sector. Policies can help promote the accelerated diffusion of low-carbon technologies (Jaffe *et al.*, 2005). The implementation pathways of low-carbon technologies can also be shaped by organizational, psychological, and human factors, despite an enabling climate policy landscape (Hultman et al., 2012). Ultimately, results can help surface historical experiences and parameters that can be replicated in the creation of an enabling environment for the production of hydrogen electrolysis and the development of hydrogen pipeline infrastructure.

Nevertheless, this thesis recognizes an important caveat that there are limitations to the extent to which historical evidence can be applied to assess and forecast future technological diffusion. Projecting future growth on the grounds of historical trends can be insufficient, "*especially when the underlying causal processes are complex and liable to change*" (Grübler, 1999, p. 21). One limitation to the use of historical transition rates as benchmarks is that they may not be entirely accurate due to the potential occurrence of rapid short-term growth rates in specific regions and for individual technologies and energy resources (Napp *et al.*, 2017). Likewise, time and geographical boundaries can affect analysis, resulting in uncertainties with the comparison (Nemet, 2009). Nonetheless, this does not mean signify that governments and industries cannot overcome barriers to technology adoption and diffusion, and replicate it in large scales (Napp *et al.*, 2017). Therefore, as this thesis aspires to contribute to the literature on low-carbon and net-emission energy technologies' future forecasting, it is also important to recognize such caveats.

1.3 Research aims and questions

This thesis aims to contribute to the literature on technology forecasting within the context of energy sector decarbonization and climate mitigation technologies. Grounded on literature, the study postulates that examining the historical growth diffusion of energy technologies can offer empirical insights to anticipate and inform future energy and climate innovations. More specifically, the study addresses the following questions:

- RQ1: What are the valid reference cases to assess the feasible growth of green hydrogen electrolysis and pipelines as climate mitigation technologies?

- RQ2: What is the feasibility of green hydrogen electrolysis in light of observations from the reference cases?

- RQ3: What is the feasibility of hydrogen pipeline network in light of observations from the reference cases?

The first research question (RQ1) seeks to make broad comparisons between the growth and diffusion of historical (reference cases) and future (target cases) technologies. RQ1 involves the formulation of an analytical framework developed from selected parameters based on literature and uses this framework to identify valid and robust reference case technologies for assessing the future growth of green hydrogen electrolysis and pipelines.

Through a broad, qualitative analysis, RQ1 explores the suitability of selected reference case technologies as benchmarks for evaluating the potential growth of green hydrogen electrolysis and pipelines. By examining historical technologies that share similarities with the target cases, this question aims to understand the underlying mechanisms and deployment patterns that can be expected for future technologies. This qualitative analysis enables the study to make reliable comparisons between the growth of historical and future technologies, taking into account factors such as maturity levels, expansion speeds, and materiality. Furthermore, this macro-level examination of technological growth serves as the foundation for the more specific case comparisons explored in RQ2 and RQ3.

Building upon the method established in the initial stage, RQ2 and RQ3 undertake a more focused quantitative analysis simultaneously. RQ2 examines the potential for future growth in green hydrogen electrolysis capacity through the evaluation of a specific set of identified reference case technologies. Similarly, RQ3 assesses the feasibility of future growth in hydrogen pipelines by employing a distinct set of reference cases. Both research questions delve into the quantitative assessment of feasibility, while for different aspects, contributing to a comprehensive understanding of the growth potential in the respective domains.

1.4 Scope and limitations

The research acknowledges the broad potential of the analytical framework for forecasting reference case technologies in various sectors. Additionally, it highlights the significance of the aforementioned four specific clusters of low-carbon and net-emission technologies. However, the study narrows its focus to green hydrogen electrolysis and pipelines as climate mitigation technologies. This choice is primarily driven by the limited existing research on assessing their future growth using reference case technologies. Likewise, these two specific hydrogen technologies satisfy the parameters set in the analytical framework, which strengthens the justification behind comparing them with the historical or reference case technologies.

RQ2 specifically examines the growth forecast of green hydrogen electrolysis within the European Union (EU). While the expansion of green hydrogen production is a global priority with hydrogen markets emerging in various regions, the study acknowledges the bloc’s prominent position in terms of existing capacity and strong policy commitments. The EU's concrete targets for future green hydrogen electrolysis capacity provide a numerical basis for the study's focused and quantitative analysis. Additionally, by concentrating on the EU, the study addresses technical challenges associated with normalization. Normalization is an important mathematical step that enables the comparison of growth rates among different technologies, accounting for significant differences such as the size of the energy system and the scale of the technology (global, regional, national). Examining green hydrogen electrolysis projects at a global scale, which are not evenly distributed worldwide, presents difficulties in achieving effective normalization.

Moreover, RQ3’s objective of assessing the future growth of hydrogen pipelines focuses on Europe as a whole instead of the EU. This is primarily due to the availability of quantifiable future targets through the European Hydrogen Backbone, which includes countries like the United Kingdom and Romania. Similar to RQ2’s justification of scope, the expansion of hydrogen pipelines is a global pursuit but the absence of concrete, numerical targets at an international level inhibits the study’s focused quantitative analysis.

Overall, the study recognizes that findings are just an approximation and that numerous parameters could shape the future growth of green hydrogen electrolysis capacity in the EU and hydrogen pipelines in Europe. In the same vein, it concedes that there are limitations to the use of historical technologies as reference cases for assessing the future growth of emerging technologies.

1.5 Audience

This study is intended for researchers working in the area of technology diffusion, reference and target cases, and forecasting of climate mitigation technologies, particularly hydrogen and its various technological components. The results of the study may be useful for researchers who are interested in assessing the future growth of hydrogen electrolyzer capacity and pipeline infrastructure, either on the global or European scale.

While the outcomes of this thesis may be illustrative and subject to technical limitations, they may also have implications for policymakers in the climate mitigation sector. For instance, they may offer insights into the future feasibility of ambitious policy and investment commitments for hydrogen capacity and infrastructure, and the uncertainties they face as demonstrated by historical technological precedents.

1.6 Disposition

Having introduced the broad sustainability context and rationale, the thesis proceeds by reviewing and analyzing relevant literature, with emphasis on technology diffusion and feasibility space studies using reference cases. A brief discussion of how the study contributes to the literature is also presented. Next, the methodology section outlines the steps taken to address the three research questions. Results and discussions are presented for both broad and specific analyses, including policy explanations as to why green hydrogen electrolysis and pipelines have grown in such a manner. On top of policy recommendations on accelerating the diffusion of green hydrogen electrolysis and pipeline to achieve specific regional targets, methodological reflections on enhancing future studies in this subject are presented.

1.7 Ethical Considerations

No significant ethical considerations are anticipated given the technical nature of this study. Research design has been reviewed against the criteria for research requiring an ethics board review at Lund University and has been found to not require a statement from the ethics committee. All data used for this research are publicly available and are referenced and cited appropriately. Whereas there have been substantial changes beginning the identification of the topic for this thesis, it is also recognized that the original idea for this study came from Prof. Aleh Cherp, who is also the supervisor of the author. No potential issues arising from conflicting interests are foreseen. Lastly, guidance and support from the Political Economy of Energy Transition (POLET) Research Group is acknowledged.

2 Literature Review: Forecasting technology diffusion and growth

The literature review section focuses on studies in the areas of technology forecasting and diffusion of energy technologies. Two categories of such studies were surfaced as listed below and are discussed in detail in their corresponding sections. The majority of the studies for both literature categories forecasted technological growth under defined climate change scenarios (i.e., 1.5 °C and 2 °C average global warming scenarios).

1. Category 1: Assessing the feasibility of the growth rates of future technologies using the historical growth of technologies from the same technological cluster
2. Category 2: Assessing the feasibility of the growth rates of future technologies using the historical growth of a proxy technology or a reference case

Understanding the key differences between the two categories helps in the methodological design of this thesis in terms of the selection of reference and target technologies, normalization metrics for cross-technology comparison, climate constraints parameters for future growth forecasting, and applicability and validity of using historical evidence to assess the feasibility of future growth.

For conceptual purposes, this thesis follows IPCC's (2000) definition of technology, which is "*a piece of equipment, technique, practical knowledge or skills for performing a particular activity.*" Further, Müller (2003) disaggregates technology into three categories namely (i) hardware or the physical aspects of the technology such as machinery, equipment, and goods, (ii) software or the procedures linked to the creation and use of the hardware, and (iii) orgware or the structure of the establishment/group engaged in the acceptance and spread of technology. These form part of a technology although their significance can differ depending across technologies

Further, as defined by Firat et al. (2008), technology forecasting pertains to "*all purposeful and systematic attempts to anticipate and understand the potential direction, rate, characteristics, and effects of technological change, especially invention*" (p. 2). These forecasts are done to help policymakers make informed decisions about enabling regulations, allocating financial resources for research and development, and establishing the necessary infrastructures to help them scale. They also help investors to understand the feasibility of technologies to scale, and therefore, channel resources where the ventures are optimal. Based on historical data, these forecasts are generated from models and make specific assumptions to help infer future growth and diffusion patterns.

2.1 Metrics for measuring technological diffusion

There are two key systems of measurement for technological diffusion as pointed out by Iyer et al. (2015) in a review of technology forecasting studies. The first is the growth rate, which characterizes the difference between the two points and posits that the technology scale is inversely proportional to its growth (Höök *et al.*, 2012). The second one is logistic or S-shaped growth functions, which are characterized by several phases of technological growth (Wilson *et al.*, 2013; Gru, 1999). Under the second metric, new technology will enter specialized or niche markets, demonstrating an advantage over current technologies and attaining up to 5% of the market share. The technology's broad use will then propel it dramatically through "pervasive diffusion", until a point that it saturates to normalcy (Grübler, 1999). The duration for technologies to scale from 10% to 90% resembles an S-curve, characterizing technological growth and diffusion (*Ibid.*).

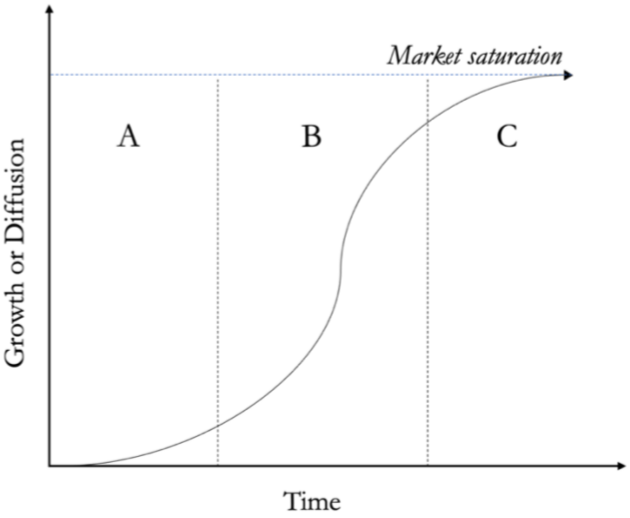

Figure 2: A simplified and stylized S-curve and its three key phases, as represented by three letters: A - formative phase; B - growth phase; and C - saturation phase.

A concept highly related to this is learning or experience curves, which are functions that capture the cost reductions that come with the increase in the unit production of technologies, particularly in their earlier stages, due to the accumulation of experience by industries and companies (Grübler, 1999). Similar to S-shaped growth functions, they can help provide an empirical basis for the competitiveness of technologies given the right investments. For instance, Neij's (1997) research forecasted the diffusion of wind turbines and photovoltaics and discovered that experience does not necessarily reduce technological costs but opens opportunities to do so. Her analysis shows increased prospects for the adoption of wind turbines and PV modules with the right policy instruments (Neij, 1997). Schilling and Esmundo (2009) share similar results when they used government R&D and cost reduction data to generate S-curves and demonstrated how wind and geothermal energy can be more economically competitive than fossil fuels in the short term if the funding gap is addressed by the government.

Lastly, Kramer and Haigh's (2009) characterization of energy-technology deployment is nuanced in the way that they stylized it in their two laws based on the expansion of energy technologies including fossil fuels, renewables, and nuclear. The first law states that new technologies undergo decades of exponential growth, which is the equivalent of 26% per year, until a certain point that technology achieves “materiality”, which they define as attaining approximately 1% of world energy. The second law dictates that after reaching this point, growth becomes linear or approximately 2% - 4% growth annually and remains at a certain share of the market. For emerging green technologies to diffuse pervasively, government policies should promote major shifts in infrastructure and ensure a continuous flow of financial resources (Kramer & Haigh, 2009).

2.2 Conventional future technology forecasting

The first category of literature captures studies that assess the feasibility of future technologies’ growth rates using the historical growth of the same technologies under stringent climate mitigation or growth scenarios. Discussing such studies presents the initial context of technology forecasting and their methods of choice. A summary of these key studies falling under the first category is presented in Table 1.

Studies by Iyer *et al.* (2015) and Napp *et al.* (2017) effectively represent future growths of various energy technologies under strict climate scenarios. Iyer *et al.* (2015) used the historical average annual growth rates of bioenergy, nuclear, CCS, and renewables, and examined how they would grow in the future if capped at a maximum growth rate of 5%, 10%, and 15% a year. They found that factors related to organizations, human actions, and societal norms and values can significantly affect both the feasibility and costs of attaining carbon budget targets, which can be impeded by delays in climate policies. Broadly, delaying the deployment of CCS and renewables only increases their costs dramatically, to nuclear or bioenergy (Iyer *et al.*, 2015).

Napp *et al.* (2017) nuanced their study by assessing existing mitigation scenarios for various periods and atmospheric stabilization levels (e.g., 450, 550 ppm CO_2) by matching them against the deployment rate of low-carbon technologies and transitions between primary energy sources. Their findings reveal that these scenarios often overestimate the historically established deployment rate of low-carbon technologies which is 20% per year. Applying constraints to the models, the study showed that scenarios failed to achieve a 2° stabilization level, underpinning the need to deploy low-carbon energy supply technologies and slash fossil fuel use at an unprecedented rate and scale.

Similarly, the study by van Sluisveld et al. (2015) focuses on the comparison of the different methods used by studies that employ historical data and evidence as benchmarks for future energy transition analyses and used such methods to assess model results. Using a set of indicators e.g., average annual capacity additions, average annual emissions decline rates, etc., they tested how modeled future changes in rate fare against actual historical evidence. Whereas they found that none of the indicators could categorically tell if scenarios are feasible, they point out that indicators that consider broader system developments such as GDP indicate that changes in the future are generally consistent with historical evidence.

In a different vein, one possible challenge with examining the future growth of emerging low-carbon technologies such as hydrogen and CCUS is the availability of historical and robust data. To address this, Chen et al. (2010) used bibliometric and patent analysis to explore the components of hydrogen energy and fuel cell technologies and fitted these data into technological S-curves. Complementing this with empirical analysis through a survey of experts and co-word analysis, they found that hydrogen generation and storage technologies are still on their way to maturity due to strict requirements for storage systems and technological constraints, while fuel cell technology is already mature if not close to approaching maturity.

van Sluisveld et al. (2015) also pointed out the different issues faced by future energy transition models based on historical data namely system focus, temporal and spatial scales, and normalization, all of which are to be considered in the design of the study's model and ensuring its technical soundness. For example, Napp et al., (2017) stress the need to normalize temporal and spatial elements to avoid unfair comparisons between future energy transition models and historical evidence.

Table 1: Key studies that assess the feasibility of future technologies' growth rates using the same technology's historical growth in climate change scenarios

Author	Reference Case or Technology	Target Case[2] or Technology	Model/Methodology Used
Grübler (1999)	Energy technologies (combustion gas turbine, conventional coal power plant, nuclear, renewable power plants, etc.)	Impact of technological changes on the global environment (i.e., global warming)	Combination of historical analysis and new modeling techniques
Kramer & Haigh (2009)	Global primary energy sources (oil, nuclear, biofuels, wild, solar, CCS, etc.)	Emerging renewables in Shell's decarbonization scenario (i.e., Blueprint Scenario to 2050)	Energy-technology deployment curve to 2050
Chen *et al.* (2010)	Hydrogen generation, storage, proton exchange membrane fuel cell, solid oxide fuel cell, and direct methanol fuel cell/direct alcohol fuel cell	Hydrogen energy and fuel cell technologies	Bibliometric and patent analysis into the logistic growth curve; Empirical analysis via an expert survey; co-word analysis using the USPTO database
van Sluisveld *et al.* (2015)	Indicators including technology expansion and diffusion, emissions, and energy supply investments	Patterns of energy system change in future 2°C scenarios	Harmonized methods from studied models
Iyer *et al.*, (2015)	Major supply-side electricity generation technologies (bioenergy, renewables, CCS, nuclear)	Feasibility of climate scenarios using three annual technological growth rate constraints (i.e., 5%, 10%, and 15%)	GCAM Integrated Assessment Model
Cherp *et al.*, (2021)	Growth of wind and solar power (national and global)	Global and regional growth of wind and solar in climate mitigation scenarios (1.5 °C and 2 °C)	Maximum growth rates in S-curves

2.3 Forecasting using reference cases and historical analogies

This section of the literature focuses on studies that use historical data of one set of technology to serve as a reference case – or points of comparison – for the modeling and forecasting of another set of technologies. In the context of this study, reference case studies inquire on the growth of a future technology using a different set of technology as a proxy e.g., fossil fuel power plants to forecast hydrogen electrolysis growth. A summary of these key studies is presented in Table 2.

Höök *et al.*, (2012) used "*forecasting-by-analogy*" (p.34) to examine the past production time series data for six energy sources that account for 95% of the world's energy system namely oil, coal, natural gas, biomass, nuclear, and hydropower. They determined the scaling behavior of these energy technologies – or the proportionality between growth rate and size – which they used to assess the feasibility of future energy systems (renewables including wind, solar, etc.) that hinge on accelerated renewable energy deployment. Using their empirical and theoretical data, they suggest that it is impractical to anticipate that the growth patterns of the future energy system will significantly deviate from those of the past. Therefore, even if new energy systems follow extreme historical comparisons such as oil, which grew by 7% annually for a century, the global energy systems cannot be significantly altered by new energy systems alone.

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[2] Technology or scenario/pathway being forecasted, often under specific conditions.

The approach of Odenweller et al. (2022) mirrors this by also using technologies that followed high growth rates like wind and solar power, and unconventional ones like nuclear power in France and high-speed railway in China. Following an S-shaped logistic technology diffusion model and fitting the data using a probabilistic parameterization method, Odenweller et al. (2022) investigated the probable deployment trajectories of electrolysis capacity, a crucial component for the production of green hydrogen. They found that even if electrolysis capacity achieves the unprecedented growth rates of wind and solar, the supply of green hydrogen will stay inadequate in the immediate future and speculative in the long run, with ≥75% probability of supplying <1% of the final energy by 2030 in the European Union and 2035 at the global level. Their study reveals that it is a combination of insufficient supplies in the immediate term and technology uncertainty in the long term that hinders investments in hydrogen end uses and infrastructure. Insufficient supplies in the short run are problematic due to a "three-sided chicken-and-egg problem", where hydrogen supply, demand, and infrastructure have to be delivered and accelerated at the same time (Schlund et al., 2022).

To examine how carbon capture technologies can diffuse, van Ewijk and McDowall (2020) studied the diffusion patterns of flue gas desulfurization (FGD) as a historical analogy, noting its fundamental similarity with CCS, both being end-of-pipe technologies designed to filter emissions from flue gases, for storage, disposal, or byproduct conversion. Despite the obvious differences between the two such as the need for transport and storage infrastructures in the case of CCS, they share similar aspects such as regulatory needs, financial feasibility, and economies of scale, analyzing FGD growth as a robust basis to understand possible growth patterns of CCS (van Ewijk & McDowall, 2020). Two normalized indicators were calculated: the first is the rate of FGD diffusion formulated as the number of years between 10 and 90% of the saturation level and is expressed in Δt, and the second is the extent of diffusion by either absolute capacity or share of the total market, presented as the saturation level of the logistic curve. To enable comparison, FGD models were compared with CCS diffusion models taken from two scenario databases, namely the SR15 database of scenarios, and the AMPERE database by the International Institute for Applied Systems Analysis (van Ewijk & McDowall, 2020). Models for both technologies were normalized using each respective model's global GDP projection and global GDP data. Contrary to established literature and the second law of energy-technology development as proposed by Kramer and Haigh, (2009), findings characterize FGD diffusion as a "*stepwise*" process that continues to diffuse beyond materiality, as opposed to a single S-curve that slows down. Nonetheless, is it very uncommon for normalized CCS diffusion models to surpass the maximum diffusion rates of FGD, and that robust, forward-looking regulations are critical to support the extensive diffusion of end-of-pipe technologies such as CCS (van Ewijk & McDowall, 2020).

Table 2: Assessing the feasibility of future technologies' growth rates using the historical evidence of a proxy technology or a reference case in climate change scenarios.

Author	Reference Case	Target Case[3]	Model/Methodology Used	Criteria used for valid comparison between technologies studied
Höök *et al.* (2012)	Fossil fuels (coal, oil, gas)	New energy systems (renewables)	Year-over-year (YoY) growth rates	Proportionality between growth rate and size
van Ewijk & McDowall (2020)	Flue gas desulfurization (global coal market)	CCUS in 1.5 °C and 2°C average global warming scenarios	Regressions of logistic curves; calculated rate of diffusion (Δt) and extent of diffusion (saturation level of the logistic curve, either in absolute capacity or share of the total market)	Both end-of-pipe technologies; function as flue gas filtration (for storage, disposal, or conversion to new products)
Odenweller *et al.* (2022)	Wind and solar (fastest relative growth period of 1995–2010)	Future deployment of electrolysis capacity for green hydrogen production	S-shaped logistic technology diffusion model, integrated with a probabilistic parameterization method	Unconventional growth rates (faster than annual growth rates of most technologies)

2.4 Combining conventional and reference case forecasting

Lastly, it is worth mentioning that a number of studies can be classified under both in the sense that they use a wide range of historical technologies, covering both familial/related technologies and reference cases. A summary of these technologies is presented in Table 3.

For instance, Lund (2006) examined the market penetration rates of 11 emerging energy production and end-use technologies by fitting real market data to an S-shaped technology diffusion model. Using 20 data sets across various energy technologies in different regions (e.g., biomass in Finland, photovoltaics in Germany, global wind energy, etc.), as well as global nuclear power and oil data as reference cases or benchmarks, it was found that the emerging energy technologies' exponential penetration rates can vary by a range of 4% to 40% annually. Similarly, the penetration rates of these technologies are inversely proportional to their market share and time interval.

Wilson (2012) studied a range of energy technologies spanning end-use technologies (e.g., cars, compact fluorescent light bulbs, mobile phones, etc.) and energy supply technologies (e.g., refineries, large-scale fossil-fuel fired power plants, small to medium-scale renewable power plants), and explored how fast and prevalently these technologies diffused in the past. Delineating growth at a unit level (defined as up-scaling) and industry level (cumulative production), he observed that the growth in the unit size is dependent on the extensive experimentation and research of smaller-scale units, and that market and economic forces can counteract the rate and timing of unit-level up-scaling. More importantly, he suggests that there are major risks to drastically catapulting unit size of smaller-scale unit energy technologies without going through a formative phase – a period where technologies undergo cycles of testing, modification, and development to match market demands (Jacobsson and Bergek, 2004; as cited by Wilson, 2012). At a policy level, this suggests ensuring optimal timing when introducing technology policies to promote unit-level technology growth and encouraging up-

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[3] Technology or scenario/pathway being forecasted, often under specific conditions.

scaling investments that are backed up by robust small-scale applications or "commercial experiments" or else run the risk of premature policy intervention.

Table 3: Key studies that assess the feasibility of future technologies' growth rates using the historical growth of familial/related technologies and reference cases

Study and Author	Reference Case or Technology	Target Technology[4] or Case	Model/Methodology Used	Rationale and Criteria for technology selection
Lund (2006)	Nuclear power (World 1965–2003 and France 1965–2003), and oil (World 1880–1980 and France 1965–2003)	Market penetration rates of the 11 emerging energy technologies (different stages of maturity across different geographical areas)	Penetration rates are determined by fitting market data to an S-shaped technology diffusion model	Range of energy production and energy end-use technologies across regions and with varying levels of market maturity; Nuclear power and oil are established technologies and can serve as reference cases
Wilson (2012)	Energy supply technologies (refineries, renewable plants, etc.), and end-use technologies (jet aircraft, etc.)	Unit-level growth (up-scaling) and industry-level growth (cumulative production) for energy technologies	Logistic growth function following three parameters i.e., *K* or saturation level or asymptote, Δt or duration of growth, and t_0 or maximum growth	Unit and industry scaling properties apply to historical and emerging technologies
Wilson *et al.*, (2013)	Energy supply technologies (refineries, natural gas) and end-use technologies (e.g., passenger cars, CFL light bulbs, etc.)	Forecasted capacity expansions of low-carbon energy technologies, against diffusion based on historical evidence	Capacity growth trajectories from MESSAGE	Shared properties between reference and target cases: technology cumulative installed capacity

2.5 Feasibility Space: tool for assessing future technological growth

Feasibility spaces are a tool for evaluating the feasibility of a climate strategy or solution based on its specific characteristics, contextual factors, and implementation levels (Jewell & Cherp, 2023). It is characterized as a "virtual, multidimensional space" (Jewell & Cherp, 2023, p12) that juxtaposes a particular climate change solution in a plot depending on the likelihood that it can materialize or deliver its objectives in the future, depending on certain benchmarks. One defining property of this method is how it enables the visual representation of a solution's feasibility by a gradient called "implementation levels" (Jewell & Cherp, 2023), which can be constructed from the presence of historical precedents. Relatedly, Odenweller et al., (2022) employed a probabilistic approach to feasibility spaces in forecasting the future growth of green hydrogen electrolysis globally and in the EU by looking at the historical precedents of conventional energy sources such as solar and wind power. The use of feasibility space and how it is operationalized in the context of this study is discussed further in the methodology section.

On a more practical level, feasibility spaces are used to help in the prioritization of climate solutions and build scenarios using hypotheses that are based on evidence and empirical data (Jewell & Cherp, 2023). They provide insights into their feasibility, which consequently support decision-making in favor of solutions that have been demonstrated and have precedents in the past.

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[4] Technology or scenario/pathway being forecasted, often under specific conditions.

2.6 Assessing the future of hydrogen: Contribution to literature

Considering the scope of the literature review, studies that assess the future growth of hydrogen-related technologies using reference cases are rather limited. As previously mentioned, the methodology of Odenweller *et al.* (2022) allows for the assessment of electrolysis capacity for green hydrogen production using the high yet conventional growth rates of solar and wind, as well as the exceedingly high growth rates of non-energy technologies. As of this writing, it is only their study that examined the future growth of green hydrogen electrolysis. Further, their methodology plays an important role in shaping the design of this research in terms of constructing a feasibility space to assess future growth, but more importantly the use of reference cases to assess the future growth of green hydrogen electrolysis and pipelines.

On the other hand, Pye *et al.* (2022) used historical examples of energy transitions to understand the regional deployment of direct reduction iron using hydrogen (DRI-H2) and examined how the effects of regional spillovers enable faster diffusion of these technologies in peripheral geographies as they leapfrog and benefit from the experiences of core regions. However, the emphasis of the study is on DRI-H2, a process for producing green steel, and not renewable hydrogen per se. In addition, the study of Chen *et al.* (2010) would not be compatible with that of Odenweller *et al.* (2022) in the sense that it examined the future growth of hydrogen energy and fuel cell technologies by using a bibliometric and patent analysis, as opposed to using a reference case or technology. Lastly, McDowall and Eames (2006) performed a meta-analysis of studies of hydrogen futures literature *e.g.,* roadmaps, visions, etc. for a hydrogen economy. Nonetheless, these studies did not examine the future capacity of green hydrogen production. Some of the covered literature centers on the penetration of hydrogen fuel cell vehicles (Christidis et al., 2003; Thomas *et al.*, 1998), while one performed a survey expert to approximate the time for polymer electrolyte fuel cells to diffuse in Japanese society (Kosugi, 2004).

In terms of infrastructure, the use of reference cases is also limited in the context of assessing the potential growth of hydrogen pipelines. The study by Schoots *et al.*, (2011) is the most relevant as it explored the cost reductions of pipeline construction for CH_4, CO_2, and H_2, which can be indicative of the learning experience and curve of this technology. They found that in the worst case, there have not been significant historical reductions in pipeline construction costs (i.e., no technological learning), which they assume is possibly linked to the rudimentary nature of the technology. And on the best case, possible reductions in pipeline construction costs have been minimized by variability in materials and inputs prices. In comparison with reference case studies that use other proxies or benchmarks, this study used real data of existing pipelines globally and input material costs. Bento's (2008) application of insights from the historical growth of electricity and gas infrastructures proves to be related to this thesis in the sense that it makes use of a reference case. However, his methodology focuses on network economics to determine the emerging need for hydrogen infrastructure and integrates theories like demand club effects and positive socio-economical externalities in doing so.

Other studies on hydrogen infrastructure focus on the technical feasibility of repurposing natural gas pipelines (Haeseldonckx & Dhaeseleer, 2007), optimizing hydrogen planning including refilling stations using spatial models (Johnson & Ogden, 2012; Agnolucci & McDowall, 2013), and designing models for long-term hydrogen investment planning (Hugo et al., 2005).

Grounded on the reviewed studies, this thesis contributes to the literature on three levels. Firstly, this thesis formulates an analytical framework composed of selected parameters to help the process of selecting reference cases. As far as the scope of the reviewed literature is concerned, existing studies do not apply a framework for identifying reference cases to assess the future growth of future cases. Instead, these studies proceed to the direct technology selection solely on similarity. The study's framework can provide structure and guidance for future studies that aim to assess the future growth of emerging technologies using reference technologies. To a certain extent, it relates to the framework of Jewell & Cherp (2023) on reference cases and feasibility spaces, which is discussed further in the methodology section. Overall, the formulation of an analytical framework for the valid identification of reference cases for forecasting the future growth of energy technologies is a contribution on its own.

Secondly, this study contributes to the limited body of literature on the *examination of green hydrogen future growth using various reference case technologies*. Discussed in greater detail in the result section, the thesis employs a combination of nuclear and renewable energy technologies at various scales as reference cases. This complements what has been done by Odenweller *et al.,* (2022), which uses solar and wind as reference cases to forecast the market ramp-up of green hydrogen production.

And thirdly, the thesis contributes to the area of technology forecasting in the context of hydrogen pipelines' future expansion and diffusion. Limited work has been done in this subject, even more so for the application of natural gas technological experience to forecast the future expansion of hydrogen pipelines. This study can help lay the ground for future research on forecasting how hydrogen pipelines will grow in the future, in light of energy targets and climate neutrality commitments.

2.7 Technology diffusion drivers and barriers

Studies agree that technologies undergo growth and diffusion patterns, which can be affected by a multitude of factors depending on underlying backgrounds. Iyer et al., (2015), for example, reviewed the historical diffusion rates of technologies to contextualize the idea of slow and rapid diffusion and presented that despite robust climate policies, a list of parameters namely technology costs, and organizational, psychological, and human factors can deter low-carbon technology diffusion. Jaffe *et al.* (2005), meanwhile, posit the idea of "dynamic increasing returns" (p. 4), which signifies that the net benefit gained from the use of technology goes up the more people use it within a specific context. They also discuss the importance of "network externalities" (p.4) in promoting technological diffusion, which occurs when the value of a technology increases due to compatibility with existing technologies or products. For example, Odenweller et al., (2022) argue that repurposing existing gas pipelines forms part of the necessary infrastructure to avoid delays in the deployment of green hydrogen.

On the other end of the spectrum, such technological linkages can also work against new technologies trying to penetrate the market and public use. "Path dependence" can create barriers to the scaling of new technologies when suboptimal decisions taken in the past inhibit the penetration of new technologies (Arthur, 1989). In a similar vein, network externalities can go against new technologies due to their incompatibility with existing infrastructures (Jaffe et al., 2005). The existence of legacy technologies whose components are intertwined and reinforce their use have evolved together for long periods, and such system poses difficulties for new technologies to compete despite the quality and technological advantages (Grübler, 1999).

This underlines the importance of looking at energy transitions holistically. Institutions have to organize themselves in ways that leverage local knowledge when it comes to introducing new technologies (Grübler, 1999). Further, no single intervention can drive system-level transitions in the energy sector. Green hydrogen, for example, would require a combination of policies and regulations, subsidies, and emergency measures to mimic high rates of technological diffusion (Odenweller et al., 2022). The successful penetration of solar PV and wind power in Germany is one example of how policies and subsidies can have dramatic effects on technological diffusion (Lund, 2006).

2.8 Technology diffusion studies and policymaking

Technology forecasting studies can help guide governments' innovation strategies, particularly considering the uncertainties around future innovation. Analytical tools such as future learning rates of low-carbon energy and climate technologies can be used to guide the formulation of technology policies (Nemet, 2009). A case in point is ethanol production in Brazil, which makes use of learning curves to rationalize public funding and support for biofuel (Goldemberg et al., 2004).

Similarly, Bengisu & Nekhili (2006) analyzed publications and patents from the ISI Web of Science database and LexisNexis Database, on 20 emerging machine and material technologies. Using S-curves, they found a high correlation between the increase in patents and publications in the case of most technologies. Results of their study show that the Turkish government's innovation strategy is misaligned, suggesting the need to reformulate the national policy, prioritize specific innovations with increased chances of scaling, and rechannel investments in research and development.

3 Methodology

The study's methodology follows a two-pronged approach. To address RQ1, the study presents the formulation of an analytical framework, the selection of reference case technologies, and a discussion on the use of historical technologies for assessing the feasible growth of green hydrogen electrolysis and pipelines.

On the other hand, to address RQ2 and RQ3, the study tests the results of the analytical framework through a more focused, quantitative analysis. More specifically, the second method involves determining the maximum growth rates of the reference case/historical technologies and calculating the required growth rates to achieve the future targets of green hydrogen electrolysis in the context of the EU and hydrogen pipelines in Europe. Ultimately, these growth rates are plotted in a feasibility space to better visualize the historical growth rates against the required future growth rates. This provides the basis for the identification of policy and investment recommendations for scaling green hydrogen electrolysis capacity and hydrogen pipeline network.

3.1 Qualitative analysis: Identification of reference case technologies

The selection of reference cases of historical technologies forms an important part of this study as outcomes of this process can influence the succeeding steps and data selection. To identify valid reference cases to assess the feasible growth of green hydrogen electrolysis and pipelines as climate mitigation technologies, an analytical framework has been formulated composed of parameters grounded on literature. As shown in Figure 3, the analytical framework begins with a long list of relevant technologies, which can be categorized either as historical or future ones. All historical technologies are subject to four parameters namely (i) social function, (ii) granular lumpy scale, (iii) technology readiness level, and (iv) historical growth rate or extent. The same parameters are applied to future technologies, with a minimal difference from the fourth parameter i.e., required growth rate.

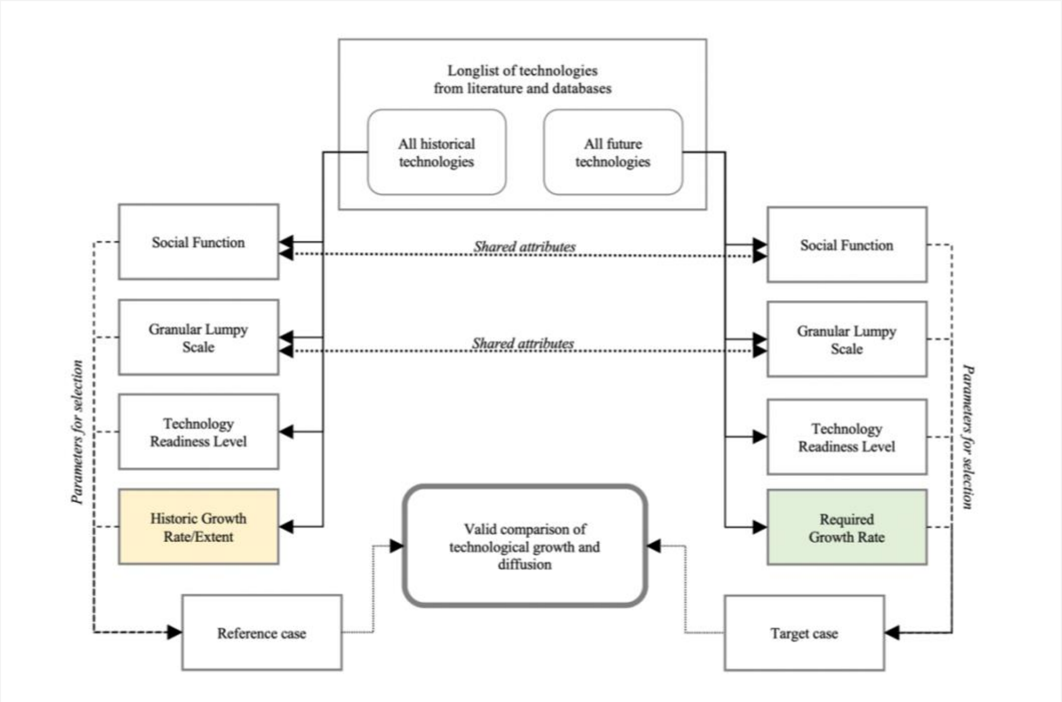

Figure 3: Analytical Framework for the selection of reference case technologies to match target case technologies

Applying the four key criteria, the framework points to reference cases, whose attributes enable a sound and valid comparison with the technological growth and diffusion of green hydrogen electrolysis and pipelines. Asides from enabling the selection of technologies, another advantage of the framework is how it helps minimize bias in the selection process, e.g., unjustified identification of reference and future cases due to lack of structure and causal reasoning. Further, it strengthens the rationale that reference cases can surface feasibility insights for the target cases due to their shared attributes. Overall, it is worth considering that there are no foolproof methods for the matching of reference and target cases (Jewell & Cherp, 2023).

3.1.1 Formulation of the analytical framework

The abovementioned analytical framework is influenced by that of Jewell and Cherp (2023) for constructing feasibility spaces, as shown in Figure 4. Besides the selection of reference and target cases based on parameters such as shared social function, etc., their framework highlights the importance of normalization to help ensure comparability and account for the broader spatial and temporal differences between the two. On the other hand, the analytical framework of this thesis enables the robust comparison between two cases by specifying and proposing a set of parameters, as discussed in the succeeding subsections. The framework by Jewell and Cherp (2023) has also been used in the actual construction of feasibility spaces to visualize the actual comparison of the historical growth rates of the reference cases and the required growth rates for the target cases.

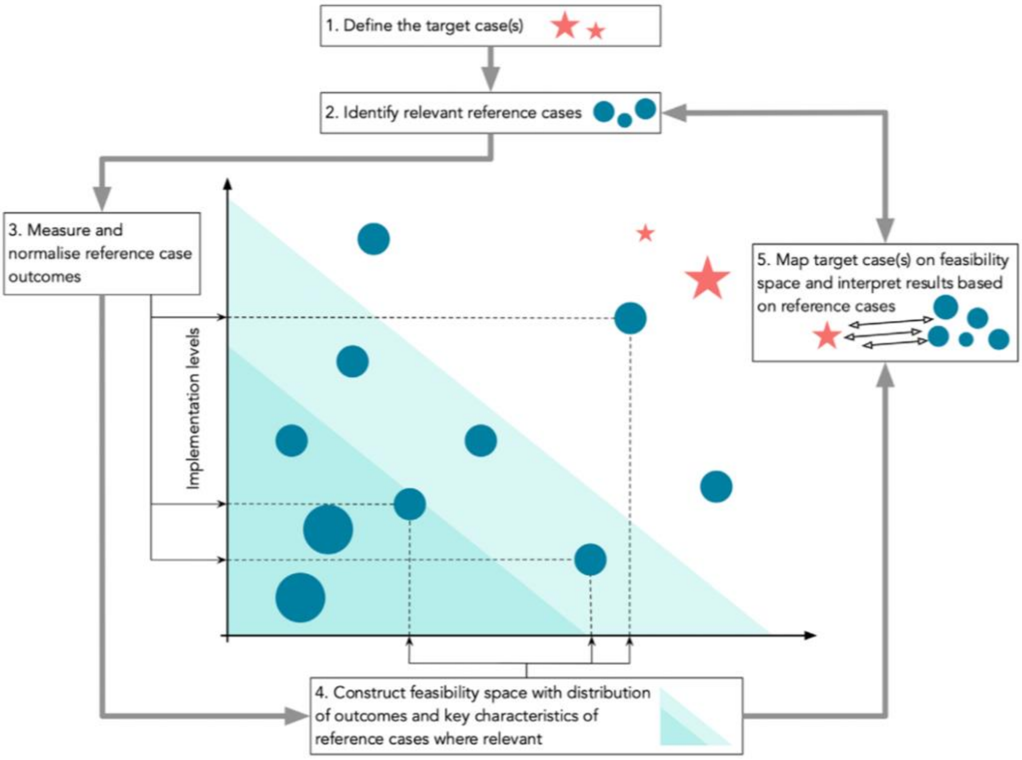

Figure 4: Five steps in constructing a feasibility space according to Jewell and Cherp (2023)[5]

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[5] This framework is directly lifted from Jewell & Cherp (2023) without modification from the author of this thesis.

3.1.1.1 Social function

According to Jewell and Cherp (2023), the reference and target cases should share a similar function and fall under shared "*social processes.*" This means that the cases should more or less offer the same provisions or benefits to society. In the context of this thesis, social function is identified as *energy sector decarbonization or energy/climate technologies*, and the reference case should share this with hydrogen electrolysis and pipelines. More specifically, this should also mean that the reference case for pipelines should be in the form of *infrastructures that transport or deliver goods or services.* As discussed earlier, one example of how this criterion is evidenced in literature is van Ewijk and McDowall's (2020) use of flue gas desulfurization technology as a reference case for the future growth of CCUS due to their shared social function of *flue gas emission filtration* and *converting to useful by-products.*

3.1.1.2 Granular-lumpy scale

Wilson *et al.* (2020) define the granular-lumpy scale as a spectrum of the scale and complexity of technology. The granular end refers to technologies that are smaller and have more variability in terms of unit size. Due to their modular property and lower complexity, granular technologies are easier to replicate, diffuse faster, and entail less investment and risks. On the other hand, their lumpy counterparts come in bigger and more complex units and come with greater investment costs and risks (*Ibid.*). In addition, the use of this scale in the analytical framework mirrors the technology typology of Malhotra and Schmidt (2020), where they discussed the different levels of complexity of energy technologies. In the context of the thesis, both reference and target cases must be found within an approximately similar scale in this technological continuum for their comparison to be valid.

To disaggregate the technological components of the identified cases into the same level of granularity, the IEA's Clean Energy Technology Guide has been used. The guide is a digital platform housing the designs and components of more than 500 technologies and innovations critical to achieving net zero emissions (IEA, 2022).

3.1.1.3 Technology readiness level

Technology Readiness Level (TRL) is a scale that assesses the maturity of each technology across sectors while enabling cross-technology comparison (IEA, 2020). This scale was initially used by NASA beginning of the 1970s as a system to gauge the level of development reached by specific technology and how it can be compared to other types of technologies (Mankins, 1995). As shown in Table 4, IEA operationalizes this scale to enable its applicability to technologies across the energy system. Nonetheless, reference and target cases recognizably differ in terms of the TRL given that the former has achieved market penetration and societal penetration, and the latter could still be emerging or requires support to achieve the same level. Noting this, the thesis focuses on the identification of technologies with *at least TRL 9* in the scale below, as this could signify that the reference cases have gone through a formative phase and could scale further given the necessary investment and support.

Table 4. Technology Readiness Level scale as operationalized by the IEA

TRL	IEA Operational Definition
TRL 1	Initial idea: Basic principles have been defined
TRL 2	Application formulated: Concept and application of solution have been formulated
TRL 3	Concept needs validation: Solution needs to be prototyped and applied
TRL 4	Early prototype: Prototype proven in test conditions
TRL 5	Large prototype: Components proven in conditions to be deployed
TRL 6	Full prototype at scale: prototype proven at scale in conditions to be deployed
TRL 7	Pre-commercial demonstration: Solution working in expected conditions
TRL 8	First-of-a-kind commercial: Commercial demonstration, full scale deployment in final form
TRL 9	Commercial operation in relevant environment: Solution is commercially available, needs evolutionary improvement to stay competitive
TRL 10	Integration needed at scale: Solution is commercial and competitive but needs further integration efforts
TRL 11	Proof of stability reached: Predictable growth

3.1.1.4 Growth rate

The growth rate is the last parameter, and it differs for the reference and target cases. Reference cases are established technologies; hence, their growth rates or increases in their capacity can be measured and calculated at any point in time in their history. Their growth rates suggest historical precedents and therefore may be replicated by exploring the broader environments and factors that potentially play a role. For target cases, on the other hand, their growth rates are not fully determined yet as they have not fully saturated the market and society in general. In addition, they are subject to uncertainties caused by the market, policies, and related infrastructures, making their growth even more difficult to predict. Nonetheless, target cases are expected to grow rapidly considering technological capacity targets in the immediate and long term.

3.1.1.5 Other framework considerations

Whereas it is not included in the analytical framework, the scale of implementation and system size (Jewell & Cherp, 2023) is also considered to ensure the comparison between the two cases is robust and valid. This means that the scale i.e., global, regional, national, etc. between the two cases are similar, otherwise, risking accounting for spatial factors that render the comparison irrelevant. Lastly, the availability of time series data is also considered, which is crucial to the quantitative analysis component of the thesis. Whereas valid reference cases can be identified for the target cases but without the necessary time series data, they are not prioritized but instead can be recommended for future studies.

3.1.2 Application of the framework and technology selection process

Following the analytical framework, the selection of reference cases began with a broad scoping of energy and climate technologies. Several reports were reviewed for this purpose including the Climate Technology Progress Report 2022 (UNEP CCC, 2022), the World Energy Transitions Outlook 2022: 1.5° C Pathway (IRENA, 2022), the Energy Technology Perspectives 2020 Report (IEA, 2020), Energy Technology Perspectives 2023 Report (IEA, 2023), and Clean Energy Technology Guide (IEA, 2022). Reviewing these sources is an important step to aggregate existing and critical energy technologies and enable the thesis to scope down by applying a set of parameters for a systematic selection. A summary of the technology contents of each reference is presented in Table 5. Various datasets from key energy-related organizations such as IEA, BP, etc. were also reviewed to determine data availability for the identified reference cases.

Table 5: Summary of technology-related references for broad scoping of reference cases

Publication and Institution	Technology Focus	Presentation of the Technology
Climate Technology Progress Report 2022 (UNEP CCC, 2022)	Agriculture, energy, and water technologies in Africa and globally	Multidimensional feasibility assessment using six criteria areas i.e., economic, environmental-ecological, geophysical, institutional, technological and sociocultural
World Energy Transitions Outlook 2022: 1.5° C Pathway (IRENA, 2022),	Renewables, energy efficiency, hydrogen CCUS, electrification, and sustainable biomass	Normative pathway of technological advancement and critical policies and investments to reach the 2050 Paris Agreement target
Energy Technology Perspectives 2020 Report (IEA, 2020)	Renewables, energy efficiency, end-use electrification, renewables, bioenergy, and hydrogen and hydrogen-derived fuels	Technical and analytical disaggregation of technologies supply chains and policy and investment needs; Maturity levels of technologies for energy-sector decarbonization by 2070
Energy Technology Perspectives 2023 Report (IEA, 2023).	Renewables, energy efficiency, end-use electrification, renewables, bioenergy, and hydrogen and hydrogen-derived fuels	Analysis of risks and opportunities around the deployment of clean energy and technology supply chains to achieve energy security, resilience, and sustainability
Clean Energy Technology Guide (IEA, 2022)	Energy technologies across the whole energy system	Interactive database containing technological readiness levels and disaggregated technical components of technologies, with corresponding data on capacity and investment targets

The thesis identified the final list of reference case technologies and matched them against the target cases, as shown in Table 6. The table also shows the capacity unit, TRL for target cases, and system scale (e.g., global). The identified reference case technologies are presented further in the discussion section.

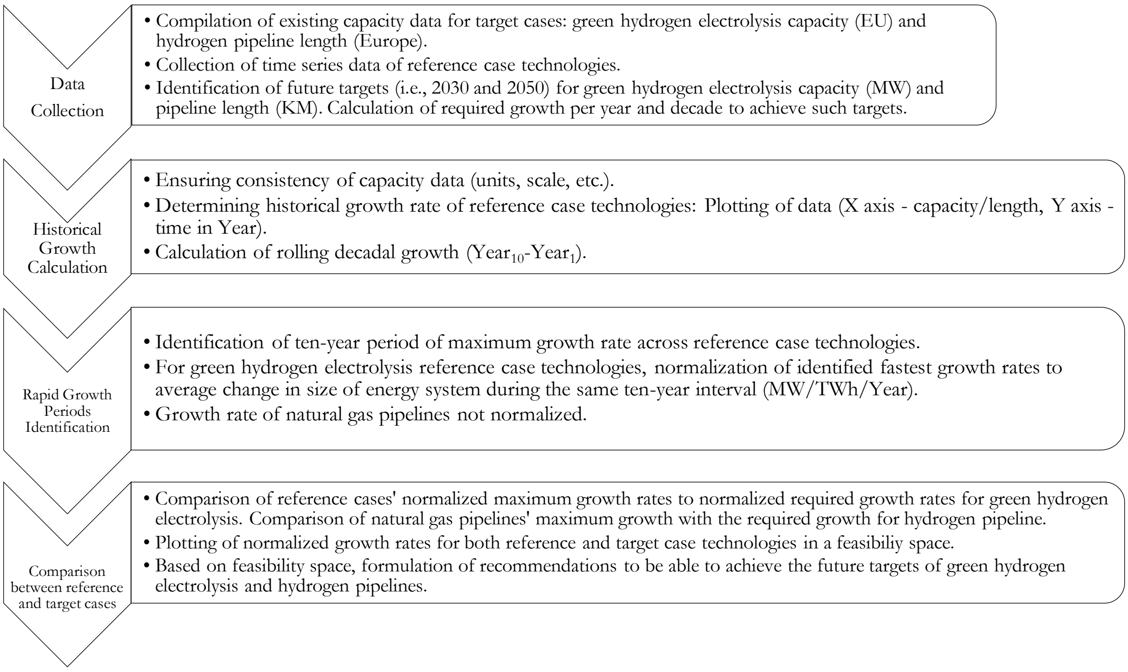
Table 6: Identified reference cases to assess the feasibility of the future growth of the target cases

Target Case	Reference Case
Green hydrogen electrolysis technologies **(i) Alkaline electrolysis** TRL 9 Total capacity in MW **(ii) Polymer electrolyte membrane electrolysis** TRL 9 Total capacity in MW EU	**Nuclear power - Nuclear reactor units** (i) Global; (ii) France Total capacity (MW) **Solar – Photovoltaic Panels** Total capacity (MW) (iii) Global; (iv) EU; (v) Germany **Wind power - Wind turbine unit** Total capacity (MW) (vi) Global; (vii) EU; (viii) Denmark

Hydrogen pipeline TRL 10 Total length in KM Europe	**Natural gas pipelines** Total length (KM) Europe

3.2 Quantitative analysis: Calculation of growth rates of technologies

Following the formulation of an analytical framework, the thesis proceeds with specific and quantitative analyses. This process aims to assess the robustness of the identified reference cases as benchmarks or historical precedents to assess the future growth of the target cases. A summary of the processes involved in the quantitative analysis is shown in Figure 5**.**



- Compilation of existing capacity data for target cases: green hydrogen electrolysis capacity (EU) and hydrogen pipeline length (Europe).
- Collection of time series data of reference case technologies.
- Identification of future targets (i.e., 2030 and 2050) for green hydrogen electrolysis capacity (MW) and pipeline length (KM). Calculation of required growth per year and decade to achieve such targets.

- Ensuring consistency of capacity data (units, scale, etc.).
- Determining historical growth rate of reference case technologies: Plotting of data (X axis - capacity/length, Y axis - time in Year).
- Calculation of rolling decadal growth (Year$_{10}$-Year$_{1}$).

- Identification of ten-year period of maximum growth rate across reference case technologies.
- For green hydrogen electrolysis reference case technologies, normalization of identified fastest growth rates to average change in size of energy system during the same ten-year interval (MW/TWh/Year).
- Growth rate of natural gas pipelines not normalized.

- Comparison of reference cases' normalized maximum growth rates to normalized required growth rates for green hydrogen electrolysis. Comparison of natural gas pipelines' maximum growth with the required growth for hydrogen pipeline.
- Plotting of normalized growth rates for both reference and target case technologies in a feasibiliy space.
- Based on feasibility space, formulation of recommendations to be able to achieve the future targets of green hydrogen electrolysis and hydrogen pipelines.

Figure 5: Summary of processes for the quantitative analyses of the study

3.2.1 Data collection: Green hydrogen electrolysis and reference cases

The IEA Hydrogen Project Database was used to identify existing alkaline and PEM electrolysis projects, collectively making up 2023 green hydrogen electrolysis capacity. The IEA database contains a total of 1,477 hydrogen projects worldwide for energy and climate mitigation purposes (IEA, 2022b). Given the study's focus on green hydrogen via alkaline and PEM electrolysis, hydrogen projects based on other technologies like biomass, biomass with CCUS, fossil fuels (coal, gas, oil) with CCUS, solid oxide electrolysis, and other forms of electrolysis have been excluded. In addition, electrolysis projects powered by nuclear electricity have been omitted as well, and only alkaline and PEM electrolysis projects powered by dedicated renewables or excess renewables from the grid have been considered in the study. Applying these parameters, the study has identified a total green hydrogen electrolysis capacity of 500 MW (.5 GW) in the EU for 2023.

Moreover, time series data were collected for the identified reference case technologies namely (i) nuclear power – global, (ii) nuclear power – France, (iii) solar power – global, (iv) solar power EU, (v) solar power Germany, (vi) wind power – global, (vii) EU, and (viii) wind power Denmark. This time series dataset enables the plotting of the growth of the technologies against time, calculation of growth rates, and identification of specific periods of rapid technological growth.

Their total cumulative capacity in MW shall be used to enable the calculation of their growth rates and the identification of periods of rapid technological diffusion in their history. Time series data for the reference cases are derived from the Scaling Dynamics of Energy Technologies (SD-ET) Database of the International Institute of Applied Systems Analysis (Wilson, 2012; Bento, 2013), BP Statistical Review of World Energy (BP, 2022), and curated database of energy technologies and their capacities by the POLET Research Group. The identified cumulative capacities and calculated growth rates for the green hydrogen electrolysis' reference cases are presented in the results section of the study.

3.2.2 Data collection: Hydrogen pipeline and reference cases

In comparison with green hydrogen electrolysis projects, data for hydrogen pipelines are scarcer and more inconsistent. As a result, the scope has been brought down from the global to the European scale to address data limitations, among other considerations. Additional market research has been done to validate specific data points and aggregate them from various data sources (Global Energy Monitor, 2023; Perrin et al., 2007). Overall, a total of 1,595.00 KM of hydrogen pipelines exist in Europe by 2023 (H2 Tools, 2016).

On the other hand, a total of *423 natural gas pipelines* with a total cumulative length of *85,425.39 km* have been identified in Europe, following the database of the Global Energy Monitor (GEM, 2023). However, according to the CEER (2016), as cited by (Nuffel et al., 2019), there is a total of more than 200,000 km of transmission pipelines and more than two million KM of distribution networks in the EU. This would suggest that a significant majority of the actual pipeline data is not included in the dataset and have to be considered as a limitation of the study.

Another consideration to note is the categorization of pipelines in general. Distribution pipelines refer to short-distance infrastructure facilities, while transmission pipelines are long-distance infrastructure facilities (Schoots et al., 2011). However, due to data limitations and inconsistency in terms of pipeline capacity, diameters, and other attributes, the study does not discriminate between transmission and distribution pipelines. Hence, all pipeline data are considered and calculated only for their length.

3.2.3 Data processing and growth calculations

For RQ2, the overall objective of this exercise is to determine the maximum normalized growth rate (MW/TWh/Year) of the reference case technologies and compare that to the normalized required growth rate of green hydrogen electrolysis. On the other hand, RQ3 intends to determine the maximum growth rate of natural gas pipelines and compare that to the future pipeline targets of the European Hydrogen Backbone by 2030 and 2040. Furthermore, following Wilson's (2012) argumentation, the cumulative capacity of the identified technologies, as opposed to installed capacity or period-specific growth rates, shall be used to account for and mitigate short-term fluctuations and biases favoring specific growth periods.

3.2.3.1 Reference case technology demonstrated growth rates

The purpose of calculating the growth rates of the reference case technologies is to identify their highest recorded growth rates within a given timeframe. These maximum growth rates are then compared to the required growth rates of the target cases or future technologies, to achieve policy and roadmap objectives. Essentially, the historical maximum growth rates serve as benchmarks that can be used as models for scaling up green hydrogen electrolysis and hydrogen pipelines.

The calculation of the maximum growth rates of the reference case technologies for green hydrogen electrolysis began by plotting the time series data: cumulative capacity in MW in the Y-axis and time in the X-axis. These values were used to calculate their rolling decadal change in capacity and to identify the ten-year period of maximum growth i.e., addition in capacity. The capacity value for the period of fastest growth was normalized to the average change in the total electricity supply during the same ten-year interval, leading to final maximum normalized growth rates comparable to the required growth rate of green hydrogen electrolysis.

On the other hand, the same process applies to the sole reference case technology for hydrogen pipelines, i.e., natural gas pipelines. Cumulative length in pipeline data was plotted in the Y-axis, against time as the X-axis. A rolling decadal growth rate was calculated. The fastest growth rate in hydrogen pipelines has been identified, which is compared to the required growth rate for hydrogen pipelines. Given that there is a limited divergence between hydrogen pipelines and natural gas pipelines, normalization is not necessary for this study.

3.2.3.2 Future case technologies required growth targets

To understand what kind of growth is expected from the target cases (green hydrogen electrolysis and hydrogen pipelines), the thesis identified capacity targets that are captured in relevant policy objectives and climate pledges. This mirrors the approach of Odenweller *et al.*, (2022) in integrating the "*pull*" effect of mid and long-term policies and commitments into the market ramp-up of hydrogen electrolysis.

In terms of green hydrogen electrolysis, the capacity target by the EU is *100 GW by 2030*, as enshrined in its REPowerEU Plan, and shall be derived from local production (EC, 2022). On the other hand, a 500 GW capacity of green hydrogen shall be attained by the region by 2050, according to its 2050 Climate Neutrality and Hydrogen Strategy (EC, 2020).

Meanwhile, the targets for the hydrogen pipelines are *28,000 km by 2030*, and *53,000 km by 2050*, following the targets set by the European Hydrogen Backbone (van Rossum *et al.,* 2022). Therefore, the required growth from hydrogen electrolysis and pipelines is equivalent to the gap in capacity/length between 2023 and these decadal targets, divided by the number of years remaining before these decadal targets lapse. The specific required growth rates of the target cases/ future technologies are presented in the study's result section.

Overall, the existing capacity for green hydrogen electrolysis in the EU and the length of hydrogen pipelines in Europe are summarized in Table 7, as well as the future targets as outlined by relevant policy targets and roadmaps. The required growth rates to achieve future targets are presented in the results chapter of the study.

Table 7: Existing capacity of target cases and their corresponding future expansion targets

Target case/ Future Technology	2023 Capacity	2030 Target	2040 Target	2050 Target
Green hydrogen electrolyzers	.500 GW	100 GW[6]	X	500 GW[7]
Hydrogen pipelines	1,595.00 KM	28,000 KM	54,000 KM	X

3.2.3.3 Data normalization

The future growth of the target cases or future technologies will take place within an exogenous environment where the energy system also expands, including the infrastructures, human capacities, financing, and supply chains. Hence, it would be erroneous to make comparisons between historical evidence and future trends without determining a common metric that can normalize both temporal and spatial scales (Napp *et al.*, 2017).

In this regard, the total size of the energy system (i.e., electricity supply data in TWh) data was used to normalize both the required growth of green hydrogen electrolysis and the maximum growth rates demonstrated by its reference case technologies. The specific normalization values used (i.e., average change/growth in total electricity supply during the decade of fastest growth) are summarized in the results section, as well as the specific values used to normalize the required growth of green hydrogen electrolysis. These normalization values are determined by both (i) the scale of the reference case technologies, i.e., global, regional/EU, and national/country-specific, and the period of growth in question. Lastly and as discussed earlier, natural gas and hydrogen pipeline data were not normalized given the minimal divergence of these technologies from each other.

3.2.4 Feasibility spaces and comparison of growth rates

By comparing the demonstrated maximum growth rates of the identified reference cases or historical technologies with the required growth of the target cases or future technologies, the study assesses the feasibility of the future growth of the latter. The study visualized this comparison in a feasibility space, plotting both the maximum normalized growth rates of the reference case technologies and the normalized required growth rates of green hydrogen electrolysis. This analysis allows the study to determine if the expected growth rates for green hydrogen electrolysis have been achieved in the past. Additionally, the maximum normalized growth rates of the reference case technologies serve as historical benchmarks, providing insights into the investments and policies that have facilitated such growth.

The last process is conducting an analysis of the relevant policies, targets and commitments, and broader sociopolitical factors that could have contributed to such high growth rates. These events were examined and served as the basis for policy recommendations to help replicate such conditions that can enable rapid technological diffusion or growth for the target cases.

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[6] Future target according to the REPowerEUPlan (EC, 2022)

[7] Future target according to the EU Hydrogen Strategy (EC, 2020)

4 Results

The findings for the three research questions are presented in this section. It begins by restating the use of the analytical framework for identifying the historical technologies and the parameters that render them valid and robust reference cases (RQ1). This is followed by the comparison between the maximum normalized growth rates of the reference case technologies and the required growth rates to achieve the future targets for green hydrogen electrolysis in the EU (RQ2). Similarly, the future targets for the development of hydrogen pipelines in Europe are presented, followed by a discussion on the historical growth rates of natural gas pipelines used for assessing the feasibility of hydrogen pipelines' future growth in Europe (RQ3). The comparison between the maximum growth rates of the reference case technologies and the required growth rates to achieve future targets for the target case technologies is presented through a feasibility space. The constructed feasibility spaces visualize the varying implementation levels, which are a function of demonstrated historical precedents. Thus, the closer the target cases' required growth rates are to historical implementation levels, the greater the feasibility of their future growth.

4.1 Reference case technologies for green hydrogen electrolysis and pipelines

As mentioned earlier, there is a lack of standardized and unfailing methodologies for identifying reference cases as benchmarks for the future growth of emerging technologies. Furthermore, based on the reviewed literature, technology forecasting studies typically do not employ systematic frameworks for identifying reference cases, but just often rely on technologies within a shared sector or technological cluster. Therefore, the development of an analytical framework serves two purposes: it provides a structured methodology for reference case technology selection and establishes a strong rationale for their inclusion, thereby supporting subsequent quantitative analyses. Utilizing this analytical framework, the study has identified the following reference cases or historical technologies for examination.

Target Case	Reference Case
Green hydrogen electrolysis technologies **(i) Alkaline electrolysis** TRL 9 Total capacity in MW EU **(ii) Polymer electrolyte membrane electrolysis** TRL 9 Total capacity in MW EU	**Nuclear power - Nuclear reactor units** (i) Global; (ii) France Total capacity (MW) **Solar – Photovoltaic Panels** Total capacity (MW) (iii) Global; (iv) EU; (v) Germany **Wind power - Wind turbine unit** Total capacity (MW) (vi) Global; (vii) EU; (viii) Denmark
Hydrogen pipeline TRL 10 Total length in KM Europe	**Natural gas pipelines** Total length (KM) Europe

A total of eight (8) reference case technologies have been identified to assess the future growth of green hydrogen electrolysis in the EU. Meanwhile, only one reference case has been identified for assessing the feasibility of hydrogen pipelines' future growth in Europe. Whereas having multiple reference cases for assessing the growth of hydrogen pipelines is ideal, data limitations inhibit the selection of more historical technologies.

Most notably, the reference case technologies for green hydrogen electrolysis are available in three scales i.e., global, regional (EU), and national. Whereas literature argues for matching the target case using only the same scale, this study also explores global and national scale technologies. As long as normalization is performed, adding these two scales expands the calculation of historical growth rates, which can be compared to the required growth rate for green hydrogen electrolysis in the EU. For instance, determining the growth rate of solar power in Germany and wind power in Denmark can also yield relevant insights into how such energy technologies have grown in a smaller energy system. Such insights have their place when considering how to scale the growth of green hydrogen electrolysis, even at the EU level.

In this chapter, these reference case technologies are presented in a broad, qualitative analysis, highlighting the rationale behind their selection. The four key parameters used for selecting the reference case technologies are (i) social function, (ii) granular-lumpy scale, (iii) technology readiness level, and (iv) historical growth rate/extent. It is only the first two parameters that are shared between the reference and target cases for obvious reasons. For one, historical technologies are well established in the market and therefore have completely high TRL, compared to their future technology counterparts. In the same vein, the growth rates between the two sets of technologies also differ, with future technologies having more uncertainty around the pace of their diffusion, while historical technologies have varying growth rates throughout their diffusion.

In terms of *social function*, the identified reference cases are similar to green hydrogen electrolysis in the sense of *energy provision*. Whereas they fall under different kinds of energy production technologies namely renewables, nuclear, and fossil fuels, the ultimate function of these technologies is energy generation to support economic activities, as opposed to energy consumption, efficiency, and end-use technologies. Using a variety of technologies within the energy provision function expands the opportunity to assess hydrogen electrolysis across a variety of technologies in the energy system and identify historical precedents or experiences that may be useful and replicated in scaling its growth.

The *granular-lumpy scale* represents the second parameter shared by green hydrogen electrolysis and the reference case technologies. The selected reference cases are defined within the same *functional units* that represent complete operational technologies. This means that the units between green hydrogen electrolysis and the reference case technologies are presented at the same level of technological complexity, i.e., plant/system level, technological unit level, modular piece component, etc. For instance, matching an entire nuclear power plant with a modular solar PV installation does not make for a fair comparison as far as the scale of their technological complexity is concerned. Further, to facilitate cross-technology comparisons between the target and future cases, the study quantifies the technologies based on their capacity (in megawatts, MW) and normalizes them relative to the size of their respective energy systems, specifically the total electricity supply (TWh). Capacity is a parameter that reflects the service offered by the technology (Bento, 2013). Further, the comparison of energy technologies using capacity is advantageous because it is a general metric not influenced by variations in factors such as efficiency, capital investment, or labor productivity (*Ibid.*). Overall, this makes capacity a suitable and reliable parameter for evaluating and comparing different energy technologies for this study.

The third parameter used is *TRL*. The reference cases are established, historical technologies that have either achieved complete market saturation or are approaching that point of saturation, depending on the jurisdiction. It is therefore not expected that TRL is a shared parameter between green hydrogen electrolysis and the identified reference cases/historical technologies. Nevertheless, being established technologies means that they are valid benchmarks for the assessment of other technologies' future growth.

On the other hand, it is worth discussing that green hydrogen electrolysis is at TRL 9, according to the TRL scale of the IEA (2020). This designation indicates that green hydrogen electrolysis is already a commercially available technology and is currently in operation in certain markets, such as the EU, United States, China, etc. However, continuous improvement is still necessary for it to maintain competitiveness and to further expand its presence in the market.

The fourth parameter – *growth rate* – is related to the third one in the sense that it is not shared between green hydrogen electrolysis and the reference case technologies. The *required growth rate* to achieve the green hydrogen electrolysis capacity targets by the EU tends to be high, considering that the technology is still emerging and that there is a significant gap between the current capacity and the target future capacities. Looking at the *historic growth rate/extent* of reference cases, especially those that have grown relatively fast, allows for a more robust assessment of the future growth of green hydrogen based on the maximum and rapid technological growth of historical technologies.

Moreover, by analyzing the historic growth patterns of the selected reference case technologies, it is possible to identify specific periods in history when their diffusion or expansion rates were notably rapid. These patterns provide valuable insights and serve as a rationale for replicating similar parameters to support the future growth of green hydrogen electrolysis in the EU. By understanding the factors and mechanisms that contributed to the successful growth of these technologies in the past, efforts can be made to apply similar strategies and conditions to facilitate the expansion and widespread adoption of green hydrogen electrolysis in the future.

In relation to this, the use of the different scales for the reference case technologies i.e., global, regional/EU, and national/country-specific, serves several purposes. Firstly, it enables the study to see how the growth rates of the global-scale reference case technologies could differ from growth rates observed on a regional scale. This underlines the challenge of scaling green hydrogen electrolysis due to the sheer size of the global energy system to which it belongs. For this reason, including global nuclear power, solar power, and wind power as reference case technologies in the analysis makes for a strong empirical case.

Secondly, it supports an understanding of the growth of reference case technologies under unique national or country-specific conditions. For instance, it is noted that nuclear power in France and wind power in Denmark have grown differently due to the smaller size of their energy system, but also due to the nationwide orchestration of different policies, market forces, and political will to enable such rapid growth. This brings the discussion for the need to contextualize energy policies as influenced by factors like the availability of natural resources, technology investments, and public demand. This renders nuclear power in France, wind power in Denmark, and solar power in Germany as strong reference case technologies for assessing the future growth of green hydrogen electrolysis in the EU.

Thirdly, including regional or EU-level reference case technologies allows the study to identify examples or precedents of growth rates that are comparable to the required growth of green hydrogen electrolysis, while accounting for factors such as shared energy systems (albeit with different periods) and other parameters. Thus, it helps address the question of what regional-level policies, investments, or interventions have been made in the past for other energy technologies that could potentially yield the same level of technological diffusion for green hydrogen electrolysis targets in the EU. For this reason, solar and wind power at the EU scale makes for a strong reference case technology for assessing the future growth of green hydrogen electrolysis in the region.

Furthermore, only one reference case technology has been identified for hydrogen pipelines. Natural gas pipelines are an obvious reference case as they are the same technology by nature.

Hence, in terms of *social function*, they are *connective infrastructure-related technologies* that help transport fuel or energy from the site of generation to the point of end-use or consumption, i.e., *energy transport*.

Both pipelines are also approximated to be similar in terms of the *granular-lumpy scale*. Essentially, they are modular, rudimentary technologies that do not involve complex innovation or machinery. Whereas there may be differences in terms of their chemical composition due to the nature of the fuels that they transport, they are equally granular technologies with little complexity to them.

The third parameter is *TRL* and is arguably different for hydrogen and natural gas pipelines. The latter is a well-established technology that has diffused into society and economies, while the former is still an emerging technology. IEA classifies hydrogen pipelines at TRL 9, which suggests that they are already commercially operational in specific contexts such as Germany, Belgium, France, etc., but ensuring they remain competitive would require consistent enhancement and growth.

On the other hand, natural gas pipelines have diffused pervasively in most global markets, and do not necessarily require additional technological evolution for them to remain competitive. Related to this parameter, natural gas pipelines can provide quantitative insights into the *required growth rates* for hydrogen pipelines to successfully grow and achieve future length targets.

In the succeeding section of this chapter, the study dives into a focused, quantitative analysis of the reference cases by comparing their growth rates with the required growth for green hydrogen electrolysis in the EU and hydrogen pipelines in Europe.

4.2 Feasibility of green hydrogen electrolysis expansion

This section aims to assess the feasibility of the future growth of green hydrogen electrolysis using the historical experience of the identified reference case technologies i.e., nuclear, solar, and wind power. Specifically, it presents the required growth of green hydrogen electrolysis in light of the EU's capacity targets for 2030 and 2050 and determines if there have been historical precedents of such pace of growth among the reference case technologies. Overall, the growth rates of the historical case technologies were used as a reference to examine the future growth of green hydrogen electrolysis in the region.

4.2.1 Required growth for green hydrogen electrolysis

In the context of this study, the growth rate is quantified as additional capacity in green hydrogen electrolysis over a decade (GW/decade). To determine the growth rate required to achieve the future targets for green hydrogen electrolysis capacity, the current capacity in 2023 was first calculated, which is then subtracted from the capacity targets in 2030 and 2050. The differences between the capacity in 2023, and in 2030 and 2050 represent the necessary green hydrogen electrolysis that has to be added to the system.

The IEA Global Hydrogen Project Database (IEA, 2022b) was used to determine the existing capacity of green hydrogen electrolysis both at the global and the EU levels. Aside from electrolysis-based hydrogen technologies, the database also includes projects based on other technologies including nuclear (pink hydrogen), methane (blue hydrogen), and fossil fuels (gray hydrogen) with CCUS components. With the scope of the study, only online hydrogen electrolysis projects that are powered using renewables (*i.e.,* dedicated renewable energy source, excess renewable power from the grid) beginning 1975 until 2023 have been selected. Further, the study has only selected projects that are electrolysis-based ones that either use (i) alkaline electrolyzer and (ii) polymer electrolyte membrane (PEM) electrolyzer (also called proton exchange membrane) – two of the most widely used and advanced electrolysis technologies in the market (IEA, 2022a).

The final selected projects amount to a total capacity of *1,446 MW* in *2023* globally. The distribution of these projects across the continents is shown in Figure 6. Europe is the leading region in existing capacity size at almost 500 MW, followed by South America at 347 MW, and North America at 225 MW.

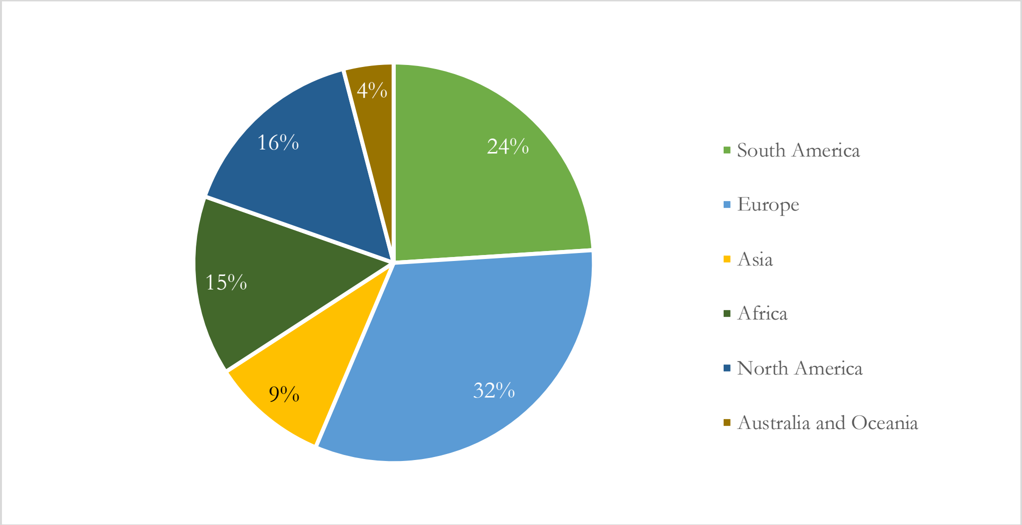

Figure 6: Capacity distribution of global electrolysis projects from 1975 – 2023

As discussed in the scope of the study, however, focusing on the EU for assessing the future growth of green hydrogen electrolysis makes for a strong empirical case not only due to the region's strong policy push for the development of a hydrogen economy within a broader climate-neutrality plan by mid-century e.g., *REPowerEU Plan, EU Climate Neutrality Plan*, etc., but also for its leading position in terms of existing capacity.

But more importantly, the EU has specific future capacity goals, which provide a quantitative benchmark for the calculation of required target growth rates. Similarly, focusing on the EU addresses calculation issues related to normalization, which is an important step to enable the valid comparison of growth rates of different technologies. Through normalization, the growth rates can be compared while considering the different energy sizes across varying spatial (i.e., global, EU, national) and temporal (specific ten-year periods) parameters that could substantially influence the varying paces of growth across the reference case technologies. The process of normalization is methodologically easier to execute at the EU level given that existing and forecasted green hydrogen electrolysis capacity is not normally distributed at a global level.

Using the same dataset, a total of 93 green hydrogen projects were identified for the EU, with an average operational capacity of 5 MW. Overall, these projects amount to a total of 500 MW, and their distribution across the region is shown in Figure 7. Germany has the highest capacity for green hydrogen electrolysis at 164 MW, followed by Norway (54 MW), Portugal (38 MW), Italy, and the Netherlands (34 MW). However, it must be noted that the represented capacities in Figure 7 may be limited by the robustness of data from the IEA Hydrogen Database such as unregistered projects or missing capacity data. Therefore, the study recognizes sources of downstream data limitations and biases when making any inferences. Moreover, disaggregation down to the national scale provides an additional level of granularity that can help in the formulation of bespoke green hydrogen policy and planning recommendations.

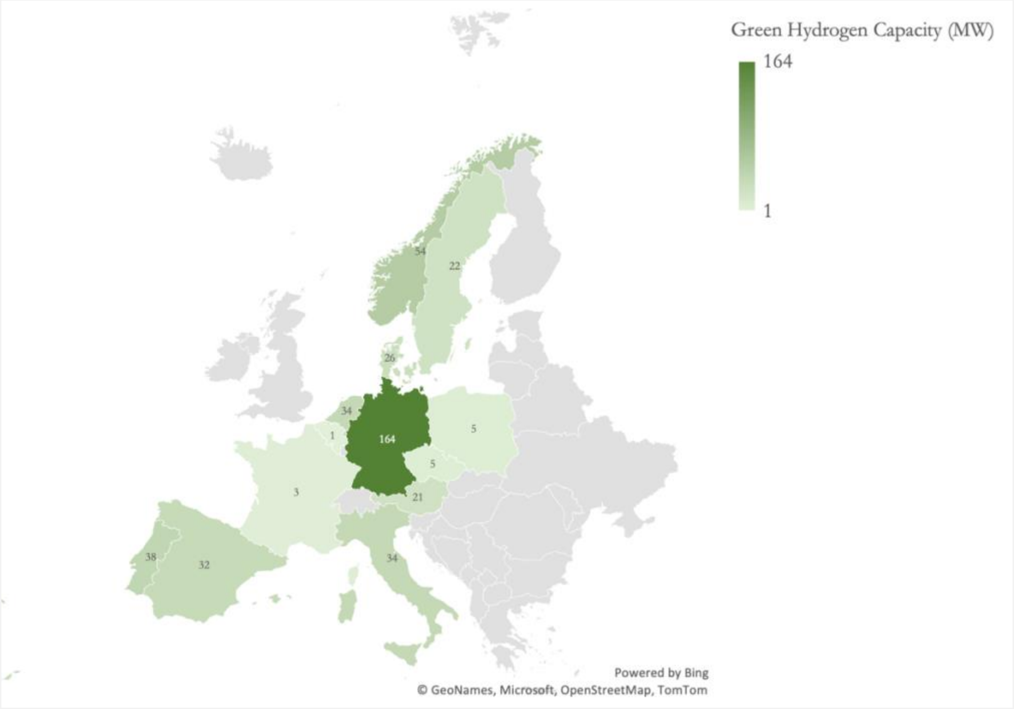

Figure 7: Distribution of existing green hydrogen electrolysis capacity in MW across the EU[8]

As outlined in the bloc's regional policies, the EU aspires to develop 100 GW capacity of green hydrogen by 2030 and 500 GW by 2050 (EC, 2020, 2022). Determining the growth rate needed to achieve these targets thus begins by subtracting the existing capacity from the targets. However, the existing capacity of green hydrogen is severely limited and comparatively negligible against the future capacity targets. Therefore, the study assumes the actual capacity targets for 2030 of 100 GW and 2050 of 500 GW as the capacities required to achieve the future targets. These capacity values are then divided by the remaining number of years between 2023, 2030, and 2050 to determine the required growth rate. The values and final required growth rates are summarized in Table 8.

Table 8: Required growth rates to achieve 2030 and 2050 green hydrogen electrolysis capacity targets in the EU

Target year	Future EU targets[9] (GW)	Remaining years to achieve targets considering 2023 capacity (Year)	Required decadal growth rates to achieve targets (GW/Decade)	Required decadal growth rates to achieve targets (MW/Decade)	Size of electricity supply for normalization (TWh)[10]	Normalized required growth rate (MW/TWh/Decade)	Normalized required growth rate (MW/TWh/Year)
2030	100	7	142.86	142,857.14	3,273.0 (2021-2030)	43.65	4.37
2050	500	27	185.19	185,185.19	3,990.0 (2021-2050)	46.41	4.64

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[8] Map generated by author using data from the IEA's Global Hydrogen Projects Database (IEA, 2022b)

[9] Given the limited and considerably negligible green hydrogen electrolysis capacity of the EU, the study assumed the capacity targets in 2030 (100 GW) and 2050 (500 GW) as the respective additional capacities needed for calculating the required growth rate.

[10] Total size of electricity supply data for normalization were derived from the IEA World Energy Outlook 2022, EU's announced pledges and not stated policies. Total electricity supply data for 2021 instead of 2023 were used due to availability issues.

The last column shows the required annual growth rates (MW/TWh/Year) to achieve the 2030 and 2050 targets in the EU, normalized to the forecasted size of their electricity supply. In the succeeding sections, these values are compared to the maximum annual growth rates (MW/TWh/Year) of the reference case technologies. The growth rates for both the target and reference case technologies are plotted in a feasibility space to determine if the required growth rates for green hydrogen electrolysis have been made possible historically. Relevant drivers of historical technological growth are then identified for contextualization and replication for scaling green hydrogen electrolysis in relevant markets and geographies.

4.2.2 Growth of reference case technologies for green hydrogen electrolysis

Following the calculated growth rates required to achieve the 2030 and 2050 targets, the next step is to calculate the historical growth rates of the eight reference case technologies. This process began by plotting the cumulative increase in their capacity as shown in Figure 8. It has to be noted that there are gaps in the plotted lines due to either limited time series data or the inexistence of the technologies during that period. For example, the renewables reference cases only show in the chart in the latter years as they have only been introduced beginning of the mid-90s into the energy systems.

Due to the sheer size of their energy systems, global wind, solar, and nuclear data reflect the biggest cumulative capacity values and growth trends, followed by EU wind and solar. It is also observed that nuclear power is a well-established technology that formed a significant piece of the global energy system for the majority of the 20th century, together with fossil fuels. However, its capacity has been surpassed by wind and solar power in 2016 and 2018, respectively, at the global level. These two global renewables capacities demonstrate a continuous upward growth trend. The national-level reference case technologies show the flattest cumulative capacity given the size of their energy systems, which is significantly smaller compared to the global and EU scale technologies.

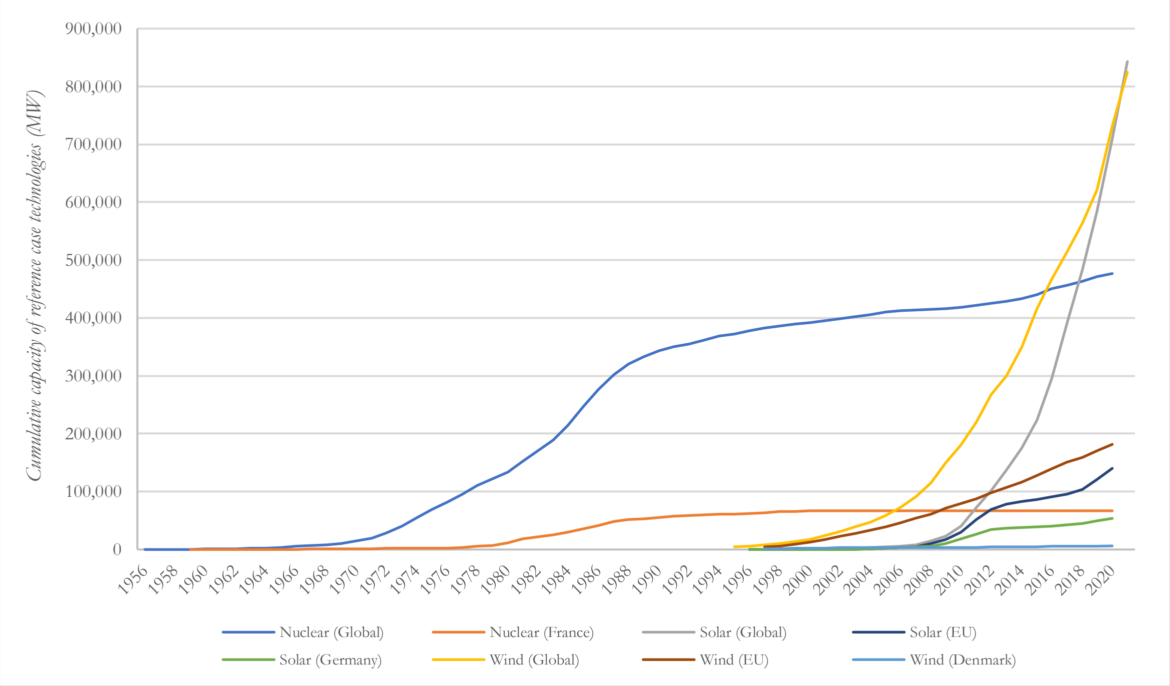

Figure 8: Cumulative capacity of the reference case technologies in MW

To enable the valid comparison of the cumulative capacity of the eight reference case technologies spread at different scales (i.e., global, regional, national), the study performed normalization across all the technologies. As discussed in the literature review, this process enables the comparison of measuring the growth of energy technologies while considering the size or scale of the energy system to which it belongs. Further, the capacities (MW) of the eight reference case technologies have been normalized to their total electricity supply in TWh. For example, the cumulative capacity of global nuclear power is normalized to the global electricity supply, while nuclear power in France is normalized to the total electricity supply of France. The normalized cumulative growth of these technologies in MW/TWh is shown in Figure 9.

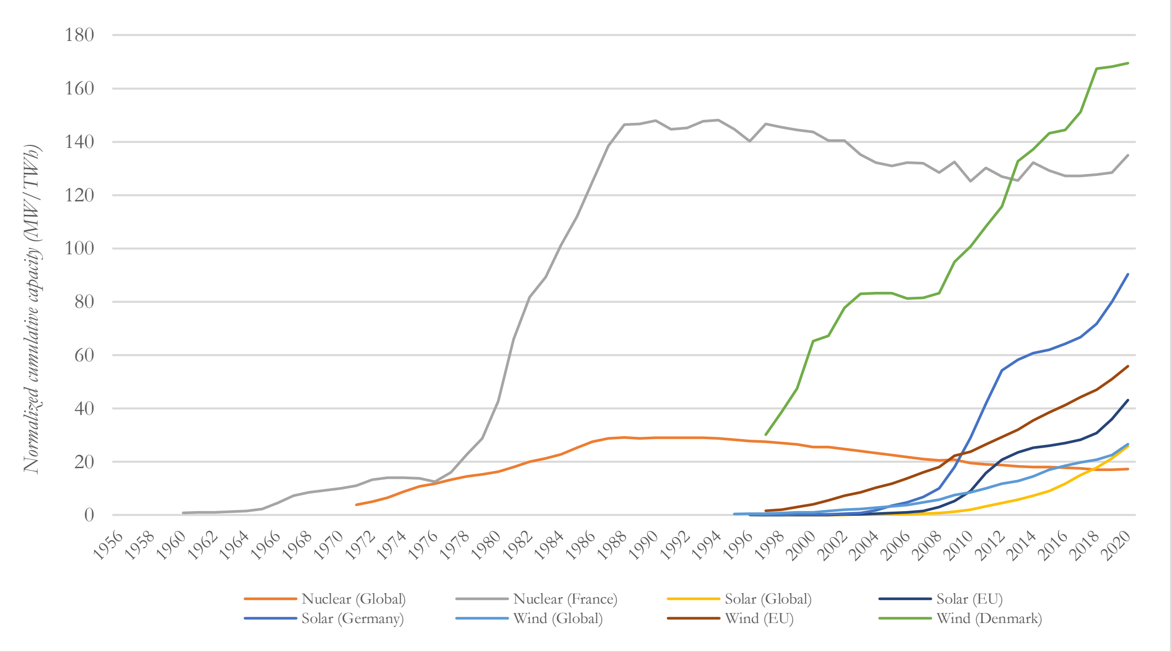

Figure 9: Cumulative capacity of reference case technologies (MW) normalized to the size of their energy system i.e., electricity supply (TWh)

One key observation with the growth rates in Figure 9 is how the national-level reference case technologies i.e., wind power in Denmark, nuclear power in France, and solar power in Germany, show the biggest growth in capacity compared to their regional and global counterparts. This suggests that these three technologies have grown significantly more rapidly in relation to their total electricity supply. And whereas global wind, solar, and nuclear capacities were growing significantly as shown in Figure 8, they were not growing as fast compared to their respective total electricity supply.

Another observation made in Figure 9 is that with the exemption of global nuclear and nuclear power in France, all reference case technologies show a positive growth trend. This could be indicative that no addition to their total capacities is being made and potentially the transition away from nuclear power toward other energy sources.

Furthermore, the cumulative capacities in Figure 8 have been used to calculate the rolling decadal growth rates as shown in Figure 10. This calculation was performed to determine the ten-year periods of the fastest or maximum increase in capacity across the reference case technologies. The decadal growth rates were calculated by subtracting the cumulative capacity in the first year of a decade from the tenth year's capacity, and were executed on a rolling basis, *i.e.*, the ten-year interval or window moves through the time series data until the end of the time series. Each point in Figure 10 represents a growth rate quantified as an additional MW per decade.

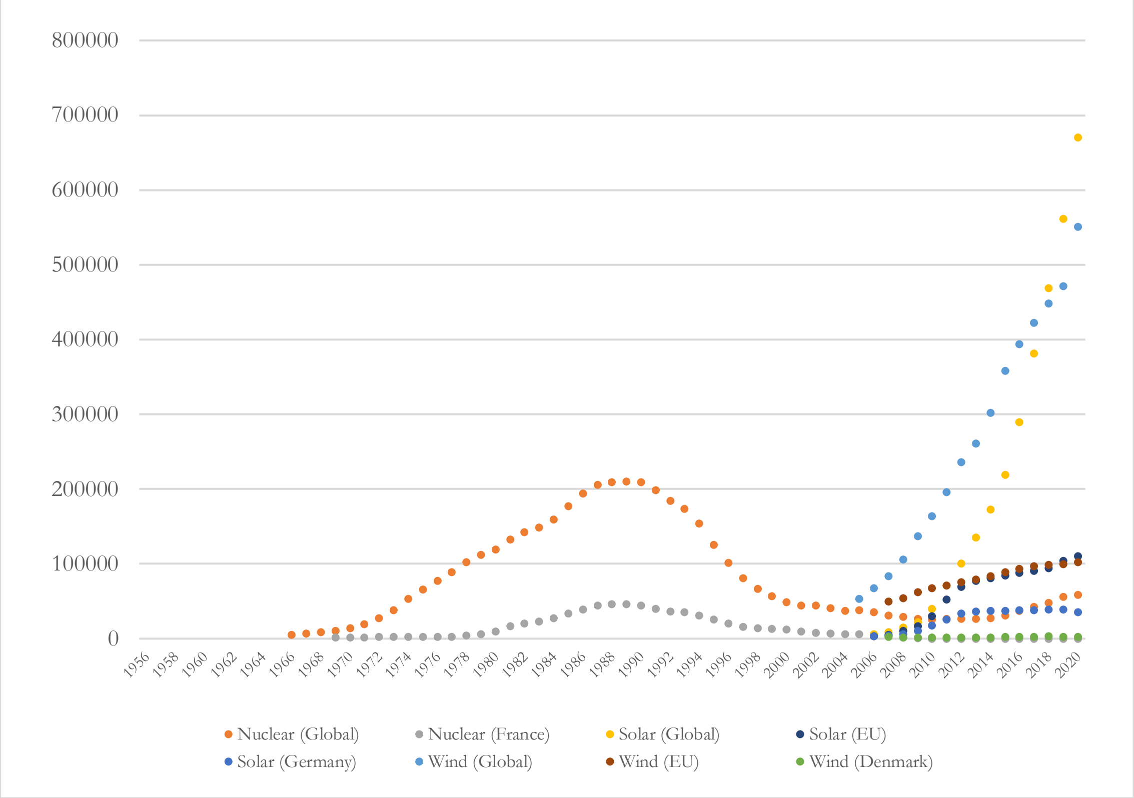

Figure 10: Rolling decadal growth rates across the reference case technologies (MW/decade)

Across the eight reference case technologies, global solar power and wind power show the steepest growth rates. Further, global nuclear and nuclear power in France peaked around the late 1980s and started to decline in the early 1990s. The other reference case technologies show slow yet steady decadal growth rates.

Using the rolling decadal growth rates in Figure 10, the maximum or fastest decadal growth rates have been noted and converted to annual rates, as summarized in Table 9. These values have also been normalized to the average change/growth in their corresponding total electricity supply (TWh) during the same ten-year period. The average of the electricity supply for the normalization process is used to avoid underestimating or overestimating the energy system.

Table 9: Ten-year periods with the fastest recorded growth rates renormalized to their respective electricity supply

Parameters	*Reference Case Technologies*							
	Nuclear – Global	Nuclear – France	Solar – Global	Solar – EU	Solar – Germany	Wind – Global	Wind – EU	Wind – Denmark
Decade of Fastest Normalized Growth	1979 – 1989	1978 – 1988	2010 – 2020	2010 – 2020	2008 – 2018	2010 – 2020	2010 – 2020	2008 – 2018
Maximum increase in capacity (MW) (Y_{10}-Y_1)	210,086.5	46,480.0	669,943.3	110,229.0	39,036.0	550,911.0	102,272.8	2,952.0
Average electricity supply[11] *(TWh)*	9,509.9	292.6	24,801.4	3,346.2	642.0	24,801.4	3,346.2	36.5
Maximum normalized annual growth rate *(MW/TWh/Year)*	2.2	15.9	2.7	3.3	6.3	2.2	3.1	8.1

Across the eight reference case technologies, nuclear power in France has the highest maximum normalized annual growth rate of 15.9 MW/TWh/Year, followed by wind power in Denmark (8.1 MW/TWh/Year), and solar power in Germany (6.3 MW/TWh/Year). Notably, it is the national-level reference case technologies that have demonstrated the fastest maximum normalized annual growth rate, which indicates the rapid increase in their capacity, relative to the size of their energy system (spatial factor) and specific period in history (temporal factor).

The list is followed by solar and wind power in the EU, with maximum normalized annual growth rates of 3.3 MW/TWh/Year and 3.1 MW/TWh/Year. It is noted that for these two reference case technologies, the most rapid increase in their capacity is observed between 2010 and 2020, thus, they have been normalized using the same average total electricity supply.

Lastly, the global reference case technologies follow the list with solar capacity at 2.7 MW/TWh/Year, and wind and nuclear both at 2.2 MW/TWh/Year. While the maximum normalized annual growth rates are similar for global nuclear and global wind, it should be noted that they grew in different energy systems (total electricity supply) and different ten-year periods.

Ultimately, the maximum normalized annual growth rates summarized in Table 9 are plotted in Figure 11 as a scatterplot. This scatterplot shows an X-axis of the total electricity supply (energy system on a logarithmic scale) and a Y-axis of the recorded maximum annual growth rate.

The global reference cases are further on the right side of the scatterplot due to the bigger energy systems in which they grew. Meanwhile, the national-level reference case technologies are plotted higher in the Y-axis due to the smaller size of their energy system, which pulls up their growth rates. The EU-level reference case technologies lie between the national and global-level reference case technologies.

Overall, these maximum decadal growth rates provide the points used for constructing the feasibility space in the succeeding section, where the maximum historical growth rates are used

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[11] The average change in the total electricity supply is taken during the ten-year period to avoid over/under estimating.

for assessing the feasibility of the required growth rate for green hydrogen electrolysis. In the succeeding section, the maximum normalized growth rates of the reference case technologies are compared to the required growth rates to achieve the 2030 and 2050 targets for green hydrogen electrolysis in the EU.

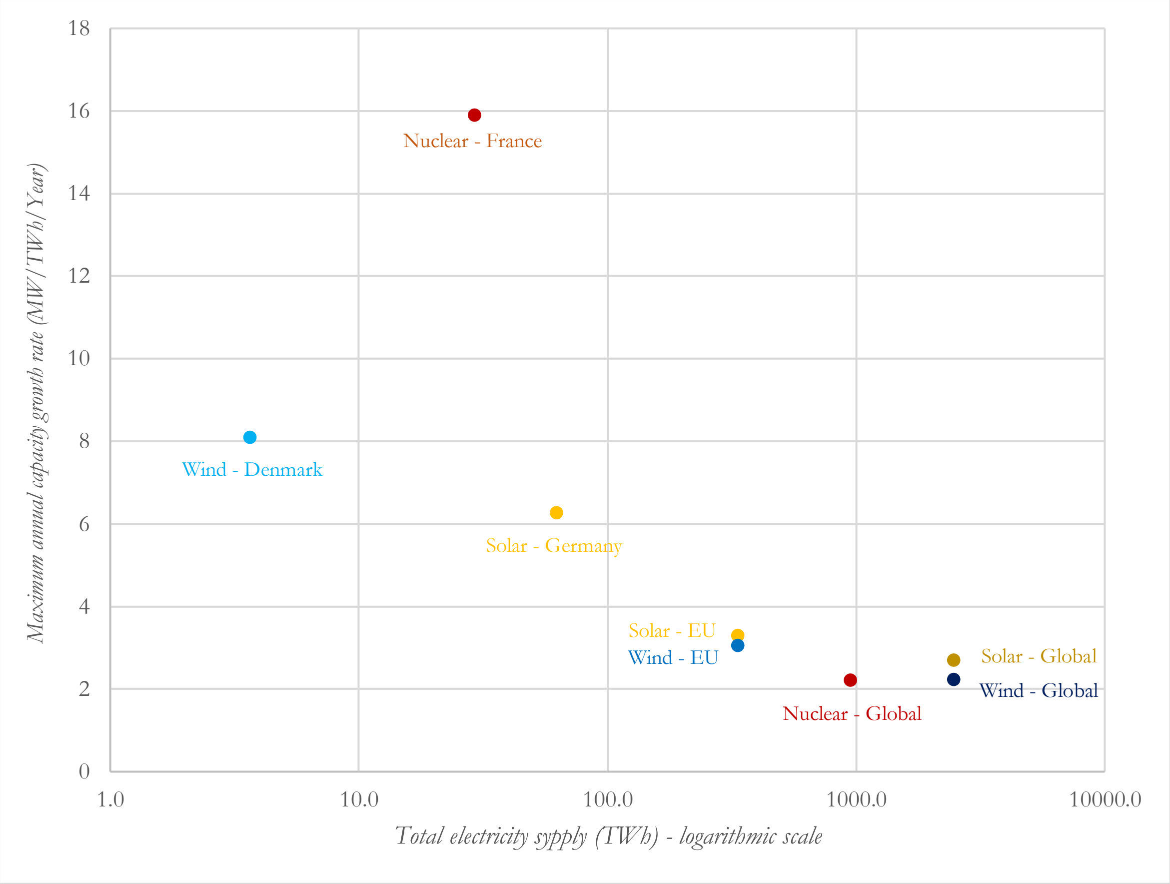

Figure 11: Maximum annual capacity growth rate of the reference case technologies normalized to the size of their energy system (i.e., total electricity supply)

4.2.3 Comparison of the required growth and growth in reference case

In this section of the chapter, the study compares the maximum normalized annual growth rates of the reference case technologies with the required normalized growth rates to achieve the 2030 and 2050 targets for green hydrogen electrolysis in the EU. Table 10 merges the key data in Table 8 and Table 9 to summarize these growth rates of interest.

Period refers to the ten-year interval of maximum increase in capacity for the reference case technologies, and the remaining growth period in the case of the target case i.e., green hydrogen electrolysis capacity. *Capacity* is the maximum increase in capacity addition during the aforementioned ten-year periods for the reference case technologies and the required additional capacity to reach future targets for the target case. *Total electricity supply* is the value used to normalize the maximum decadal growth of the reference case technologies. As discussed, the average change in growth/capacity during the respective ten-year period is used to avoid over or underestimating the total electricity supply. In the context of the target case, the study used the average between the 2021 EU total electricity supply and the forecasted values for 2030 and 2050. These forecasted electricity supply data were derived from the IEA's World Energy Outlook 2022, Announced Pledges Scenarios.

Table 10: Comparison of maximum growth rates of reference case technologies and required growth rate for green hydrogen electrolysis

Parameters	*Reference Case Technologies*								*Target Case Technologies*	
Technology	Nuclear – Global	Nuclear – France	Solar – Global	Solar – EU	Solar – Germany	Wind – Global	Wind – EU	Wind – Denmark	Hydrogen – EU	Hydrogen – EU
Period (Period of fastest increase in capacity for reference case technologies; Remaining period for reaching capacity targets for green hydrogen)	1979 – 1989	1978 – 1988	2010 – 2020	2010 – 2020	2008 – 2018	2010 – 2020	2010 – 2020	2008 – 2018	2023 – 2030	2023 – 2050
Capacity (Max. increase in capacity for reference case technologies; required increase in capacity for target case)	210,086.5	46,480.0	669,943.3	110,229.0	39,036.0	550,911.0	102,272.8	2,952.0	142,857.1	185,185.2
Total electricity supply (TWh)	9,509.9	292.6	24,801.4	3,346.2	642.0	24,801.4	3,346.2	36.5	3,273.0	3,990.0
Normalized growth rate (MW/TWh/Year)	2.2	15.9	2.7	3.3	6.3	2.2	3.1	8.1	4.37	4.64

In addition to the normalized values from Table 10, Figure 12 also shows the normalized required growth rates to achieve the 2030 and 2050 green hydrogen electrolysis targets for the EU. The points in Figure 12 show the relative position of the maximum normalized annual growth rates of both the reference and target case technologies. The shaded region indicates the implementation levels, which are formed from the maximum normalized growth rates of the reference case technologies. The darker region indicates more feasible implementation levels while lighter regions indicate growth rates with fewer historical precedents and are thus less feasible. Naturally, the bigger the energy system gets, the lighter the feasibility region becomes. Likewise, the higher or steeper the maximum normalized annual growth is, the more likely that it is in a lighter region. These observations are also captured by the downward trend line, signifying that the normalized maximum annual growth rate tends to decrease as the size of the energy system i.e., total electricity supply, expands. The curvature in the trend line is due to the logarithmic scale of the X-axis.

Figure 12: Feasibility space for green hydrogen electrolysis capacity in the EU formed the maximum normalized annual growth rates of the reference case technologies

The analysis reveals that nuclear power in France has experienced the highest recorded growth rate, followed by wind power in Denmark and solar power in Germany. However, it is important to consider that these growth rates cannot be solely attributed to national efforts and investments. The size of their respective energy systems, which is relatively smaller compared to other reference case technologies, has also played a role. Nevertheless, the rapid technological growth and significant capacity increase achieved within a limited timeframe by these technologies can still provide valuable insights. These observations can inform important policy and investment recommendations for scaling up green hydrogen electrolysis production in the EU. By applying similar strategies and approaches, the aim is to foster comparable growth rates and rapid deployment of green hydrogen electrolysis technology in the region. The proposed replication and tailor-fitting of such policy experiences are explored in the discussion section of the study.

Additionally, it is observed that the maximum growth rates of wind and solar power in the EU are relatively closer to the required growth rates for green hydrogen in 2030 and 2050. This similarity can be attributed to the shared size of their energy systems. However, it is important to note that the required growth rates for the 2030 and 2050 targets exceed the maximum growth rates achieved by wind and solar power in the EU. This implies that achieving the desired growth rates for hydrogen will necessitate unprecedented investments and policy coordination beyond what has been observed for wind and solar power in the region.

Similarly, it is worth highlighting that the required growth rate for the 2050 green hydrogen electrolysis target is greater when compared to the 2030 target. This discrepancy in growth rates can be attributed to the significant increase in capacity targets. Specifically, the 2030 target aims to attain a capacity of 100 GW, whereas the 2050 target sets a much more ambitious goal of reaching 500 GW. As a result, meeting the 2050 target will demand a level of investment and implementation of policies that surpass those employed to achieve the 2030 target.

Using the same set of growth rates, a feasibility space has been constructed in Figure 13 to compare the growth of the reference cases and the required growth for green hydrogen electrolysis in absolute values.

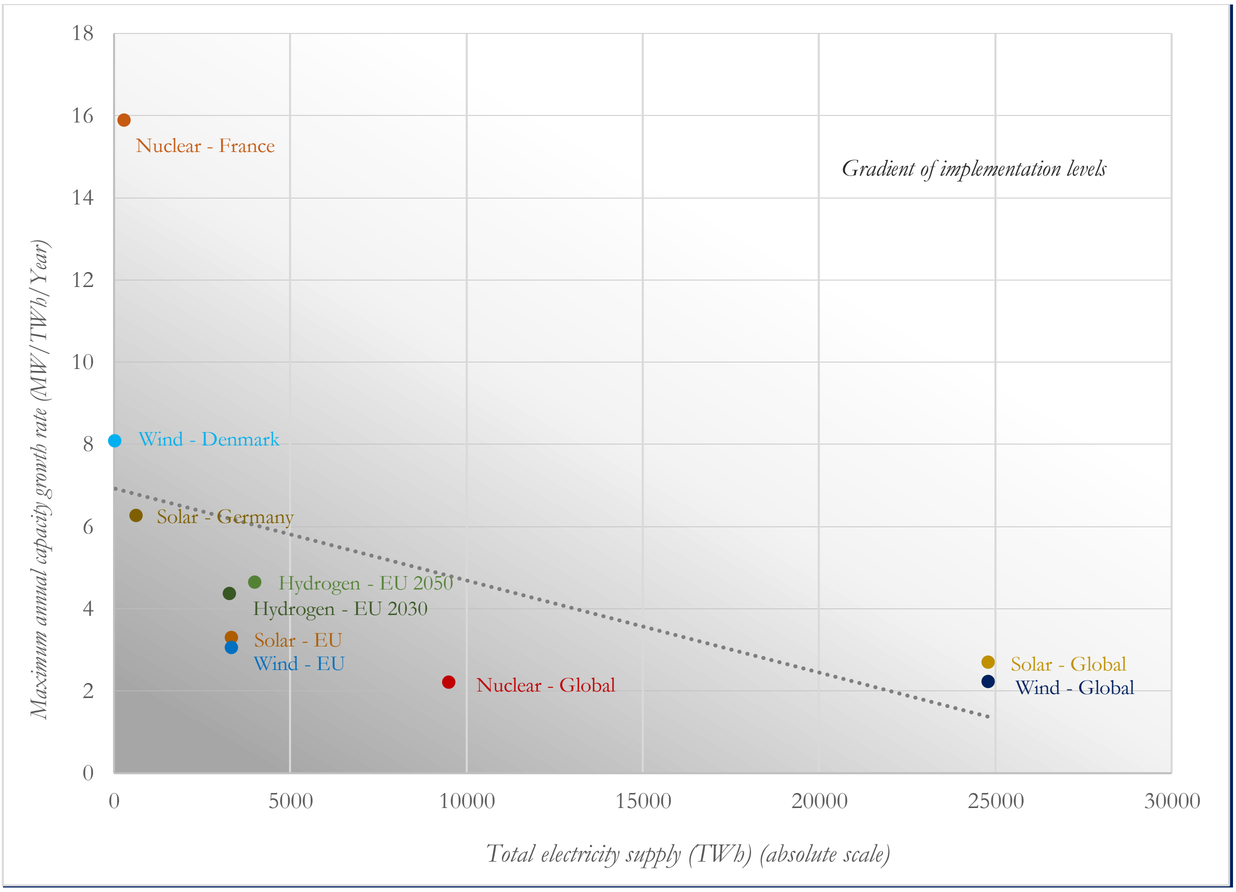

Figure 13: Feasibility space for green hydrogen electrolysis capacity in the EU formed by the maximum normalized annual growth rates of the reference case technologies in absolute values

Similar to that of Figure 12, a trend line in Figure 13 shows that the maximum normalized annual growth rates of the reference case technologies go down the bigger the energy system or total size of electricity supply is. Additional observations and inferences are problematized in the succeeding chapter of the study.

4.3 Feasibility of hydrogen pipeline network

This section aims to assess the feasibility of the future growth of hydrogen pipelines set by the European Hydrogen Backbone, using the maximum growth rates of natural gas pipelines in Europe. Specifically, it presents the required growth of hydrogen pipelines by 2030 and 2050 and identifies historical precedents of such a pace of pipeline expansion.

4.3.1 Required growth for hydrogen pipeline network

The construction of an interconnected pipeline network from production sites to points of consumption remains one of the key challenges of scaling hydrogen. Globally, there are approximately 4,500 KM of green hydrogen pipelines, mostly in the United States (2,608 KM) and Europe (1,598 KM) to date (H2 Tools, 2016; Perrin et al., 2007). There are also several short pipeline networks in other parts of the world including China, Singapore, Thailand, Australia, and Brazil (337 KM) (*Ibid.*). In Europe, the majority of the existing pipelines are owned by Air Liquide (1,351 KM) and are located in Belgium, the Netherlands, Germany, and France. The distribution of operational hydrogen pipelines in the region is shown in Figure 14.

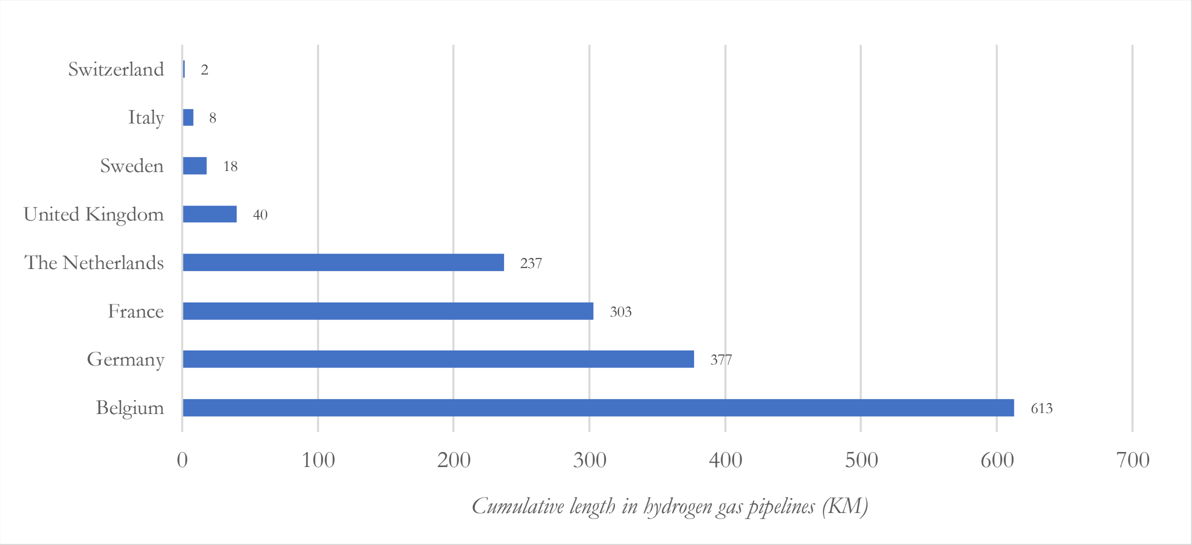

Figure 14: Distribution of existing hydrogen pipelines in Europe[12]

The selected scope for the analysis of hydrogen pipelines growth is the European continent and not the European Union, which is the scope for green hydrogen electrolysis. The key reason for this is that the continent has set clear specific hydrogen pipeline length targets for 2030 and 2040 through the European Hydrogen Backbone (EHB). As discussed in the introduction of this study, the EHB aims to construct *28,000 KM of hydrogen pipeline by 2030 and 54,000 KM by 2040 (van Rossum et al., 2022).* Thus, it has to be noted that the United Kingdom is added to the analysis in terms of both the target and reference cases *i.e.,* the inclusion of natural gas data expansion in the UK. Countries such as Russia and Turkey are also not included in the analysis.

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[12] Recreated by author using data from H2 Tools (2016)

Similarly, while it is ideal to assess the future growth of hydrogen pipelines at a global level, there are also no clear future targets yet at this scale. The lack of an overarching international target for hydrogen pipelines in terms of length can be attributed to the technical challenges of constructing trans-continental infrastructure, the relatively nascent international cooperation in the sector, and limited coordination or market supply and demand (IEA, 2022a).

Overall, the presence of clear future targets in 2030 and 2040 makes Europe an ideal context for both the examination of the historical growth of natural gas pipelines and assessing the future growth of hydrogen pipelines in the region. Noting the aforementioned EHB targets, the gap between the existing pipeline infrastructure in 2023 and the 2030 target is what is needed to achieve the EHB's first milestone, equivalent to 26,402 KM. Consequently, hydrogen pipelines need to be built at approximately *3,770 KM of pipelines per year (37,700 KM/ decade)*. On the other hand, between 2023 and the second target of 54, 000 KM in 2040, hydrogen pipelines have to be constructed at *3,083 KM/year* (*30,825 KM/decade*). The more stringent time left for achieving the 2030 target results in a more demanding growth rate for this milestone to be achieved.

Using the historical example of natural gas pipelines in Europe, the next section aims to determine any historical precedents of such growth i.e., *37,700 KM/decade and 30,825 KM/ decade.* The availability of such historical precedents or the absence thereof shall provide a quantitative reference example for assessing the feasibility of future hydrogen pipeline targets. Essentially, these historical precedents form the feasibility space of pipeline construction, and the required growth rate needs to be within the frontier of the space to support any claims of historical precedence and thus feasibility.

4.3.2 Growth of natural gas pipelines as a reference case

This section presents the growth of natural gas pipelines across Europe which provides the basis for identifying historical precedents of rapid technological diffusion. Examples of historical precedents are used to assess the feasibility of hydrogen pipeline growth targets in 2030 and 2040 as outlined in the EHB. Figure 15 shows the growth of natural gas pipelines beginning in 1948 until 2023. On average, natural gas pipelines in Europe grew by 1,170 KM annually and 11,300 KM every ten years. The slowest decadal expansion was observed between 1948 and 1958. The growth rates shown in Figure 15 provided the basis for calculating the decadal growth rates of natural gas pipelines.

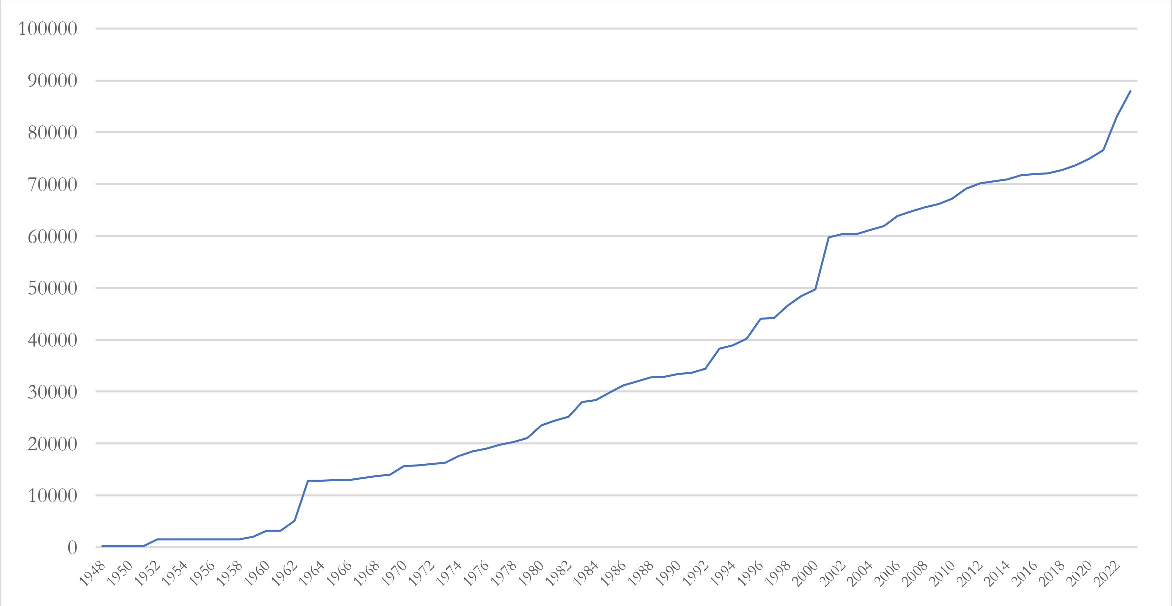

Figure 15: Cumulative addition of natural gas pipelines in Europe in KM (1948 - 2023)

To determine ten-year intervals of rapid expansion of natural gas pipelines, decadal growth has been calculated, which is a function of subtracting the length in the first year of the period from the tenth year. The rolling ten-year growth rates are shown in Figure 16. Each point represents the decadal growth of natural gas pipelines in Europe and forms the feasibility space for hydrogen pipelines as the target case. Using these calculated values, the ten-year period of the fastest expansion of natural gas pipelines in Europe was identified, which was from 1991 to 2001, with a growth rate of *26,153 KM per decade*. This is followed by the decadal growth rate between 1992 and 2002 at *25,939 KM per decade*.

In the succeeding section, the study makes a comparison between the historical growth of natural gas pipelines and the future targets for hydrogen pipeline expansion in Europe. This section provides the answer to the third research question of assessing the future growth of hydrogen pipelines using the experience of natural gas pipelines.

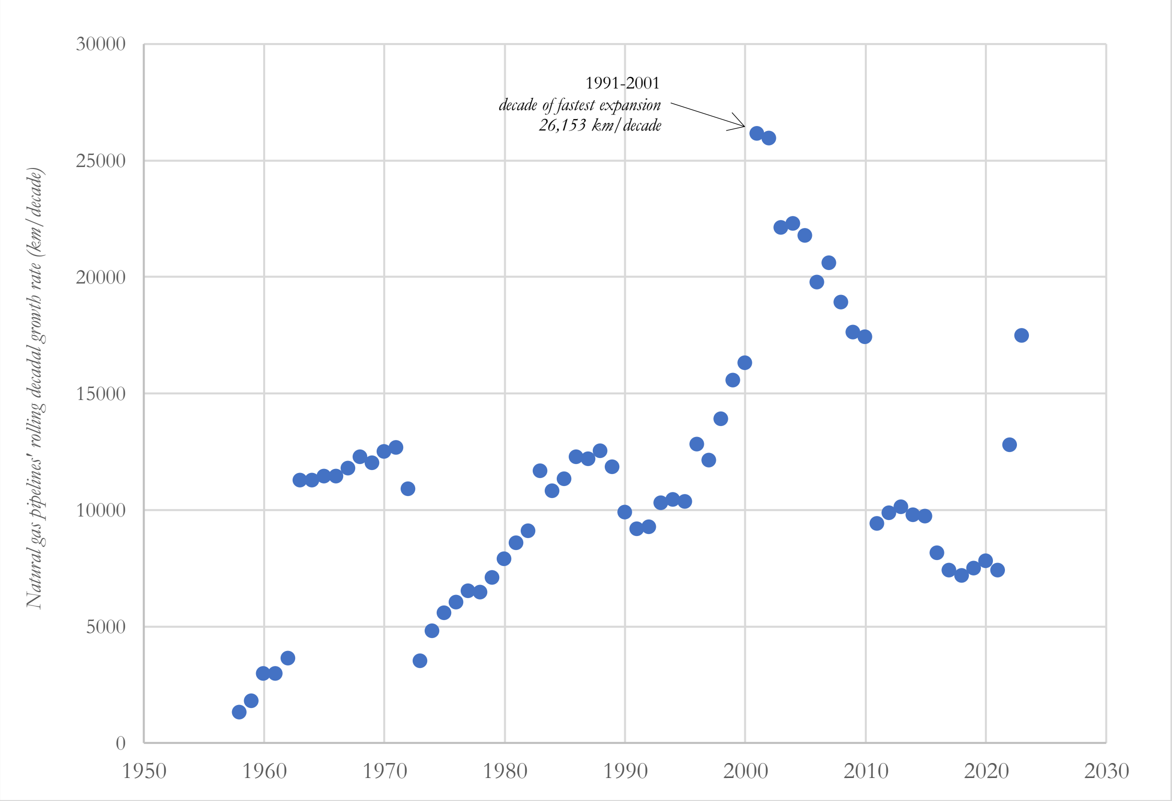

Figure 16: Rolling decadal growth rate of natural gas pipelines in Europe (1948 - 2023)

4.3.3 Comparison of the required growth and growth in reference case

The length targets for hydrogen pipeline expansion for 2030 (37,700 km/decade) and 2040 (30,825 km/decade) are plotted in red broken lines in Figure 17. Considering the decadal growth rates for natural gas pipelines and the feasibility space formed from these points, it can be inferred from Figure 17 that the future targets for hydrogen pipelines are not within the frontier and that there have been no direct historical precedents of such a pace of pipeline expansion. On these grounds, it can be inferred that the hydrogen pipeline targets are ambitious.

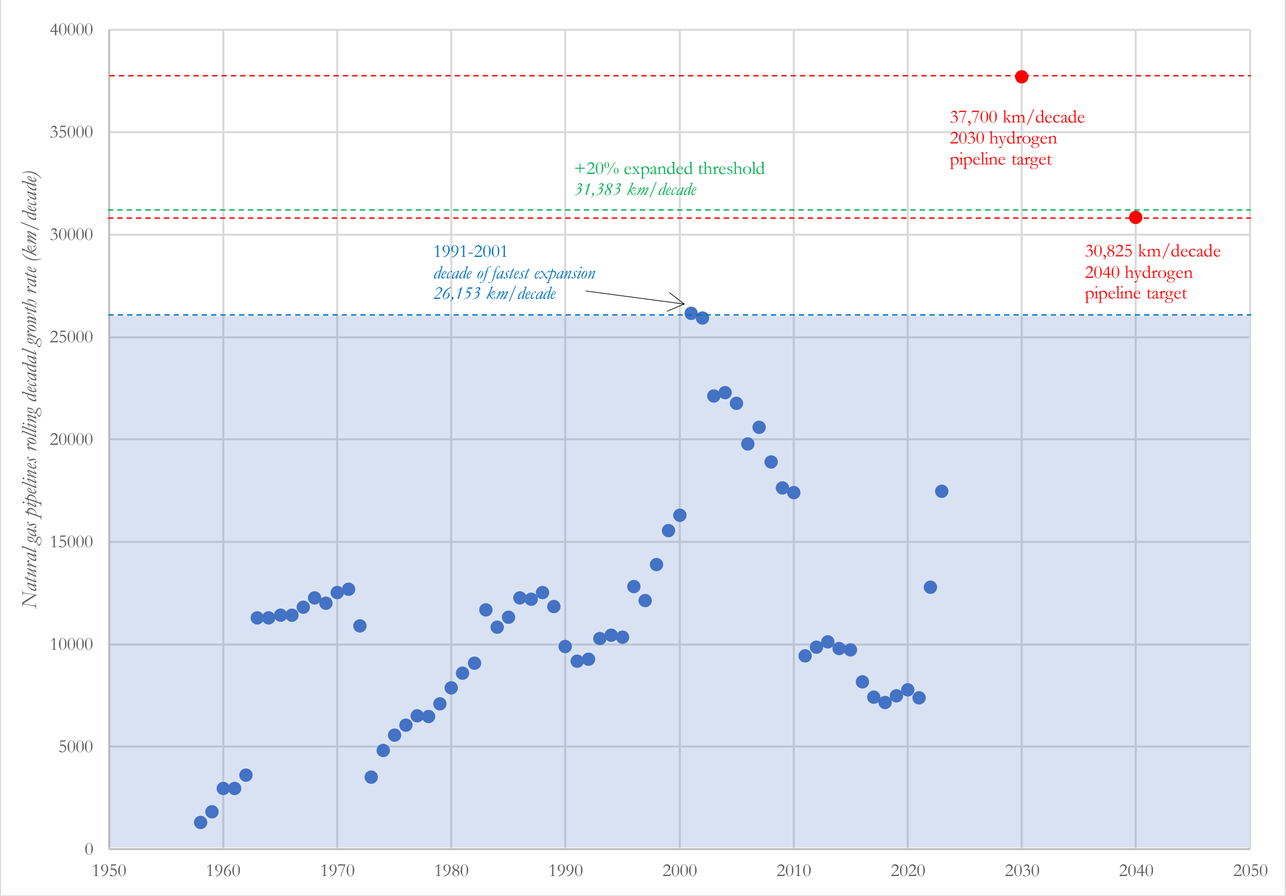

Figure 17: Feasibility Space constructed from the historical growth rates of natural gas pipelines for the assessment of the future growth targets of hydrogen pipelines in Europe

However, to account for limitations and uncertainties in the natural gas dataset (e.g., missing projects, projects excluded from the natural gas pipeline database, additional natural gas pipelines added in 2023, etc.), the upper threshold of the maximum growth has been expanded by +20%, giving a growth rate of 31, 383 km/decade (shown in broken green line in Figure 17).

With the expanded upper threshold of the feasibility space, it can be inferred that the 2040 hydrogen pipeline can be within reach and is plausible. This would suggest that by replicating the conditions and dedicated efforts executed during the decade of the fastest expansion of natural gas pipelines, it is possible to build 30,825 km/decade of hydrogen pipelines until 2040.

However, the 2030 target appears to be ambitious and stringent when using the historical growth experience of natural gas pipelines. Even with the expanded upper threshold of the feasibility space (i.e., +20%), the 2030 target remains too ambitious.

In the next section, the study proceeds with exploring the policy and broader socioeconomic landscape that took place during decades of rapid pipeline expansion and identifying ways to replicate such conditions to support the growth of hydrogen pipelines in Europe, especially for the 2040 target. In the case of the 2030 target, however, the thesis provides recommendations on how this can still be achieved by exerting unprecedented efforts and investments, building on the experience of the fastest historical growth of natural gas pipelines.

5 Discussion

This chapter presents and problematizes the study's findings to the three research questions.

5.1 There are multiple reference cases for green hydrogen technology and infrastructure

Deploying green hydrogen at a massive scale faces significant technological challenges, which entail the simultaneous delivery and acceleration of hydrogen supply, demand, and infrastructure, otherwise known as the "three-sided chicken-and-egg problem" (Schlund et al., 2022). It is this complexity and the underlying risks that hinder the needed investments for hydrogen production, end uses, and infrastructure. In this regard, examining the learning experiences from successful historical technologies provides powerful insights for scaling the future growth of emerging innovations. In the context of this study, accelerating the uptake of green hydrogen electrolysis in the EU and hydrogen pipelines across Europe, is even more pronounced, as a result of the energy crisis brought about by the Russian invasion of Ukraine, on top of the diminishing window to achieve relevant climate objectives.

Recognizing these challenges, the study proposed an analytical framework to facilitate the selection of reference cases, whose technological growth experience can help in assessing the feasibility of hydrogen-related targets presented in the EU's REPowerEU Plan and 2050 Climate Neutrality Roadmap, and the European Hydrogen Backbone (EHB). The analytical framework is composed of selection criteria namely (i) social function, (ii) granular-lumpy scale, (iii) technology readiness level, and (iv) historical growth rate/extent, which the study applied to identify valid and robust reference cases.

In terms of green hydrogen electrolysis, the target cases – or future technologies whose growth is being assessed – include (i) alkaline electrolysis and (ii) polymer electrolyte membrane, the two most advanced green hydrogen electrolyzer technologies in today's market (IEA, 2022a). After applying the framework, a total of eight (8) reference case technologies have been identified for assessing the future growth of green hydrogen electrolysis in the EU namely (i) global nuclear power, (ii) French nuclear power, (iii) global solar power, (iv) EU solar power, (v) German solar power (vi) global wind power, (vii) EU wind power, and (viii) Danish wind power. In the case of assessing the feasibility of the future hydrogen pipeline targets of the EHB, only natural gas pipelines have been identified. Overall, accounting for other considerations such as the availability of time series data, the study reveals that there several reference cases of similar technological attributes that can be used to assess the targets of related policies. They are valid reference cases based on the four framework parameters discussed as follows.

The first parameter used for reference case selection is *social function*, which in the context of green hydrogen electrolysis is *energy provision*. Both the reference and target cases, down to their core, provide energy for powering economic activities, as opposed to energy efficiency, or consumption/end-use technologies. Further, nuclear power and renewables are used for generating electricity, a versatile energy carrier that cannot only be used on its own but can also be converted into heat or mechanical energy to serve industrial or other purposes. Electrolyzers share these attributes in the sense that they produce hydrogen, also an energy carrier that has various versatile industrial and mobility applications.

Secondly, the reference and target cases fall within the same gauge in terms of the *granular-lumpy scale*. As discussed, the scale should not be regarded as a black-and-white categorization of technologies but instead a spectrum of their scale and complexity (Wilson *et al.*, 2020). Granular technologies are smaller, more modular, and exhibit lower complexity, which makes them easier to scale due to the lower risks associated with them. On the other hand, lumpy technologies are more complex and constitute more components, making them riskier in terms of investments and scaling. In the context of this thesis, the reference and target cases are found approximately within the same dimension in this scale. Specifically, they are examined at their *minimum functional or operational unit*, instead of disaggregating them into their more modular components or aggregating them into bigger energy systems. In addition, the use of capacity data (MW) for comparing their growth rates provides the advantage of quantifying the service they provide (Bento, 2013). Using capacity provides a neutral parameter that can isolate variables such as efficiency, capital investment, or labor productivity (*Ibid.*). Thus, using capacity as a metric supports a fair and valid comparison between the two sets of technologies.

Thirdly, the next parameter applied is *TRL*. The reference cases selected are established historical technologies and are technologically mature in most markets and energy systems. As a result, they would not be in the same tier as the target cases. Green hydrogen electrolysis is at TRL 9, signifying that it is already a commercially available technology in various markets (IEA, 2020), including the EU and the United States, etc. Being at this tier, however, demands continuous improvement to ensure it remains competitive and to secure its spot in the market. Being categorized at TRL 9 presents an important advantage for this study, that is, it is an indication that it has gone through the extensive formative phase of technological growth and would not retract or devolve into more rudimentary or nascent forms. Therefore, insights into scaling technological deployment as surfaced by the reference cases remain applicable and relevant for the target cases.

Lastly, the analytical framework's fourth parameter is *historic growth rate/extent*. Similar to TRL, growth rate/extent is not a parameter that is expected to be shared between the reference and target cases for obvious reasons. The study leverages this parameter in two ways to effectively assess the future growth of green hydrogen electrolysis.

First, the selected reference cases are situated in different scales namely global, regional/EU, and national/country-specific. The study acknowledges that there are broader socioeconomic forces that could influence the growth of energy technologies depending on the scale, and it is worthwhile examining them to surface the diversity of technological diffusion insights. For example, including national-level reference cases such as nuclear power in France or solar power in Germany recognizes the possible variables that are unique to each country and could be contributing to the pace of technological growth. Meanwhile, the use of regional or EU-level reference cases (i.e., EU solar power and wind power) provide a more direct and explicit comparison with green hydrogen electrolysis as a target case due to technologies' shared energy system and stakeholders. And using global-level reference cases i.e., global nuclear, solar, and wind power, underpins the challenge of scaling energy technologies at a huge magnitude, under time constraints and issues related to the connectivity of global infrastructures. And despite the apparent variations in the sizes of the energy systems associated with the reference cases, the study performed normalization to address the spatial and temporal differences resulting from scale and growth periods. This approach ensures a fair and consistent basis for comparing the reference and target cases, facilitating meaningful comparisons between them.

The second way the study leverages *historic growth rate/extent* as a parameter is by selecting reference cases that are not only diverse but technologies that have also demonstrated high growth rates. This is particularly evident in the renewable energy sector, where global, regional, and national scales have witnessed rapid growth. By comparing the required growth rates of green hydrogen electrolysis with these historical precedents of fast technological diffusion, the study identifies potential benchmarks that can be tailored and replicated for the target case.

Overall, these four parameters make the identified historical technologies as valid and robust reference cases for assessing the future growth of green hydrogen electrolysis in the EU.

Additionally, only one reference case has been identified for hydrogen pipelines, which are natural gas pipelines. This choice is logical as they share the same fundamental nature and purpose. Therefore, in terms of their *social function*, both technologies serve as infrastructure for connecting and transporting energy or fuel from generation sites to end-use points, fulfilling the role of *energy transport*.

Furthermore, hydrogen and natural gas pipelines are similar in terms of the *granular-lumpy scale*. They both involve modular components without intricate innovations or complex machinery. Although there may be variations in their chemical composition due to the nature of the fuels they transport, they are equally characterized by their simplicity and limited complexity.

The third parameter, *TRL*, differs between hydrogen and natural gas pipelines. Natural gas pipelines are well-established technologies that have successfully diffused into society, while hydrogen pipelines are still considered emerging technologies. Just like green hydrogen electrolysis, hydrogen pipelines are classified at TRL 9 (IEA, 2020), indicating their commercial operation in specific contexts like Germany, Belgium, France, and others. However, to maintain their competitiveness, continuous enhancements, and growth are required. On the other hand, natural gas pipelines have already achieved widespread diffusion in global markets, even more so in Europe, and do not necessitate further technological evolution to remain competitive. Taking this parameter into account, the growth rates of natural gas pipelines can offer quantitative insights into the required growth rates for hydrogen pipelines to achieve their future length targets successfully.

Ultimately, the analytical framework has successfully identified multiple historical technologies that serve as reference cases for evaluating the growth of green hydrogen electrolysis in the EU and hydrogen pipelines in Europe. This demonstrates the versatility of the framework while maintaining the crucial aspect of ensuring the validity, reliability, and comparability of the relationship between the reference and target cases. Through the selection of appropriate reference cases, the study highlights the importance of adopting an "outside view" perspective in the context of the clean energy transition.

As cited by Jewell and Cherp (2023), Kahneman and Lovallo (1993) define the "outside view" as the use of historical analogies – reference cases – to examine the feasibility of a particular climate change strategy or solution. This is in contrast to the inside view, which approaches climate change as a distinct challenge that can be addressed through political decisions and expertise (Kahneman & Lovallo, 1993). Whereas the use of historical examples as reference cases are bound to be met with criticisms like the inability to explain specific causal effects (van Sluisveld et al., 2015) or failure to account for the changing dynamics of future policy and socioeconomic landscape (Wilson et al., 2013b), it stands to provide logical observations and "*natural observations*" (Dunning, 2012; as cited by Jewell & Cherp, 2023), which could support feasibility assessments nonetheless.

To reconcile the approaches of the inside and outside views, this thesis took inspiration from the framework of Jewell and Cherp (2023) for formulating a feasibility space, which visualizes the maximum normalized growth rates of the reference cases and the required normalized growth rate of green hydrogen electrolysis. The same feasibility space is created for hydrogen and natural gas pipelines, albeit without normalization. As discussed in the second section of this chapter, the formulated feasibility spaces test the robustness of the analytical framework in selecting reference cases using a focused, quantitative analysis of the technological growth rates.

5.2 Required growth of hydrogen infrastructure is feasible but would require unprecedented efforts

This section problematizes the results of RQ2 and RQ3, which aimed at assessing the future growths of green hydrogen electrolysis in the EU and hydrogen pipeline in Europe, respectively. By placing the maximum growth rates of the reference cases and the required growth rates of the target cases in shared feasibility spaces (see Figure 12 and Figure 17), the study enabled the normalized comparison of the rate of their diffusion, providing the basis for assessing their growth feasibility.

In terms of RQ2, the study demonstrated that it is feasible to achieve the 100 GW electrolysis capacity target by 2030 as envisioned by the REPowerEU Plan (EC, 2022) and the 500 GW capacity target by 2050 through the EU Hydrogen Strategy (EC, 2020). Essentially, as far as the scope of the reference cases of this study is concerned, there have been three distinct historical precedents that such future growth rates can be attained namely the expansion of nuclear power in France in 1978 – 1988, wind power in Denmark in 2008 – 2018, and solar power in Germany in 2008 – 2018. Interestingly, all the national-level reference cases have exceeded the required growth rates for green hydrogen capacity targets in the EU by 2030 and 2050.

However, it is also crucial to account for the smaller size of their energy systems, which could have played a role in the relatively rapid increase in their capacities. At the same time, coordination of relevant market and political stakeholders on a national scale is arguably easier than at a regional scale, where there may be more opposing views and greater bureaucracy and the need for cross-border transactions can be more challenging.

By reproducing the efforts made during specific periods for these energy technologies, the feasibility of achieving the 2030 and 2050 green hydrogen electrolysis capacity targets increases. This would suggest reviewing the specific country-level conditions and strategy approaches (policies and investments) to orchestrate such high growth rates and replicate them on the scale of the EU.

The rapid rise of French nuclear power in the 1970s and 80s represents one of the most successful accelerated deployments of an energy system in the contemporary history of the developed world (Grubler, 2010). With a $50-billion investment (Dickson, 1986), France launched its Pressurized Water Reactor (PWR) Program and constructed 58 reactors beginning in the early 1970s, which generated approximately 400 TWh/year of electricity through 2000 or 80% of the country's electricity generation (Grubler, 2010). The rapid pace of French nuclear power technological expansion can be explained by a multitude of factors.

First is the French Government's unwavering technocratic dedication across the political spectrum to prioritize the development of nuclear energy above all other energy sources. This commitment has been driven by practical considerations such as the limited availability of domestic energy sources, as well as the strong desire to ensure energy security, which is a pillar of employment and economic progression (Dickson, 1986). Its highly centralized government also eased permitting, construction, and other major processes that would have been otherwise delayed by a distributed administration (Hecht, 2009). For instance, the national utility Electricite de France or EDF holds the responsibility for the design, development, and operation of all nuclear power plants across the entire country (Dickson, 1986). In relation, France continued working with single technology providers for its reactor vessels, turbine generators, and the like (*Ibid.*), cutting down on bureaucracy. Further, another factor is the strong public acceptance and support for nuclear power in the country, with the energy source portrayed as an emblem of national pride and a symbol of technological superiority (Hecht, 2009).

In comparison to the French experience, the maximum growth rate of wind power in Denmark is much more recent (2008 – 2018) and is interestingly influenced by strong anti-nuclear sentiments driven by local cooperatives and civil society organizations (Johansen, 2021). With an extensive coastline, Denmark also has the benefit of having abundant and consistent wind throughout the year (Johansen, 2021). But beyond these, Denmark's global reputation as a frontrunner in wind power can be credited to its extensive development of technology beginning in the 1890s (Meyer, 2007). The ideas and technological advancements pioneered by Poul la Cour – a Danish innovator – established the foundation for wind-powered electrification in this Scandinavian country beginning early 1900s through the 1950s (Meyer, 2007).

More importantly, contemporary energy policies leverage Denmark's historical background and abundance of natural resources and aim at the development of a sustainable and decarbonized energy system by promoting the use of RES and electricity based on RES (Meyer, 2007). But what is more relevant is Denmark's broad political coalition Energy Agreement from 2012 to 2020, which adhered to ambitious energy efficiency targets, strategies for streamlined integration of additional RES into the energy system, and marked initiatives for nearshore wind farm development (Johansen, 2021).

In relation to Denmark's maximum recorded growth rate for its wind power, Germany's solar power has been observed to have grown the fastest in the same ten-year period of 2008 – 2018. What makes Germany a promising case is its rapid phase-out of nuclear beginning in the 1990s and transition toward an energy system based on renewables (Cherp et al., 2017). The German Energiewende (Energy Transition) came about from a prevalent anti-nuclear backlash, and an alternative narrative of low-carbon development (Morris & Pehnt, 2012).

Overall, a confluence of policies has contributed to Germany's rapid uptake of solar power. For one, the German Renewable Energy Sources Act (Erneuerbare Energien Gesetz, EEG) has proven to be highly effective in fostering the market growth of various renewable energy technologies, including solar PV. This success can be attributed to the implementation of feed-in tariffs, which ensure a stable and predetermined price for electricity generated from PV systems for 20 years beginning in the year of the installation, protecting private investment through a more stable premium. Economics also played a role in the rapid deployment of solar power. For every doubling of solar PV capacities, the prices of German PV modules dropped at a lower rate than the global average (Schaeffer et al., 2004). Despite limited solar irradiation, the economic viability of solar power in Germany is a testament to the effectiveness of its feed-in tariff policy. It has managed to achieve the lowest solar power prices globally and this accomplishment can be attributed to the investment certainty and market maturity fostered by the feed-in tariff system. Overall, Germany's feed-in tariff policy has enabled the country to establish itself as a leader in cost-effective solar energy generation (Morris & Pehnt, 2012).

In summary, the national-level reference cases in the study demonstrated rapid growth rates that surpass the required targets for green hydrogen electrolysis capacity in the EU, indicating historical precedents. By learning from the successes of these country-level historical cases, it becomes possible to scale. However, the unique regional context of the EU necessitates tailoring these country-level interventions and accounting for their unique conditions and experiences.

The second critical observation from the feasibility space (Figure 12) is the proximity of the maximum growth rates recorded for EU solar power and EU wind power and the similarity in terms of the period (2010 – 2020)[13]. When comparing the required growth rates for green

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[13] However, it must be noted that due to the absence of capacity data for years 2021 and 2022, it is possible that solar power and wind power have not plateaued yet and are still growing.

hydrogen electrolysis targets in 2030 and 2050, it becomes apparent that the historical experiences of solar and wind power in the EU fall short. By identifying EU policies and interventions that have contributed to the maximum growth rates observed for wind and solar power, the study determined the baseline for the scale of effort, investment, and coordination to achieve future green hydrogen capacity targets.

The rapid expansion of solar and wind power in the EU can be explained by a convergence of policies. To transition the EU into an energy-efficient and low-carbon economy, the EC unveiled a renewable energy roadmap in 2007, which outlined specific targets for energy and emissions reduction (EC, 2007). These targets are presented in the EU's Climate and Energy (CARE) Package - a portfolio of laws to ensure the EU achieves its climate and energy targets for 2020, namely (i) a 20% cut in greenhouse gas emissions (from 1990 levels), (ii) 20% of EU energy from renewables, (iii) 20% improvement in energy efficiency (European Commission, 2007). Two years after, the EU adopted Directive 2009/28/EC, which marked a significant step toward the promotion and facilitation of renewable energy among its member countries (Ervine, 2015). This directive solidified the EU's objective of attaining a 20% share of RES in the total final EU energy consumption by the year 2020 by establishing mandatory RE targets specific to each EU member state, with certain variations, i.e., some surpassing the 20% threshold while others fall below it (Ervine, 2015).

Overall, based on the maximum growth rates observed for solar power and wind power in the EU, it can be inferred that the green hydrogen electrolysis targets are ambitious but can still be within reach with heightened, exceptional efforts never seen before by the bloc. Beyond this, green hydrogen policies should also be mindful of the tradeoff between the direct use of renewable electricity for economic activities or green hydrogen production through electrolysis, which is a potential source of competition that can endanger the 2030 and 2050 targets.

Lastly, looking at the growth rates exemplified by the three global reference cases i.e., nuclear, solar, and wind power, it can be inferred that to achieve the 2030 and 2050 green hydrogen electrolysis targets, capacity has to be scaled more than what has been observed for these three reference cases, entailing significantly more investments and concentrated effort.

The thesis recognizes that there may be limitations with the use of global-level reference cases, particularly after applying a normalization parameter (i.e., total electricity supply). It is possible that for these three reference cases that their capacities are not well distributed globally and are only concentrated in certain pockets worldwide, which would yield lower growth rates if total electricity supply at the global scale is used.

With the data points in Figure 17, the study infers that there may also be historical precedents of rapid expansion of natural gas pipelines in Europe – albeit very limited – which can attest to the feasibility of the future targets of the European Hydrogen Backbone. Between 1991 and 2001, Europe observed its fastest expansion of natural gas pipelines, equivalent to 26,153 km/decade. In the following rolling decadal growth rate (1992 – 2002), the second fastest pace was observed at 25,939 km/decade. While these are the fastest recorded growth rate in Europe, it does not meet the required growth rate for the 2030 target of 37,700 km/decade and the 2040 target of 30,825 km/decade. As discussed in the methodology, a +20% to the maximum recorded growth rate has been applied to account for the limited data included in the analysis. With the expanded upper threshold, the 2040 target could fall within reach marginally, although subject to unprecedented investments and expansion of the network. Having said this, the study emphasizes the scale of the expansion that needs to occur to achieve the 2040 target.

Further, it appears that there have been no historical precedents of the growth rate required to achieve the 2030 hydrogen pipeline target. Part of the reason is the inadequate amount of time left to construct such pipeline addition, resulting in a more stringent pipeline addition of 3,770 km/year beginning in 2023. Further, the construction of pipelines is regarded as a significant infrastructure undertaking, entailing environmental and safety considerations, cross-border transactions, complex engineering installations, and high investment costs (Schoots et al., 2011). This is made even more complex by the need to ensure that there is a supply of liquified green hydrogen to be transported, or else risking the creation of an infrastructure system that serves a limited purpose, equating to investment losses (Hydrogen Council & McKinsey & Company, 2022).

Whereas the maximum growth rates demonstrated by natural gas pipelines in their history in Europe do not exactly meet the required growth rates to achieve the targets of the European Hydrogen Backbone, it remains worthwhile to explore the relevant interventions that were put in place *within* or *approximate* that ten-year period (1991 - 2001), with the rationale of replicating or contextualizing them to the rapid future deployment of hydrogen pipelines. In 1985, energy stakeholders witnessed the unfolding of the European Single Market, which liberalized the EU market (Correljé, 2016) and propelled advances in the energy policy sphere (Matláry, 1997). Not so long after, the Internal Energy Market was launched in 1988, which restructured relevant energy markets around competition, efficiency, and business interest, and removed barriers to trade within the European Community (Matláry, 1997). The sweeping potential influence of these two EU-level policies on the fastest growth rate observed for natural gas pipelines in Europe in 1991 - 2001 could not be discounted.

Consequently, to reproduce the scaling effects of such policies in the context of a hydrogen pipeline network, it is recommended that the EU, other European states, and neighboring partner regions (e.g., Eurasia, North Africa, etc.) harmonize pipeline coordination, planning, and development, leveraging the European Single Market, the Internal Energy Market, as well as relevant energy and hydrogen policies i.e., REPowerEU Plan, and EU's Hydrogen Strategy, among others. Likewise, the European Hydrogen Backbone Initiative's lineup of hydrogen pipeline pledges and commitments of constructing dedicated hydrogen pipelines or converting natural gas pipelines into hydrogen-ready infrastructure has to be turned into concrete infrastructure plans and investment decisions. Lastly, such investment decisions also have to be made rather rapidly given the time-sensitivity of the targets and the bureaucracy that could hamper project development.

Nevertheless, it has to be remembered that natural gas and hydrogen are fundamentally two different energy carriers with different chemical makeup. The use of the existing natural gas pipelines is regarded as an obvious strategy for facilitating the transition toward hydrogen. However, one example of a technical bottleneck is embrittlement, which causes steel pipes to weaken, crack and rupture due to the penetration of hydrogen molecules fuel into steel pipelines (Schoots et al., 2011). This makes it more technically challenging to transport the energy carrier from one point to another,

In addition, the ability to transport hydrogen and create the pipeline network behind it is subject to the rapid scaling of hydrogen capacity in the first place. As exemplified in the "three-sided chicken-and-egg problem", the construction of hydrogen pipelines goes hand in hand with hydrogen production, therefore, there would not be market and investment interest to construct hydrogen pipelines without scaling hydrogen capacity first (Schlund et al., 2022).

Having addressed the three research questions, the study contributes to the literature on three grounds. First is its use of an analytical framework in the process of selecting reference cases. With the exemption of the framework for constructing feasibility space by Jewell and Cherp (2023), current literature does not employ a framework for reference case selection, often relying on direct identification which could undermine succeeding analysis. Secondly, this study contributes to the highly limited literature on forecasting the future growth of green hydrogen using reference cases. By using a combination of historical technologies at various scales, the study expands the approach taken by Odenweller et al., (2022), who used solar and wind as reference cases for forecasting green hydrogen production. And lastly, the thesis contributes to technology forecasting and the use of reference cases for assessing the future growth of hydrogen pipelines. Most hydrogen pipeline studies pursue an engineering angle and examine fuel mixing with natural gas, or conversion of natural gas pipelines into hydrogen-ready transport infrastructure.

6 Conclusions and Recommendations

6.1 Scaling the growth of green hydrogen

Green hydrogen plays a critical role in the decarbonization of the energy sector and the fulfillment of global climate objectives. In its current state, however, it is still an emerging technology and has not scaled to the level that can satisfy market demands, address energy security, and hit sustainability targets. Further, there are uncertainties surrounding its growth due to limited infrastructure and high investment risks, as well as its actual technological maturity. Recognizing the challenges related to deploying green hydrogen, this research study assumed a technology forecasting approach and explored the use of historical or established technologies, otherwise called reference cases, to assess the future growth of green hydrogen. More specifically, this thesis examined the future growth of green hydrogen electrolyzers and hydrogen pipelines, two of the most critical technological components to building a hydrogen economy that is based on renewable energy and not fossil fuels coupled with CCS compatibility.

An analytical framework has been formulated composed of four parameters grounded on existing technology forecasting literature namely social function, granular-lumpy scale, technological readiness level, and growth rate. Using this framework, the thesis identified multiple reference cases (historical technological) for assessing the future growth of green hydrogen electrolysis and hydrogen pipelines (target cases). Eight reference cases for green hydrogen electrolysis have been identified namely (i) nuclear power – global, (ii) nuclear power – France, (iii) solar power – global, (iv) solar power – EU, (v) solar power – Germany, (vi) wind power – global, (vii) wind power – EU, and (viii) wind power – Denmark. Meanwhile, only one reference case has been identified for hydrogen pipelines, which is natural gas pipelines – Europe.

The study tested under RQ2 the robustness of the reference cases by comparing their maximum growth rates with the required growth rates to achieve the green hydrogen electrolysis targets of the REPowerEU Plan (100 GW by 2030) and the EU's Hydrogen Strategy for a Climate-Neutral Europe (500 GW by 2050). The normalized maximum growth rates of the reference cases and normalized required growth rates of green hydrogen electrolysis were plotted in a feasibility space to visualize the feasibility levels of the latter as indicated by historical precedents. The study showed that the maximum normalized growth rates of the country-level reference cases i.e., French nuclear power in 1978 – 1988 (15.9 MW/TWh/Year), Danish wind power in 2008 – 2018 (8.1 MW/TWh/Year), and German solar power in 2008 – 2018 (6.3 MW/TWh/Year), significantly exceeded the necessary green hydrogen electrolysis growth rates to achieve future targets of 4.37 MW/TWh/Year for 2030, and 4.64 MW/TWh/Year for 2050. Further, it was nuclear power in France with the highest maximum normalized growth rate, exceeding the 2030 and 2050 green hydrogen required targets by 264% and 243%, respectively. In simple terms, these values suggest that achieving the 2030 and 2050 targets entails achieving such paces of technological growth. Practically, this requires replicating the conditions and policies observed in these country-specific reference cases and tailor-fitting them to the unique energy policy landscape and socioeconomic needs of the EU.

Whereas the country-level reference cases exhibited rapid technological growth rates, the maximum normalized growth rates for solar power and wind power in the EU fall shortly by approximately 25% to achieve the growth rates required for the green hydrogen electrolysis 2030 and 2050 targets. Meanwhile, the maximum normalized growth rates of the global level reference cases fail to reach the 2030 and 2050 targets by approximately 40%.

Under RQ3, the study showed that the maximum growth rate of natural gas pipelines in Europe (26,153 km) falls short by 31% and 15% to reach the European Hydrogen Backbone's hydrogen pipeline addition targets by 2030 and 2040. However, applying a +20% threshold for 26,153 km to account for data uncertainties would suggest that the 2040 target can still be within reach, subject to increased investment and accelerated growth observed for natural gas pipelines between 1991 and 2001.

Overall, highlighting the importance of the "outside view" to climate solutions and its reconciliation with the "inside view" in a feasibility space (Jewell & Cherp, 2023), the study showed the usefulness of historical analogies which provide reference cases to the upscaling of low-carbon infrastructure, namely green hydrogen electrolysis and hydrogen pipelines in the context of this study. Whereas there are inherent differences between the target cases (future technologies) and reference cases (historical technologies), the latter can provide useful insights into the scaling of the former given that they have gone through lengthy technological expansion and are considered established technologies. Nonetheless, it must be emphasized that while reference cases provide some level of abstraction, they are not explicit about growth mechanisms and actors of infrastructure expansion.

6.2 Methodological reflections

Firstly, future research can benefit from exploring and identifying the plausible actors of hydrogen network expansion, and complement the abstraction provided by reference cases for assessing future growth. Further, by increasing the number of reference cases and their granularity (e.g., addition of country-level reference cases), future analysis based on reference cases' implementation levels can be enhanced. In relation to this, subject to time series data availability, exploring additional reference cases for hydrogen pipelines, i.e., connective infrastructure, such as power grid lines, railways, or oil pipelines, is also worth exploring.

The study also highlighted the importance of both correctly normalizing growth and considering it in systems of comparable size. The process of normalization helps create a level playing field in terms of growth comparison for both target and reference cases by accounting for both spatial (total electricity supply TWh) and temporal (periods of rapid growth) parameters. The use of normalization can be explored for assessing the future growth of hydrogen pipelines. One potential normalization parameter is the size of required investments, although can provide different results. In terms of normalizing for green hydrogen electrolysis capacity, normalization to the size of the electricity system may not be optimal. Alternative normalization may include total GDP size or the size of the industrial sector.

6.3 Policy recommendations for green hydrogen infrastructures

Noting the maximum growth rates of the country-level reference cases that exceed the required growth rates for green hydrogen electrolysis targets, the first policy recommendation relates to the contextualization of these successful national experiences in the EU arena. There are apparent differences between the EU and Germany, Denmark, and France such as sheer size, geopolitics, and other socioeconomic factors, but their energy policies provide effective principles that can be replicated in the EU. For example, the expansion of solar power in Germany testifies to the success of its FiT policy, which boils down to the importance of protecting private investments through a guaranteed premium. Similarly, a policy mechanism can be in the form of subsidies to new entrants in the green hydrogen market, or public venture funds to help capture some of the risks from green hydrogen projects and encourage the flow of private capital.

The case of French nuclear power points to the importance of streamlining bureaucracy and institutional arrangements to reduce operational delays related to project development such as permitting, licensing, bidding, and service provision. This policy principle is particularly critical in the context of green hydrogen development in the EU given the complexity of stakeholders involved (e.g., gas operators, distributors, producers), the corresponding infrastructure required, and the limited time to achieve the targets. The availability of the REPowerEU Plan, and Europe's Hydrogen Strategy, as well as the formation of the European Clean Hydrogen Alliance, is a step in the right direction toward two things: sending a strong government signal through synergistic policies and championing the EU as the global leader in the green hydrogen economy, both of which can stimulate investor confidence and inspire public trust.

Moreover, Denmark's example highlights the need for continued research and development, and the development of green hydrogen solutions pioneered by the EU e.g., electrolyzer and pipeline designs, integrated fuel transportation, etc., the way it pioneered the design for wind turbines. Likewise, the strong anti-nuclear sentiments observed both in Denmark and Germany that contributed to their accelerated uptake of renewables signifies the importance of engaging civil society groups and the public sphere. It is important to create public trust in scaling green hydrogen and avoid or mitigate social backlashes. This mirrors the growing negative sentiments toward fossil fuel in the EU and how this should contribute to catalyzing the transition to green hydrogen.

Lastly, it is important to highlight that the challenges of green hydrogen production and transportation are unprecedented and would therefore require the same level of effort and commitment. Whereas the EU's CARE Package and RES Directive spurred a significant uptake in renewable energy and electricity in recent history, elevating the political effort will be necessary, given the unique challenges of hydrogen such as fuel safety, infrastructure connectivity, market integration with neighboring regions, and potential competition for use of renewable electricity. Overall, the study highlights that there is no single bullet to scaling green hydrogen at a rapid pace, and a mix of policies and interventions is crucial to target each dimension of the green hydrogen agenda.

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