CLEAN HYDROGEN'S ROLE IN ENERGY TRANSITION OF THE USA, GERMANY AND TÜRKİYE

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ABSTRACT

CLEAN HYDROGEN'S ROLE IN ENERGY TRANSITION OF THE USA, GERMANY AND TÜRKİYE

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This thesis examines the key determinants that enable hydrogen to become a viable solution in the energy transition, with a comparative analysis of the USA, Germany, and Türkiye. While the existing literature predominantly highlights technological innovation, financial investment and national policy frameworks, this study argues that such efforts are insufficient without international relations and diplomatic solutions. Grounded in neoliberal institutionalist theory, the research shows that resolving interstate conflicts and establishing cooperative international mechanisms are essential for enabling hydrogen trade, technology transfer and cross-border infrastructure deployment. Through an analysis of national hydrogen strategies, value chain investments and diplomatic engagements, this thesis concludes that clean hydrogen can only become a scalable and sustainable energy solution through the international cooperations.

Keywords: Energy Transition, Clean Hydrogen, USA, Germany, Türkiye

ÖZ

TEMİZ HİDROJENİN ABD, ALMANYA VE TÜRKİYE'NİN ENERJİ DÖNÜŞÜMÜNDEKİ ROLÜ

Kaya, Murat
Yüksek Lisans, Yer Sistem Bilimleri
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Bu tez, hidrojenin enerji dönüşümünde uygulanabilir bir çözüm haline gelmesini mümkün kılan temel belirleyicileri, ABD, Almanya ve Türkiye örnekleri üzerinden karşılaştırmalı bir analizle incelemektedir. Mevcut literatür ağırlıklı olarak teknolojik yenilikler, finansal yatırımlar ve ulusal politika çerçevelerini ön plana çıkarsa da bu çalışma bu unsurların uluslararası ilişkiler ve diplomatik çözümler olmadan yetersiz kaldığını savunmaktadır. Neoliberal kurumsalcı teoriye dayanan araştırma, devletler arası çatışmaların çözülmesinin ve iş birliğine dayalı uluslararası mekanizmalarının kurulmasının; hidrojen ticareti, teknoloji transferi ve sınır ötesi altyapı entegrasyonu için hayati önemde olduğunu ortaya koymaktadır. Ulusal hidrojen stratejileri, değer zinciri yatırımları ve diplomatik girişimlerin analizine dayanan bu tez, temiz hidrojenin ölçeklenebilir ve sürdürülebilir bir enerji çözümüne dönüşebilmesinin ancak uluslararası iş birlikleri yoluyla mümkün olabileceği sonucuna varmaktadır.

Anahtar Kelimeler: Enerji Dönüşümü, Temiz Hidrojen, ABD, Almanya, Türkiye

To My Family

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ABBREVIATIONS	
BOTAŞ	Boru Hatları ile Petrol Taşıma A.Ş.
CCUS	Carbon Capture and Utilization
COP	Conference of the Parties
CO_2	Carbon Dioxide
EBRD	European Bank for Reconstruction and Development
ETS	Emission Trading System
EU	European Union
FSRU	Floating Storage and Regasification Unit
GHG	Greenhouse Gas
GL	Gallon
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
IRENA	International Renewable Energy Agency
LNG	Liquefied Natural Gas
MLP	Multi-Level Perspective Theory
MMT	Million Metric Tons
NASA	National Aerospace Agency
NDC	Nationally Determined Contributions

NGO	Non-Governmental Organization
OPEC	Organization of the Petroleum Exporter Countries
PV	Photovoltaics
TÜBİTAK	Türkiye Bilimsel ve Teknolojik Araştırma Kurumu
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America

CHAPTER 1

INTRODUCTION

The aim of this study is to explore transformative potential of clean hydrogen in the global energy transition with a comparative focus on the USA, Germany, and Türkiye. This study argues that international cooperation and conflict resolution are the most decisive factors in unlocking hydrogen's potential. While it is mostly assumed that technological innovation, financing and policy frameworks are the core factors for scaling hydrogen, they are insufficient to make hydrogen ready for everyone and even to meet these three countries' short term climate targets. Drawing on a neoliberal institutionalist perspective, the analysis situates hydrogen not merely as a fuel but as an international instrument shaped by global interdependence. Through an integrated examination of national strategies, hydrogen ecosystem developments and bilateral partnerships, the thesis contributes to the broader discourse on energy transition and climate governance.

1.1 Scope and Objective

This thesis examines the political, technological, financial and international relations dimensions underpinning the clean hydrogen agendas of the USA, Germany, and Türkiye. Three countries represent diverse realities and energy transition trajectories. As the global urgency to mitigate climate change intensifies, the energy transition has become a central pillar of the international policy framework. Clean hydrogen, emerging as a low-emission energy carrier, is increasingly viewed as an important solution. However, realizing its full potential demands an integrated approach that integrates innovation, investment and diplomacy. By focusing on the efforts of the

USA, Germany, and Türkiye, this study aims to illuminate the comparative dynamics of their hydrogen policies and identify the most decisive factors whether technological advancement, political support, financial capacity and international cooperation.

This comparative analysis is made upon Nationally Determined Contributions (NDCs), national policy documents, financial instruments, hydrogen value chain investments and international energy cooperation initiatives. The USA, Germany, and Türkiye converge in their strategic commitment to the energy transition, as evidenced by their formal submission of NDCs and the publication of comprehensive national hydrogen strategies. Furthermore, each country has demonstrated substantive progress across the hydrogen value chain including production, transportation, storage and end-use applications.

1.2 Research Question

The main research question of the thesis is the following: What is the contribution of clean hydrogen into the energy transition of the USA, Germany, Türkiye and what is the most important factor to unlock clean hydrogen's potential in energy transition?

The research seeks to delve into the following sub-questions:

- What do selected countries invest in clean hydrogen?

- What are the similarities and differences regarding NDCs, political ambition, infrastructure investments, finance and international cooperation?

- What factors contribute to or hinder the fulfillment of hydrogen commitments in each country?

Through a comparative analysis, this research aims to provide a nuanced understanding of the what is the decisive factor in clean hydrogen development.

1.3 Literature Review

The existing literature on energy transition and clean hydrogen has predominantly focused on technological innovation, financial frameworks and regulatory mechanisms, while largely overlooking the critical role of international relations. Although government subsidies, project financing, and technological readiness remain central themes, the geopolitical and diplomatic dimensions of hydrogen development have received comparatively limited scholarly attention. This omission is notable given that hydrogen, like oil and natural gas, possesses the potential to evolve into a globally traded commodity. Historically, fossil fuels transitioned from local solutions to globally energy resources only after becoming embedded within international trade networks. It highlights that clean hydrogen's viability may similarly hinge on the establishment of cross-border cooperation and multilateral governance frameworks.

Though the concept of clean hydrogen has become a new solution for decarbonization in last years, it is not a new phenomenon. Hydrogen dates to 1800s when it was first used as a lifting tool in ziplines. Then fuel cell technology was developed in 1950s, and it was used in NASA's Apollo and Gemini space missions as a power source. In 1970s, the concept of "hydrogen economy" was firstly used with the emergence of the oil crisis.[1]

Hydrogen as an energy solution was discussed academically by Frovjin, Baneke and Kramer and they claimed that there are historically three stages in its development. In the first stage, in 1970s, it emerged as a utopian energy solution. In the second stage, in 1990s, it was announced much more for transportation sector. In the third

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[1] Siddique, Zahed, and Md Monjur Hossain Bhuyan. 2025. "Hydrogen as an alternative fuel: A comprehensive review of challenges and opportunities in production, storage, and transportation." *International Journal of Hydrogen Energy*, pp.1026-1027.

stage, in nowadays, it is one of the strongest candidates for a sustainable energy sector. They claim that existing conditions; climate change, Paris Agreement and supply security present the best environment for hydrogen to develop as it has never done before. It is a historical time for hydrogen ramp-up. Obstacles and pitfalls will be easily driven out than before.[2] And Zipse supported this claim stating that hydrogen is one of the elements that can be used with natural gas or can replace it.[3]

There are many areas that hydrogen can decarbonize according to studies. First of all, according to Capurso, renewable hydrogen will be most beneficial for balancing excess renewable electricity production by storing it in hydrogen format. There is storage problem in electricity generation in the world and no concrete solition has been found yet. It will be a solution for intermittency problem of renewable energy sources like solar and wind.[4]

The "clean hydrogen" concept is a new concept arising in the last years in literature. There are many evaulations to decide which hydrogen is clear. For example, the USA The Infrastructure Investment and Jobs Act defined clean hydrogen as produced with a carbon intensity less than 2 kg CO2 equivalent per kg. Inflation Reduction Act of the USA defined it as having GHG emission no greater than 4 kg CO2 equivalent per kg. Moreover, European Commission define it as having GHG emission no more than 3.38 kg CO2 equivalent per kg. These definitions are concentrated on the emissions in hydrogen's production process. There are also other names of clean

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[2] Frovjin, Laurens, David Baneke, and Gert Jan Kramer. 2025. "Imagining a Hydrogen Economy: From Grand Technological Utopia to Enabler of the Energy Transition in Three Waves Since the 1970s." *Energy Research and Social Science,* pp.2-3.

[3] Zipse, Oliver, Joachim Hornegger, Thomas Becker, Markus Beckman, Michale Bengsch, Irene Feige, and Markus Schober. 2023. "Road to Net Zero." *Springer,* p.39.

[4] T.Capurso, M.Stefanizzi, M.Torresi, and M.Camporeale. "Perspective of the Role of Hydrogen in the 21st Century Energy Transition." *Energy Conversion and Management, (2022),* p.1.

hydrogen in literature as follows; “green hydrogen”, “sustainable hydrogen”, “zero-carbon hydrogen”, “near zero carbon hydrogen”, “low carbon hydrogen”, “decarbonized hydrogen”, “renewable hydrogen”, “electrolytic hydrogen”. There are also color classification method which is done according to pathway (processes), sources (electricity or fuels) or carbon emissions (high vs. low vs. zero) with no consistent criteria. For example, “grey” shows natural gas ans steam methane reforming method (source+process), blue represents natural gas, steam methane reforming and CCUS (source+process), green represents renewable electricty, water and electrolysis (source+process).[5]

There is a theorotical discussion to analyze which factor or factors are most decisive to unlock hydrogen’s potential. According to Roque and others, technological development in hydrogen is increasing and competitiveness against other fuels such as fossil fuels is increasing.[6] According to Jolly and others, technological improvements in hydrogen will not be enough and they should be supported by developments in solar and wind power technologies. Solar and wind power costs are main components of green hydrogen unit price. Even if electrolyzer cost decreases, it may not be enough to make hydrogen competitive with other fuels.[7]

According Zhang, the start of international hydrogen trade will enhance hydrogen and lots of regions will be able to use hydrogen in a cheap way. In that regard, internationally traded hydrogen via pipelines and maritime transportation will reduce

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[5] Kusoğlu, Ahmet. "Redefining Clean Hydrogen: From Colors to Emissions." *The Electrochemical Society,* (2022), p.47.

[6] Bruno Augusto Cabral Roque et al. "Hydrogen Powered Future: Catalyzing Energy Transition, Industry Decarbonization and Sustainable Economic Development: A Review." *Gondwana Research,* (2025), p.174.

[7] Sarah Susan Jolly et al.. "Emerging paradigms in renewable hydrogen production: Technology,challenges, and global impact." *Next Energy,* (2025), p.10.

hydrogen prices by at least 11%-30%. Moreover, North and East Africa's hydrogen production potential will be unlocked and African countries will be the leading exporters while Japan, South Korea and European Union will be the top importers.[8]

Noussan and others claim that value chain approach for hydrogen economy will be decisive on unlocking its potential. Even if hydrogen production cost is lessened by technological improvements and it becomes competitive with fossil fuels, it is still hard to reach end customers without establishing whole value chain like transportation, distribution and storage infrastructure. So overall cost of hydrogen for the customers will stay to be much higher compared with fossil fuels.[9]

Since hydrogen is a new fuel in the global market, there is a strong need for regulation and incentive regimes. To unlock its potential, Nyangon and Darekar claims that policymakers should form incentives and regulations to foster hydrogen economy. Moreover high carbon emitter sectors should be disincentivized across the world like carbon taxation mechanisms and strict energy standarts.[10] He, Yuan and Liao claim that government subsidies should be given in a balanced way and to all supply chain like production, transportation and end use technologies. While financial incentives can effectively encourage stakeholder participation and industry growth, overly generous subsidies may force public finances. In the initial phases, it is important for governments to offer targeted funding and supportive policies to build the foundation of the green hydrogen sector. Providing balanced subsidies

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[8] Q.Zhang, L.Wang, W.Chen, C.Zhang, "Assessing the Impact of Hydrogen Trade Towards Low-Carbon Energy Transition." *Applied Energy,* (2024), p.12.

[9] M.Noussan, P.P. Raimondi, R. Scita and M. Hafner, "The Role of Green and Blue Hydrogen in the Energy Transition-A Technological and Geopolitical Perspective ." *Sustainability,* (2021), p.20.

[10] Joseph Nyangon and Ayesha Darekar. "Advancements in hydrogen energy systems: A review of levelized costs, financial incentives and technological innovations." *Innovation and Green Development,* (2024), p.16.

across all parts of the supply chain can help accelerate industry progress without compromising fiscal sustainability. Holistic approach in incentives is seen as a solution to unlock hydrogen's potential.[11]

There are also studies evaulating contribution of international cooperation on energy to the hydrogen ecosystem but they are mostly concentrated on potential changes in geopolitics after hydrogen revolution rather than its sole effectiveness to unlock potential. The International Renewable Energy Agency (IRENA) presents a comprehensive analysis on how hydrogen may reshape international relations in the post-carbon world. First of all, it argues that clean hydrogen could decentralize energy systems and may reduce traditional hydrocarbon-based geopolitical tensions. The second perspective is that countries with abundant renewable energy resources could become potential hydrogen exporters in future and energy dominance may shift from fossil fuel-rich nations to renewable rich ones. There are also concerns about new forms of dependencies, such as those tied to critical materials. IRENA emphasizes that an international governance is needed to coordinate hydrogen markets and avoid future geopolitical conflicts with proactive diplomacy. Energy diplomacy is adviced as a solution for eliminating potential conflicts but not for realizing hydrogen ecosystem.[12]

When hydrogen ecosystem was set up in all around the world, there is possibility for beginning of hydrogen geopolitics similar like oil geopolitics. According to Van de Graaf and others, there are advantages and risks for hydrogen geopolitics. There are abundant regions for hydrogen production like Chile, Australia and there are high demand regions like Japan, South Korea and EU countries. A new type of energy

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[11] Yong He, Jiaqi Yuan and Nuo Liao. "Exploring the impact of government subsidy on technology innovation and pricing in green hydrogen supply chain." *Energy,* (2025), pp.8-9.

[12] IRENA, Hydrogen Trade, 2025, https://www.irena.org/Energy-Transition/Technology/Hydrogen/Global-hydrogen-trade

dependency may emerge in the world. However, they also emphasize that hydrogen could avoid the deficiencies of oil geopolitics if developed through multilateral governance structures, transparency and standardization.[13]

1.4 Argument

This thesis argues that international cooperation and the resolution of conflicts among states are the decisive factors for unlocking clean hydrogen's potential as an energy transition solution. Drawing on neoliberal institutionalist theory, it contends that clean hydrogen, as an energy carrier, cannot scale without international cooperation and reduced geopolitical tensions. Technological developments, finance and government subsidies, while necessary for the ramp-up of the hydrogen, they are insufficient in the absence of such international cooperation among states. Comparative analysis of the USA, Germany, and Türkiye demonstrates that unresolved regional disputes and absence of international cooperation undermine national hydrogen ambitions and global trade potential. To become commercially viable and sustainable for everyone, hydrogen must be approached not only as a technical, financial and political issue, but as an issue of international relations.

Despite growing political attention and financial investment, clean hydrogen development remains unevenly distributed due to significant structural asymmetries among states. While some countries possess abundant renewable energy potential, others lead in technological innovation or occupy strategic locations for hydrogen transit. These divergent national strengths and constraints give rise to imbalances that cannot be addressed through purely domestic strategies. Without international mechanisms for mutual reinforcement, global hydrogen deployment risks

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[13] T.Graaf, I.Overland, D.Scholten, K.Westphal. "The New Oil: The Geopolitcs and International Governance of Hydrogen." *Energy Research and Social Science.*(2020), p.3.

fragmentation. In this context, international relations offer more than platforms for dialogue, they function as redistributive tools that coordinate asymmetric capabilities into synergistic global value chains.

The success of international cooperation in the hydrogen, is contingent not only on the willingness of states to engage, but also on the resolution of conflicts. Unresolved disputes erode potential cooperations that may enhance hydrogen. When political-economic problems are resolved between states, cooperation becomes more feasible and investments more secure. Germany’s efforts to shift energy dependency from Russian gas toward hydrogen partnerships with countries like Egypt and Chile illustrates how diplomatic engagement can enable new supply chains. Türkiye’s potential as a hydrogen hub similarly depends on its alignment with the EU energy frameworks and progress in resolving regional disputes. The USA, by focusing primarily on domestic incentives while neglecting international engagement especially with potential partners like the EU, Mexico and China risks isolating itself in the emerging global hydrogen order. Therefore, conflict resolution is not ancillary but foundational to enabling multilateral cooperation and scaling hydrogen deployment globally.

The USA, Germany, and Türkiye all recognize clean hydrogen as a strategic tool in their energy transitions, yet their approaches differ due to distinct geographic locations, and different levels of technological and financial capacity. While the general objective for decarbonization is shared, the chosen pathways reflect each country's unique structural conditions and strategic interests. Understanding these national differences is essential for analyzing the potential of international hydrogen cooperation. From a neoliberal institutionalist perspective, such variation reinforces the need for multilateral frameworks that can reduce asymmetries, coordinate capabilities cross heterogeneous actors.

1.5 Theoretical Framework

The realization of clean hydrogen’s global potential is fundamentally dependent on international cooperation and the resolution of inter-state disputes. These dynamics are best understood through the lens of neoliberal institutionalism, which provides a robust framework for explaining how cooperation can emerge and persist in an anarchic international system. By emphasizing the role of institutions in reducing conflicts, fostering trust and aligning incentives, neoliberal institutionalism offers valuable analytical tools for understanding the conditions under which states may coordinate their efforts in the development of transboundary hydrogen infrastructure, trade and global governance. In this context, hydrogen is not merely a technological innovation, but a subject of international political negotiation and institutional design.

Neoliberal institutionalism claims that international and intergovernmental institutions are essential, and they are the best ways to protect national interests. Communication and cooperation on a range of topics such as political, economic and environmental is ensured by diplomacy. From this perspective, the global advancement of the energy transition depends not solely on national technological progress or financial capacity, but on the international cooperation that facilitate collaboration and cross-border investment. The geographical differences across countries in terms of hydrogen generation capacity and different demand types pose an environment in which hydrogen cannot be utilized in full scale. Only with cooperation and institutions, these differences can be minimized, and the potential can be unlocked.[14]

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[14] Hannah Lentschig, Aliaksei Patonia and Rainer Quitzow. "Multilateral governance in a global hydrogen economy: An overview of main actors and institutions, key challenges and future pathways." *International Journal of Hydrogen Energy,* 2025, p.84.

From a neoliberal institutionalist perspective, international institutions do more than facilitate cooperation; they also serve as mechanisms for managing and resolving disputes that might otherwise obstruct collective action. By reducing uncertainty, and offering platforms for dialogue, institutions help for structured cooperation. Frameworks such as the Paris Agreement and the REPowerEU Plan exemplify how institutional arrangements can channel competing interests into coordinated strategies. In the context of clean hydrogen, the absence of such mechanisms even among technologically advanced states in hydrogen, undermines the formation of international hydrogen trade.

Liberalism also asserts that the role of international institutions and cooperation is key to unlock energy transition in the world. From this view, the Paris Agreement, COP meetings and hydrogen alliances will foster energy transition. One of the proofs is that states must announce their climate pledges to lessen GHG emissions which is called Nationally Determined Contributions. Moreover, partnerships between countries will accelerate transition. For example, Germany has a huge renewable energy demand but lacks in renewable sources. Chile, in contrast, has leader in solar power capacity but has less demand. Cooperation between Germany and Chile for hydrogen production and then export it to the Germany will unlock the potential.

According to the realist theory, international system is anarchic, states act primarily in their own interests and cooperation happens only when it serves security like energy security. Energy has always been on the focus of realist theory. Controlling energy assets and determining prices have always been political leverages of countries. Hydrogen, a new energy asset, has not same geopolitical dimensions with oil and gas but has some similarities with them. For example, controlling fossil fuel reserves are too important for countries while countries have more renewable energy potential are advantageous in hydrogen. According to realism, energy transition is not an ethical issue rather redesign of global power. States invest in energy transition and renewable technologies to lessen their dependence to outside and to have a superior place in energy transition competition. For example, Germany is developing clean technologies and hydrogen strategies to lessen its dependency in energy and to sell its technological innovations to outside. China is heavily investing on clean technologies and rare earth materials used in transition era to become leader in renewable energy. Realism also claims that energy transition is a new type of regaining power for countries against oil and gas exporter countries.[15]

1.6 Methodology

This thesis adopts a comparative case study methodology to examine the developments of clean hydrogen in the USA, Germany, and Türkiye. The analysis focuses on key dimensions including political ambition, technological advancement, financial instruments and international cooperation under the lens of hydrogen ecosystem design. Primary sources such as national hydrogen strategies, official policy documents, bilateral agreements and technical reports from organizations including the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA) and the European Commission will form the empirical foundation of the study. In addition, relevant academic literature on energy transition and hydrogen governance will be systematically reviewed. To complement the qualitative analysis, a quantitative component will assess each country's clean hydrogen production capacity, transportation and storage infrastructure, and readiness for end-use applications.

The selection of the USA, Germany and Türkiye as case studies is done by contrasting profiles in their economic development, technological capacity, energy strategy and geographical positioning. While the USA and Germany are both advanced economies, they differ significantly in their hydrogen trajectories. The

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[15] Daniel Scholten. "The Power of Energy: The Geopolitics of the Energy Transition." *E-Internatioanl Relations,* 2024, pp.4-5.

USA benefits from abundant natural resources, existing operational experience and strong financial power, whereas Germany, despite limited domestic resources, demonstrates strong political commitment and technological leadership in hydrogen innovation. Türkiye, representing a developing economy with strategic geographic positioning, shows an important hydrogen production potential but faces some constraints in financial and technological capacity. The inclusion of these three cases allows for a comparative analysis across different levels of development and capacity. Furthermore, each country is in complex regional and global geopolitical dynamics ranging from international energy relations to regional disputes that directly or indirectly influence their ability to engage in international hydrogen cooperation. These variations provide a strong analytical basis for assessing how international cooperation can enable international hydrogen integration.

1.7 Structure of the Thesis

This thesis comprises seven chapters. Introduction, Energy Transition, Clean Hydrogen, the USA, Germany, Türkiye and Conclusion.

In the first chapter, scope and objectives, literature review, argument, theorotical framework, methodology and organization of the thesis is explained.

In the second chapter, nature of the energy transition in the world history has been tried to be assessed. Moreover, the concept of energy transition is explained, countries'evaulation and future picture of the global energy portfolio were analyzed. One of the main political drivers of the transition, Paris Agreement has been explained. In the last stage, the ways to achieve energy transition like technological improvement, investments, finance and diplomacy were assessed.

The third chapter analyzes hydrogen as a molecule and energy solution. Then, hydrogen ecosystem is explained under production, transportation, storage and application headlines because they have core elements for any energy ecosystem.

The fourth chapter analyzes existing energy transition and climate pledges of the USA. Then, political papers and investments on hydrogen value chain are assessed. In the last part, international cooperation of the USA on hydrogen is assessed.

In the fifth chapter, Germany’s energy transition policy Energiewende and climate pledges which are under European Union are assessed. Then hydrogen value chain investments, key gaps in production and technological improvements are analyzed. In the last part of the chapter, international hydrogen partnerships of Germany are analyzed.

In the sixth chapter, Türkiye’s energy transition and climate pledges are analyzed. Moreover, clean hydrogen ambition of Türkiye and strategic potentials are analyzed.

The last chapter includes concluding remarks regarding the factors that are effective for clean hydrogen energy transition. From the evaulation of the hydrogen developments in the USA, Germany and Türkiye, it is concluded that technology, finance and politics are not fully effective to unlock hydrogen’s potential, however, international cooperations and instutional frameworks will unlock the potential.

CHAPTER 2

ENERGY TRANSITION

In this chapter, we will start by examining the general characteristics of the energy transition, the Paris Agreement and how to achieve energy transition. The energy transition chapter explores the shift from fossil fuel–based energy systems toward cleaner and ones such as renewables, hydrogen and emerging low-carbon technologies. It begins by outlining the historical context of the energy transitions, then examines the unique characteristics of the current transition, which is distinguished by its urgency and scale in response to the climate change. Moreover, four main enablers of the energy transition is analyzed; technology, politics, finance and international cooperation. Ultimately, this chapter provides the conceptual and empirical foundation for analyzing how states navigate the complexities of energy transition, set their energy targets and position themselves within international climate governance frameworks.

2.1 What is Energy Transition

Energy transition refers to the shift in both the energy sources used and the technologies employed to generate and consume energy. In today’s world, the concept of “energy transition” primarily refers to the shift from carbon-intensive fossil fuels to low- or zero-carbon energy sources. Moreover, it is anticipated that fossil fuel-based systems based on coal, oil and natural gas will be gradually phased out and clean energy alternatives, including solar, wind, hydrogen, ammonia and other sustainable solutions are expected to assume a central role.[16] There are specific usage areas for clean solutions rather than answering whole energy demands. For instance, renewable electricity can replace fossil fuels in transportation sector but it cannot replace coal in hard-to abate industries because of the technical constraints. So the energy transition includes many clean energy alternatives and new systems so this indicates that it is a holistic issue rather than specific, niche development.[17]

Energy transition, in terms of changes in fuel consumptions, theoretically has happened many times in the world for last 200 years. It is not a new phenomenon. The fuels that we already used today took many years to be online to everyone. On a global scale, energy transitions have unfolded over very long periods. Coal did not exceed 25 percent of the energy mix until 1871, more than five centuries after the establishment of the first commercial coal mines in England. Oil reached the same share in 1953, nearly ninety years after Edwin Drake’s 1859 well in Titusville, Pennsylvania. In contrast, hydroelectricity, natural gas, nuclear power, and newer sources like wind and solar have yet to cross the 25-percent threshold indeed, only nuclear energy has managed to surpass 5 percent so far.[18] During 2010-2019 period, GHG emissions has reached to 53 Gt CO2 equivalent in 2023 which is higher than at any time. Top six emitters in the world are China, the USA, the EU, India, Russia and Brazil.[19]

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[16] Platts. *spglobal.* February 2020. https://www.spglobal.com/en/research-insights/market-insights/what-is-energy-transition.

[17] C.Bachorz, P.C. Verpoort, G.Luderer, F.Ueckerdt, Exploring techno-economic landscapes of abatement options for hard-to-electrify sectors, *Nature Communications*, 2025, p.1.

[18] Benjamin K. Sovacool, The history and politics of energy transitions: Comparing contested views and finding common ground, 2016, *Wider*, p.2.

[19] European Commission. GHG Emissions of All World Countries. *European Commission*. 2024, pp.5-15.

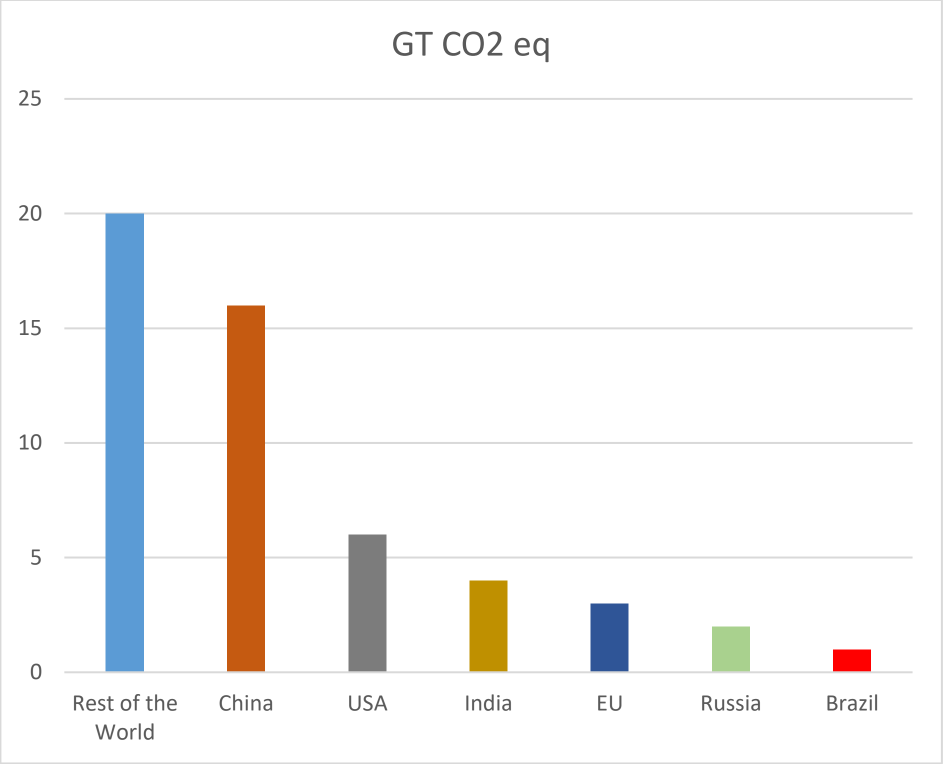

Figure 2.1 Top Six GHG Emitters in the World[20]

When we compare GHG emissions according to sectors, the global energy system is the biggest source of emissions. While current energy sector landscpae goes, it will not limit global temperature change below 2°C. Limiting global warming to well below is not possible without swift and significant cuts in carbon dioxide and other GHG emissions from the energy sector.[21]

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[20] European Commission. GHG Emissions of All World Countries. *European Commission*. 2024, pp.5-15.

[21] Intergovernmental Panel on Climate Change, Energy Systems, 2022, p.6.

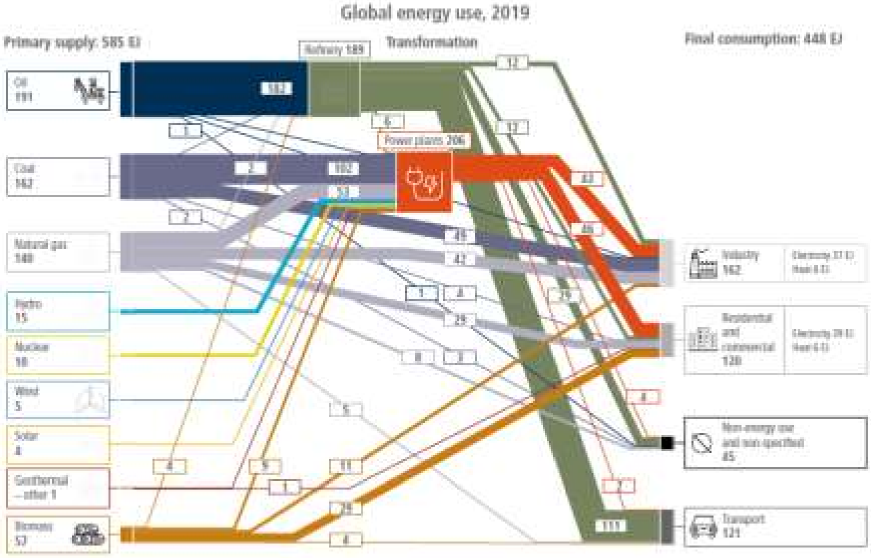

Figure 2.2 Global Energy Use According to Sources and End-Users[22]

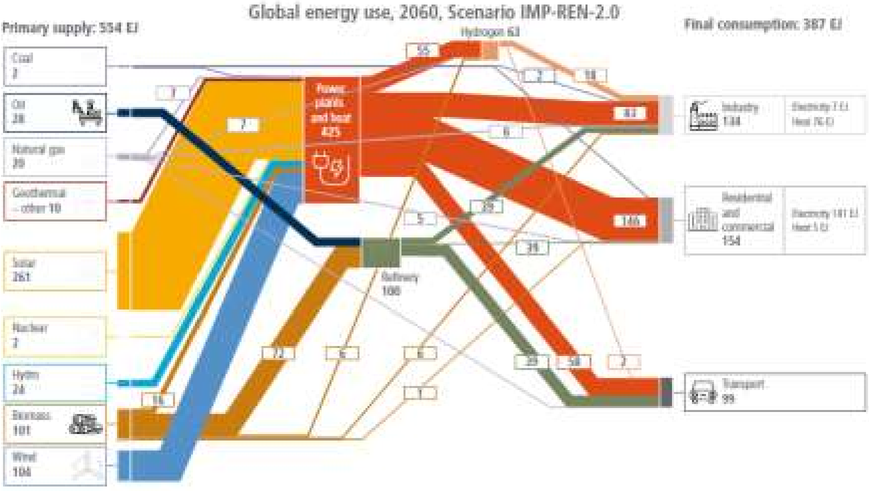

Figure 2.3 Global Energy Use Overview for 2060[23]

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[22] IPCC, Energy Systems, 2022, p.617.

[23] IPCC, Energy Systems, p.617.

Countries have made great achievements in transition, but their efforts have been uneven. World Economic Form’s Global Transition Index analyzes five dimensions of a country to assess its transition maturity. Those dimensions are regulations, finance, investment, innovation, infrastructure and education. Evaluated under these criteria, global transition index score has risen 6% since 2015. Totally 53 countries have made a strong progress in last decade. This indicates that energy transition has gained a significant momentum in international scale. According to this index, Sweeden is at the top of the list in terms of transition performance. Notably, top performers are predominantly high-income countries as well as they are politically supporting transition. In the map below, we can see the countries that have made significant energy transition performance.[24]

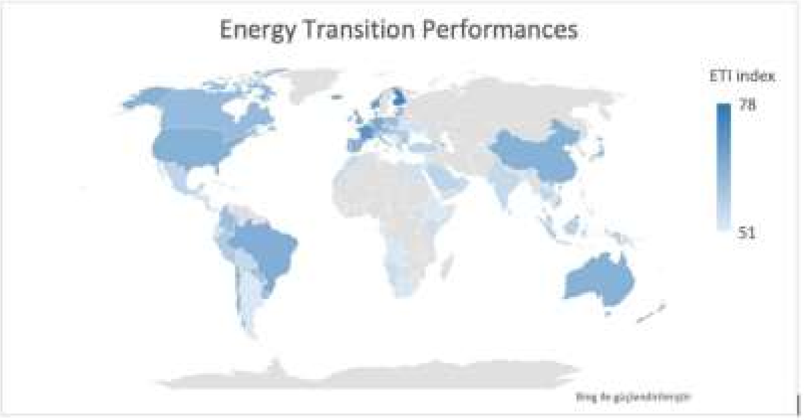

Figure 2.4 Energy Transition Performances of Countries[25]

2.2 The Paris Agreement

Energy transition did not originate only with the Paris Agreement, but it represents the most powerful political force to date. Efforts to diversify energy sources, deploy

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[24] Forum, World Economic. Fostering Effective Energy Transition. *World Economic Forum*, 2024, pp.11-12.

[25] World Economic Forum, Fostering Effective Energy Transition, 2025, p.15.

renewables and improve efficiency date back to 1990s. There have been many intergovernmental events fostering energy transition like 1992 UNFCCC, the Kyoto Protocol and national transition policies like Energiewende of Germany. The Paris Agreement can be regarded as a cornerstone in energy transition, first legally binding document for countries. It was accepted by 195 countries at the UN Climate Change Conference (COP21) in Paris, France, in December 2015. The agreement entered into force in 2016. The main objective of the agreement is limiting the temperature increase to 1.5°C above pre-industrial levels and pursue efforts to hold the increase in the global average temperature to well below 2°C above pre-industrial levels. The reason behind limiting 1.5 C increase is that after that point more harmful effects of climate change will be seen like droughts, floods, heatwaves according to UN Intergovernmental Panel on Climate Change. To keep this target, as a short-term measure, global GHG emissions must decline 43% by 2030.[26]

One of the crucial aspects of the agreement is that all nations must publish their Nationally Determined Contribution (NDC) plans for lessening GHG emissions. Since 2020, countries have been announcing their NDCs, and these NDCs can be called as legal signs of energy transition. Countries explain their plans for reducing emissions to reach the goals. The agreement is providing other beneficial tools for successful transition. In finance, the agreement says that developed nations should support developing-underdeveloped ones because transition will have too much cost for weak economies that cannot be able to compensate them. In addition, new clean technologies should be shared freely and easily in the globe so best practices will be implemented easily. Moreover, most countries do not have enough institutional capacity to fight climate change so capacity building activities should be fostered in developing nations. The agreement, since signed, has led the formation and

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[26] United Nations, The Paris Agreement, United Nations, 2015

beginning of many low carbon business sectors and not only countries and also many companies announced their net-zero targets and new clean energy business opportunities have started to emerge.[27]

2.3 How to Achieve Energy Transition

According to Multi Level Perspective theory developed by Frank Geels, energy transition is not a linear process, it is rather a multi-faceted complex process and just technology cannot achieve it. There are three analytical levels to analyze energy transition: niches, socio-technical regimes and landscape pressures. Niches are rare technologies like solar-wind powers, hydrogen electrolyzer and carbon capture technologies. They were rare and luxury technologies in the past and even before just only used in space missions. They are now available widely because there is a market pressure for decarbonization. Research laboratories are encouraged much more to find a sustainable energy solution and new clean sectors are becoming visible. Second factor is socio-technical regimes. It claims that if current cultural regimes change, then transition will become much more visible. For example, today's dominant culture is internal combusting engine and oil derivatives products like diesel and gasoil. These regimes are resistant to change. The third notion is landscape level including slow or sudden changes in the system such as climate change, supply security and geopolitical changes. This indicates that Ukraine-Russia war has been immediately decisive in European energy transition policies or climate change has been slowly effective in determining energy transition policies. MLP

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[27] United Nations. 2025. *United Nations Climate Change.* https://unfccc.int/process-and-meetings/the-paris-agreement.

framework is crucial for showing that technological innovations are not enough for energy transition. It must be supported by regulations and state policies.[28]

Another theory is Technological Innovations System theory which is a framework used to understand how new technologies emerge, develop and become widespread in an energy system. It explains the reasons behind this success as a combination of seven factors. Those factors are entrepreneur activity, knowledge development, knowledge diffusion, guidance, market formation, resource mobilization and legitimation.[29]

2.3.1 Technology

Technological developments are one of the core drivers of the energy transition. Renewable energy has already begun to transform energy systems in the world. Renewable energy has developed significant trajectory in last years. There is an important learning curve in technological improvement.[30] Moreover, in the future, costs are expected to decline much more with the help of software technologies like artificial intelligence. When renewable energy investments increase in future, the importance of artificial intelligence will become more evident.[31]

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[28] Frank W.Geels. "Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study." *Research Policy,* 2002, pp.1272-1273.

[29] Roland Ortt. "A technological innovation system framework to formulate niche introduction strategies for companies prior to large-scale diffusion." *Technological Forecasting and Social Change,* 2022, p.12.

[30] Gunther Glenk, Rebecca Meier and Stefan Reichelstei. Cost Dynamics of Clean Energy Technologies. *Schmalenbach Journal of Business Research*, 2021, pp.200-201.

[31] Q.Zhao, L.Wang, S.E.Stan and N.Mirza. Can artificial intelligence help accelerate the transition to renewable energy? *Energy Economics 134*. 2024, p.11.

Each year, humanity consumes roughly 600 × 10^{18} joules of energy, which amounts to less than 0.1% of the solar energy that could be captured on land. In other words, even if all our energy came solely from the Sun, the impact on the available supply would be negligible, as the solar potential is about 10,000 times greater than current global demand.[32]

Although renewable energy's share in total energy supply is growing, there are some claims that they are not decreasing fossil fuel production rather they total amount of energy produced. Renewable energy is much more an addition rather than a transition solution. According to York and Bell, energy transition means replacing one already used energy source rather than expanding power output. For example, addition of electricity cars and not changed fossil fueled cars do not mean an energy transition, it is rather an energy addition. However, when we say that one thousand gasoil fueled cars will be replaced by electricity cars, that means a transition.[33]

2.3.2 Politics

Political support is at the core of the energy transition. Even if private companies and agents can make investment in energy transition and as they did before in solar and wind, today's energy transition can only be achieved by political ambition and mechanisms.[34] Although there are many developments in energy transition, there are still cost gaps and they have to closed by government incentives. The methods can

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[32] Pennstate College of Earth and Mineral Science. Solar Energy Potential and Utilization. https://courses.ems.psu.edu/earth104/node/950

[33] Richard York and Shannon Elizabeth Bell. Energy Transitions or Additions: Why a Transition from Fossil Fuels Requires More Than the Growth of Renewable Energy. *Energy Research and Social Science,* 2019, p.43.

[34] Florian Kern and Karoline S. Rogge. The pace of governed energy transitions: Agency, international dynamics and the global Paris agreement accelerating decarbonization processes? Energy Research and Social Sciences 22. 2016, p.16.

be clean energy subsidies, tax and subsidy frameworks, carbon costs and removing fossil fuel subsidies. As a result, incentives are important political tools to achieve energy transition in a country.[35]

The second factor that can facilitate transition is to develop workforce skills. While the clean technologies are developing, workforce should align with this change trend. Energy sector, academia and governments must design training programs to maintain necessitated workforce for future. There will be too much demand for new type of workers in energy sector.[36]

The third factor is the support and implementation of pilot projects. Pilot projects are effective to shape innovation and public participation in the energy transition. As hydrogen and carbon capture projects are new to the public, they must be known by everyone in a society to unlock potential demand. For example, in 1882, Edison made a public representation of the newly discovered light bulb by illuminating Drexel office building in New York. After that time, no more than 15 years, light bulbs replaced gas powered lights in New York and electricity generator, electricity distribution grid was established. It is true also for energy transition projects. For example, when a hydrogen valley project is made including production and consumption by industry, awareness, new knowledge and new modes of action for decarbonization will foster in the society.[37] Moreover, learning rate will increase for new energy technologies. Once started as a pilot project, cost reductions and

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[35] IEA. World Energy Outlook 2023. p.53.

[36] Irena Arcelay et al. Definition of the Future Skills Needs of Job Profiles in the Renewable Energy Sector. *Energies*, 2021, p.20.

[37] Marianne Ryghaug and Tomas Moe Skjqlsvold. Pilot Society and Energy Transition, The co-shaping of innovations, participation and politics. *Palgrave Macmillan*. 2021, pp.1-2.

performance enhancements will be improved by learning rates as we see in transportation sector, for example in innovative electrified truck models.[38]

2.3.3 Finance

Global capital flows into the energy sector reached approximately 3.3 trillion $ in 2024, of which about 2.2 trillion $, two-thirds of total investment, was allocated to energy transition technologies (renewables, grid modernization, efficiency measures and advanced biofuels), while the remaining 1.1 trillion $ supported oil, gas and coal projects. This financing profile underscores a decisive shift towards decarbonization in the world. They were propelled in large part by net fossil-fuel importers like China and the European Union reflecting both energy security measures and climate commitments. The International Energy Agency names these dynamics as "the age of electricity," with nearly 1.5 trillion $ earmarked for power-sector expansion that is 50 percent more than fossil-fuel budgets. In the electricity sector, the leader is solar photovoltaics that captured roughly 450 billion $, the single largest part of global energy spending. These investments patterns show that electrification and renewable technologies have been core area of today's global energy transition.[39]

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[38] Auke Hoekstra and Floor Alkemade. Using learning curves to guide the energy transition with the example of heavy electric trucks. *Sustainable mobility and transport,* 2025, p.4-6.

[39] IEA. World Energy Investments 2025. 2025, p.6.

Table 2.1 Needed Investment for Energy Transition[40]

Sector (billion, bn)	**Investment Need**	**Capital Investment (billion $)**	**Share in Total**
Power $2,400 bn	Renewables and net zero carbon generation	1300	38%
	Networks	900	26%
	Storage and Flexibility	200	6%
Hydrogen $80bn	Production	40	1%
	Transport and Storage	40	1%
Buildings $500bn	Retrofits	230	7%
	Heat Pumps	130	4%
	Renewable Heating	140	4%
Transport $240bn	Road Charging Infrastructure	130	4%
	Aviation	70	2%
	Shipping	40	1%
Removals $130bn	Hybrid and Engineering	30	1%
	NCS	100	3%
Industry $70bn	Chemicals	40	1%
	Steel	10	1%
	Cement	10	1%
	Aluminum	10	1%

Table 2.1. reflets the annual spending need for energy transition unitl 2050. The total amount of money that should be spent for the transition is 3.5 trillion $. High investment level needed that is 3.5 trillion $ does not represent a long-term "cost" to the economy or long-term decrease in living standards of people. First, the power sector investments which have largest share can be done by private investment and they are bankable in nature. They give long-terms benefits to the society maintaining

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[40] Energy Transition Commission, Financing the Transition: How to Make the Money Flow for a Net-Zero Economy, 2023, p.9.

less variable energy costs and energy security. They also will give long-term low operational costs than fossil fuels.[41]

There is a strong support from creditor institutes from all around the world for energy transition. To support net-zero policies and 1.5 C targets by 2050, major banks in the world including J.P. Morgan, HSBC have announced their net-zero commitments. Total market value of the investments from banks around the world is 70 trillion $ that is enough to keep annual energy transition investments along 20 years, especially until 2045. Moreover, asset managers announced their ambition for net zero target and energy transition, and they announced their support totaled in 66 trillion $. More than 450 private financial institutions whether asset managers, banks or insurers announced that they will reallocate capital to green investments and away from fossil fuels. These voluntary commitments will support company level energy transition ambitions in all around the world.[42]

2.3.4 International Cooperation

International cooperation means acceleration of global energy transition that is just, inclusive and leaves no one's behind, promoting efficiency, renewable technologies and well-functioning global markets in the international scale. There are some types of cooperation models that states can use to foster transition as they will be analyzed in detail under this headline.[43]

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[41] Energy Transition Commission, Financing the Transition: How to Make the Money Flow for a Net-Zero Economy, 2023, p.18.

[42] Energy Transition Commission, Financing the Transition: How to Make the Money Flow for a Net-Zero Economy, 2023, p.43.

[43] European Union External Action. Energy Diplomacy. 2021 https://www.eeas.europa.eu/eeas/energy-diplomacy_en

Climate diplomacy and international cooperations are effective forces to shape a country's energy transition. In last years, the objects of energy transition have become more important between states in terms of accessibility and affordability. Moreover, these objects became the concern of the international relations also. For example, Germany is trying to buy clean hydrogen from other states and make partnerships with Chile, Australia and Canada. Moreover, European Hydrogen Backbone which is an initiative between natural gas transmission system operators of Europe is targeting an international hydrogen pipeline system among countries, making technical workshops and consulting services. Without these diplomatic channels and cooperations, clean solutions' global scale up would be fragmented and slow.[44]

Diplomatic efforts and institutions have proved their effectiveness to unlock renewable energy's potential. The Paris Agreement, REPowerEU and H2Global are not merely policy tools; they function as strategic diplomatic instruments that reshape global energy governance and foster collective climate action. The Paris Agreement institutionalized climate diplomacy by requiring all signatory states to submit Nationally Determined Contributions (NDCs) and to engage in periodic global stock takes, thereby creating a framework for mutual accountability and transparency in decarbonization efforts.[45]

It also enabled structured climate cooperation between developed and developing countries through climate finance, technology transfer and capacity-building commitments. It has been a success of a multilateral climate diplomacy between states since 1990s. There had been many efforts like UN Framework Convention on Climate Change in 1992 and Kyoto Protocol in 1997 to set up mandatory emission targets, but never one has achieved it. One of the most influential tools of the Paris

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[44] European Hydrogen Backbone. European Infrastructure Map. 2025. https://www.h2inframap.eu/#map

[45] United Nations, The Paris Agreement, 2015

Agreement is obligation of announcing Nationally Determined Contribution documents which include emission reduction target. This indicates that these targets and pledges are legal foundations of countries' energy transition efforts. For example, the USA has published Inflation Reduction Act in 2022 allocating 369 billion $ for clean energy as a clear sign of political interest.[46] Moreover, Germany has positioned itself as a leader in energy transition with Energiewende, meaning "energy transition".[47] In addition, China, one of the biggest emitters of the world, has published 14th Five Year Development Plan and this plan includes energy transition targets of China like carbon neutrality by 2060.[48] In Türkiye, National Energy Plan and Renewable Energy Roadmap were published after 2020, all of them is targeting to reach carbon neutrality by 2053. All the energy transition and decarbonization targets and political ambitions of the countries show international energy cooperation's success, especially the Paris Agreement's success.[49]

One of the EU's most important plans is REPowerEU, it is the symbol of successful international cooperation. This plan mobilizes the EU member states to collectively reduce their fossil fuel consumption. The main target is to lessen energy dependency, decrease natural gas consumption and set up green hydrogen trade routes.[50] H2Global, a market-based mechanism initiated by Germany, goes beyond subsidy allocation by establishing long-term bilateral hydrogen import agreements with countries like Namibia and the UAE. It represents a form of "energy diplomacy

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[46] UNCTAD, 2022, 369 billion $ in investment incentives to adress energy security and climate change. https://investmentpolicy.unctad.org/investment-policy-monitor/measures/4004/-369-billion-in-investment-incentives-to-address-energy-security-and-climate-change-

[47] Federal Foreign Office, The German Energiewende, 2016, p.2.

[48] UNDP, China's 14th Five Year Development Plan, 2021, p.5.

[49] Republic of Türkiye Ministry of Energy and Natural Resources, Türkiye National Energy plan, 2022, p.29.

[50] European Commission, RepowerEU Plan, 2022, p.2.

through contracts," ensuring security of supply while promoting international trust and alignment on hydrogen standards and certification.[51]

Energy diplomacy became a necessity not only to achieve energy transition but also to gain geopolitical superiority. There are various scenarios to assess energy transition in geopolitical scale. First is "Big Green Deal" scenario claiming that there will be power shift from oil-gas rich countries to green renewable energy rich ones. This scenario claims that there will be new geopolitics, but conflicts will be minimized compared with existing oil-gas geopolitics. The second one is "Dirty Nationalism" scenario. Every nation will focus on domestic renewable energy potential and will try to maximize energy independence without making any interstate cooperation. There will be slow development in renewable energy because of high level of national rivalry. Fossil fuel producers will be under threat by losing their revenues. The third one "Technology Breakthrough". According to this theory, some nations will achieve technological development like USA and China and start to become decarbonized in time. Diplomacy will be effective to spread knowledge and resources across the world. Moreover, technology leaders will become geopolitical leaders in time. The fourth one is "Muddling On". This scenario claims that there will be lack of diplomatic cooperation and stalling global progress. Clean energy systems will remain local and not spread across the globe. In all those scenarios, there will be inefficiencies and global energy transition will slow if energy diplomacy does not take an efficient and active place in countries' policies.[52]

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[51] H2Global Stiftung, Shaping the Global Energy Transition, accessed September 16, 2025, https://h2-global.org/

[52] Morgan Bazilian et al. Four scenarios of the energy transition: Drivers, consequences, and implications for geopolitics, *Wiley*, 2019, p.4.

2.4 Conclusion

This chapter has undertaken an extensive exploration of energy transition. Energy transition has been discussed historically. The factors that drive transition such as technology, politics, finance and international cooperation have been analyzed.

The analysis revelaed that energy transition is a long-term process that may take some decades. As we see in current energy systems like oil and natural gas, new energy system which comprised by renewable energy will take many years to be set up completely. However, upon careful examination of the factors affecting energy transition and urgency of the world to prevent climate change, the proposed long process may be shortened. To achieve short durations for energy transition, there has to be holistic approach by focusing on technological developments, financial, political incentives and international cooperation.

The analysis also revealed that today's energy transition is different from the previous ones. Oil, coal and natural gas all have grown mostly with market forces and government policies have been decisive. However, in today's world, there is an urgent issue that is climate change. Energy systems must have been replaced with sustainable ones as faster as possible.

CHAPTER 3

CLEAN HYDROGEN

Hydrogen is the lightest and most ample element in the universe. It can be found in many molecules such as fossil fuels and water. When we say, “clean hydrogen”, it means that GHG emission in production process is eliminated, or zero emission is released like production from water. Clean hydrogen can be generated through renewable energy, nuclear power or fossil fuel processes incorporating carbon capture technologies. There is an important amount of hydrogen production but they emit significant GHG emissions into the atmosphere because majority of it is handled from fossil fuels. When it is produced in clean ways, it becomes a candidate to lessesn GHG emissions.[53] In this chapter, questions of what is clean hydrogen, what is the importance of hydrogen ecosystem approach and what are the hydrogen specific developments.

3.1 What is Hydrogen

Hydrogen, the simplest and most abundant element in the universe, consists of a single proton and electron. Although abundant, it does not occur freely on Earth but is instead bound to other elements, such as oxygen in water or carbon in hydrocarbons like natural gas, gasoline, and methanol. Hydrogen can be produced through several processes, notably steam reforming of hydrocarbons and electrolysis of water, with biological pathways such as algae- or bacteria-mediated production also under investigation. Its high energy density and clean combustion properties

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[53] IEA, The Future of Hydrogen, *IEA*, 2019, p.13.

make hydrogen an attractive energy carrier. For decades, NASA has employed liquid hydrogen as rocket fuel and in fuel cells to generate electricity, with water as the only by-product. This highlights hydrogen's dual role as both a versatile fuel and a critical enabler of low-pollution energy systems.[54]

In terms of energy content, hydrogen has the highest energy content per weight when compared with other conventional fuels like gasoline. The origin of the sun's energy is coming from sun's hydrogen fusion reaction. This indicates that hydrogen is the core of the world's renewable energy potential. Hydrogen serves as a versatile chemical energy carrier, supported by a wide range of production, storage, distribution and utilization pathways. Its applications span power generation, transport, the chemical sector, and district energy systems. Currently, steam methane reforming of natural gas remains the most widely adopted method of hydrogen production. However, rising natural gas prices and concerns over CO_2 emissions underscore the necessity of developing cleaner and more sustainable alternatives. Although the notion of a "hydrogen economy" has existed for decades, it is only in recent years that the hydrogen value chain has gained commercial viability for energy applications beyond its traditional role in the chemical industry. Key drivers behind this shift include the sharp decline in the cost of solar and wind power, continuous improvements in hydrogen technologies and infrastructure, and growing international efforts to stimulate demand and establish supply chains. Notably, initiatives led by countries such as Japan, South Korea, China, and Germany are contributing to lowering costs across the hydrogen value chain.[55]

The advancement of a green hydrogen economy offers benefits that extend beyond the primary goal of decarbonization. When strategically designed to safeguard

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[54] Magdalena Momirlan and Nejat Veziroğlu, The properties of hydrogen as fuel tomorrow in sustainable energy system for a cleaner planet, *International Journal Hydrogen Energy*, 2004, p.796.

[55] Zainul Abdin et al. Hydrogen as an energy vector, *Renewable and Sustainable Energy Reviews*, 2020, p.28.

priority areas such as electrification, energy access, and essential services, green hydrogen and its associated commodity trade could play a vital role in fostering a just and inclusive energy transition, particularly for the underdeveloped-developing countries. Many countries such as Egypt, Namibia, Chile and Australia possess abundant renewable energy resources, enabling them to produce green hydrogen at potentially lower costs than developed countries provided that affordable financing is available. Building hydrogen trade infrastructure could position these nations as key players in the emerging global market, stimulate economic growth and enhance their role in the global economy. Additionally, the parallel development of electricity and hydrogen infrastructure could strengthen overall energy systems in these countries.[56]

Even after accounting for land-use limitations such as protected areas, forests, wetlands, urban zones, steep terrain and water scarcity, the technical potential of green hydrogen remains nearly twenty times higher than projected global primary energy demand in 2050. Importantly, this potential cannot be expressed as a single figure, but rather as an interplay of renewable energy capacity and cost. The cost of production is largely determined by renewable energy prices, electrolyser costs and the weighted average cost of capital. Achieving a net-zero energy system by 2050 will require the deployment of around 14 TW of solar PV, 6 TW of onshore wind, and 4–5 TW of electrolysis. Such large-scale expansion is expected to drive down costs significantly through technological innovation, economies of scale, and supply chain efficiencies. Under these conditions, green hydrogen production costs could fall to approximately 0.65 $ per kg in the most favourable locations and scenarios,

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[56] International Renewable Energy Agency, The potential for green hydrogen and related commodities trade, 2025, p.27.

while even in more pessimistic outlooks with higher costs, the lowest production prices would still be around 1.15$ per kg by 2050.[57]

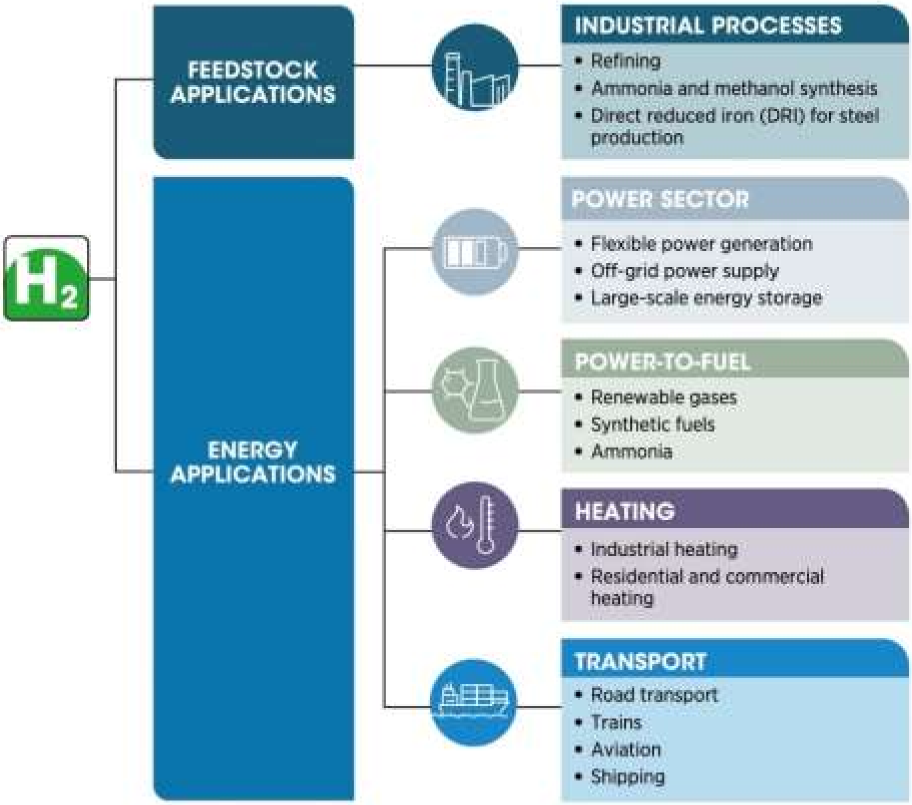

Figure 3.1 Hydrogen Applications[58]

3.2 What is Hydrogen Ecosystem

It is crucial to analyze hydrogen's development in energy transition with the lens of hydrogen ecosystem. Availability of only production or only end-use technologies will not guarantee abundant and affordable energy supply. According to Smil, any

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[57] IRENA, Hydrogen Trade, 2025, https://www.irena.org/Energy-Transition/Technology/Hydrogen/Global-hydrogen-trade

[58] IRENA, The Geopolitics of the Energy Transformation:The Hydrogen Factor, 2025, p.6.

energy system has three main elements: natural resources, conversion and available energy flows. Energy ecosystem in today's world is a complex system. To analyze today's energy systems, we can classify them as production, transportation, storage and application.Without any part of this chain, full realization of clean hydrogen ecosystem will be impossible. So, we can analyze countries' hydrogen development levels with these four criteria. In the figure below, these criteria is shown.[59]

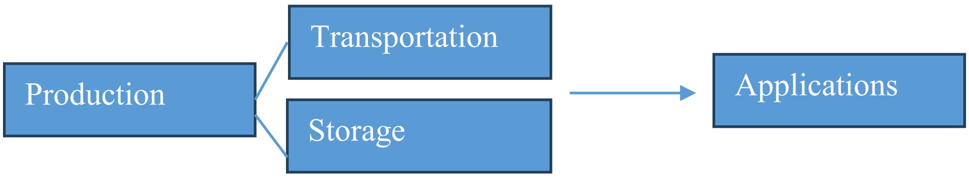

Figure 6 Components of an Energy System

3.2.1 Production

Production of hydrogen can be made with various methods and from various elements since it is included in lots of elements. In classifying which hydrogen type is "clean", there are many perspectives. According to the IEA, there is no international agreement on the use of hydrogen colors yet, nor have their meanings been clearly defined. But the IEA classifies it as hydrogen produced from renewable and nuclear electricity, biomass and fossil fuels with carbon capture and utilization ans sequestration (CCUS).[60]

Grey hydrogen represents the dominant method of hydrogen production globally, accounting for approximately 95% of total output. It is primarily generated through steam methane reforming, a process that utilizes natural gas as the main feedstock. The cost of grey hydrogen is closely tied to the market price of natural gas. In the grey hydrogen, methane is chemically split into hydrogen and carbon, releasing

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[59] Vaclav Smil, Energy Transitions: History, Requirements, Prospects, *Greenwood*, 2010, pp.1-2.

[60] Kusoğlu, Ahmet. "Redefining Clean Hydrogen: From Colors to Emissions." *The Electrochemical Society,* (2022), p.47.

significant amounts of carbon dioxide as a byproduct. This high level of emissions, estimated at roughly 10 tones of CO_2 per ton of hydrogen, poses a major environmental drawback. Despite its environmental concerns, grey hydrogen is widely utilized due to its established production infrastructure and low production costs. Grey hydrogen cost typically ranges from \$1 to \$2 per kilogram.[61]

One of the types of clean hydrogen is blue hydrogen. Blu hydrogen refers to the hydrogen produced by steam methane reforming method just like grey hydrogen but its emissions are captured and stored. It is relatively a new concept and there are limited applications across the world.[62]

The another type of clean hydrogen is “green hydrogen”. There are two main componenets in the green hydrogen: renewable electricity and electrolyser. Although commercial technologies like alkaline and PEM electrolysis are already available, they have yet to be deployed at the scale necessary to drive large-scale transformation. Enhancing the competitiveness of green hydrogen depends on lowering electrolyzer costs, advancing system integration and achieving more cheaper renewable energy prices.[63]

The largest electrolyser project currently under development is the 2.2 GW NEOM Green Hydrogen Project in Saudi Arabia. It has achieved final investment decision in May 2023 and is scheduled to begin operations in 2026. Based on this case, the construction timeline for a gigawatt-scale facility appears to be approximately three years between final investment decision and commissioning. Among the projects planned to be operational by 2030 with capacities of 1 GW or more, only four

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[61] Stargate Hydrogen, Grey Hydrogen, 2025, https://stargatehydrogen.com/blog/grey-hydrogen/

[62] Robert W.Howarth and Mark Z.Jacobson, How green is blue hydrogen?, *Energy Science and Engineering*, 2021, pp.1-2.

[63] Alessandro Franco, Green Hydrogen and the Energy Transition: Hopes, Challenges and Realistic Opportunities, *hydrogen*, 2025, pp.29-30.

(totalling 6 GW) have either secured final decision or entered the construction phase. In contrast, over 50 projects representing around 125 GW remain at the feasibility stage. Unless these projects can take final investment decision, they are unlikely to commence operations by 2030 which is the hydrogen target year by most of the countries in the world. As a result, roughly one-quarter of the total announced capacity for 2030 is at high risk of delay. It is indicated that green hydrogen production cannot achieve countries' short-term climate targets and it can ultimately decrase green hydrogen's role in energy transition.[64]

The another method for clean hydrogen is pink hydrogen which is produced by electricity handled from nuclear power. This type of hydrogen has some benefits and limitations. One of the most important benefit is that nuclear energy is a base load and continuos hydrogen production can be done as it is opposed by intermittent nature of solar and wind power. The other benefit is that electrolyzer used in nuclear hydrogen is more efficient than other electrolyzers because of the usage of nuclear heat also in the process. The limitation is that nuclear electricity, if the plant is newly established a little bit higher than solar and wind power.[65] Projections suggest that the global cost of electrolytic hydrogen could average around 3 $ per kilogram by 2035. However, under particularly favourable conditions such as solar PV deployment in the Middle East or extended operation of nuclear facilities production costs may fall below 2$ per kilogram of hydrogen. This makes pink hydrogen a sustainable solution for energy transition.[66]

Similar like green hydrogen, the countries rich in excess nuclear capacity like France, Canada, Sweeden can export pink hydrogen. The price of green hydrogen can

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[64] IEA, Global Hydrogen Review 2024, 2024, p.70.

[65] Nuclear Energy Agency, Nuclear Energy in the Hydrogen Economy, 2025, https://www.oecd-nea.org/jcms/pl_20492/nuclear-energy-in-the-hydrogen-economy

[66] OECD and NEA, The Role of Nuclear Power in the Hydrogen Economy, 2022, p.47.

compete with pink hydrogen but baseload advantage of nuclear power plants make 7/24 hydrogen production available. There are already established pink hydrogen production but they are not enough to cover existing hydrogen needs. The number of operational pink hydrogen facilities are three. They are Nine Mile Point facility in the USA, Oskarshamn plant in Sweeden and Kola Nuclear Plant in Russia. The total production capacity is 300 tons per year which is too small to meet energy transition demand. There are planned and feasiblity staged projects but they are also not enough to meet 2030 demands.[67]

3.2.2 Transportation

Hydrogen is a molecule that can be transported via pipeline or vessels just like natural gas. Although it has a distinct molecular characteristics, technical options of transportation may change than other energy products. Transportation of hydrogen is a necessity because there is a uneven distribution of production capacity according to different regions and demand centers. The pipelines, liquefaction plants, vehicles used in hydrogen delivery are all considered transportation infrastructure.[68]

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[67] IEA, Hydrogen Production Database, 2025

[68] US Department of Energy, Hydrogen Delivery, 2025, https://www.hydrogen.energy.gov/program-areas/production

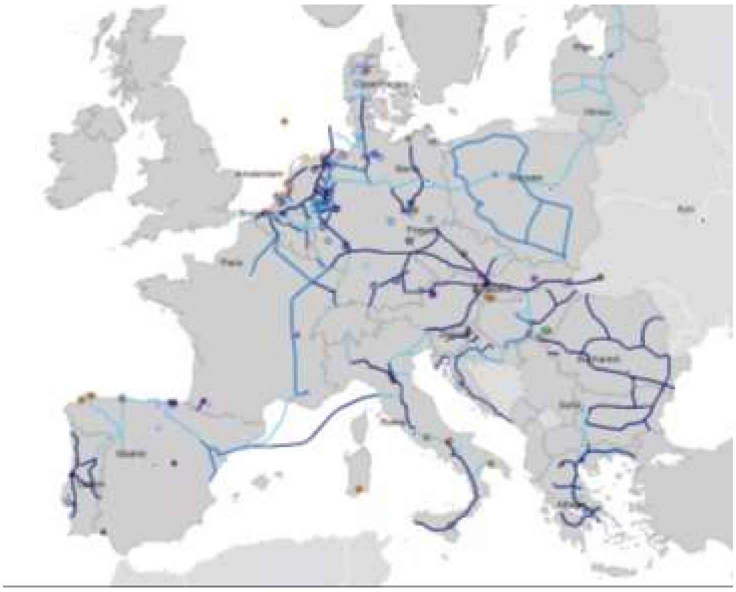

Figure 3.3 Planned European Hydrogen Pipelines[69]

Hydrogen can technically be transported via pipelines in both short and long ranges. Similar to natural gas, hydrogen in its gaseous form can be transported through pipelines. Pipeline transportation is the most cost-effective method for delivering large volumes. However, building an entirely new pipeline specifically for hydrogen would involve high cost investment. Instead, when feasible, modifying and reusing existing natural gas pipelines for hydrogen transportation emerges as a more economical and practical alternative.[70]

The second proposed solution is transportation of hydrogen via maritime vessels. This option may enable resource rich countries export high volumes of cargoes to the demand-high countries. Transporting hydrogen by ship becomes more cost-effective than constructing a new pipeline when the distance exceeds 7,000 km. While pipelines are a practical option for long-distance hydrogen delivery, they are geographically dependent on stable political conditions in transit countries, which

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[69] H2, Hydrogen Infrastructure Map, 2025, https://www.h2inframap.eu/

[70] Miao Yang et al. A review of hydrogen storage and transport technologies, *Clean Energy*, 2023, p.207.

can pose risks to long-term projects. In contrast, shipping offers greater flexibility and independence, making it a more adaptable alternative to pipelines.[71] Hydrogen transportation in gaseous form is not a feasible option in terms of security and finance. Instead, hydrogen can be transported in ammonia format. Technologically, transportation of ammonia is a mature technology and trade of ammonia has been doing for many years in the world. The first example of clean hydrogen via vessels was the blue hydrogen transportation from Saudi Arabia to the Japan in 2020.[72]

3.2.3 Storage

Storage of hydrogen is crucial for the ecosystem because the intermittent supply of green hydrogen prevents full time hydrogen flow to the customers. A successful storage regime can support full time hydrogen flow to the customers. Without cheap and large scale storage of hydrogen, green hydrogen trade between countries may fail. Existing storage costs are low enough and operation technology is mature in the world. There are 60 hydrogen storage projects in the world and they are planned to start operation at least by 2030-2040.[73]

There are also small type storage technologies to maintain small scale hydrogen applications like fueling station. For the development of hydrogen and fuel cell technologies in fields including transportation, portable electricity and stationary power, hydrogen storage is a crucial enabling technology. Despite having the maximum energy per mass of any fuel, hydrogen has a low energy density per unit

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[71] Miao Yang et al. A review of hydrogen storage and transport technologies, *Clean Energy*, 2023, p.208.

[72] Saudi Aramco, World's first blue ammonia shipment opens new route to a sustainable future, 2020, https://www.aramco.com/en/news-media/news/2020/first-blue-ammonia-shipment

[73] IEA, Hydrogen Production Database, 2025

volume due to its low ambient temperature density. As a result, new storage techniques with the potential for higher energy density must be developed.[74]

3.2.4 Application

The widespread application of clean hydrogen across industry, transportation and chemical sectors represents a pivotal driver for the realization of a hydrogen ecosystem, as it transforms hydrogen from a niche solution into the one of the most important parts of the energy transition. According to IEA, clean hydrogen, along with hydrogen-derived fuels, can significantly contribute to the decarbonization of many sectors where reducing emissions is challenging and where alternative solutions are either lacking or complex to execute.[75] We can clarify those sectors as ones in which electrification is not possible, if possible there will be enormous amount of electricity needed which is not feasible to supply. Hydrogen can be used in many sectors not just as a fuel replacing oil but as a feedstock replacing grey hydrogen. The sectors that hydrogen can be used is very wide. However, end use technological maturity level for each sector is different and there are some areas that renewable electricity can compete with hydrogen in decarbonization. In the graph below, you can see the clean hydrogen end use policy priorities of the world according to IRENA.[76]

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[74] US Department of Energy, Hydrogen Deliver, 2025, https://www.hydrogen.energy.gov/program-areas/production

[75] International Energy Agency, IEA Hydrogen, 2025, https://www.iea.org/energy-system/low-emissions-fuels/hydrogen#tracking

[76] IRENA, Green Hydrogen for Industry, 2022, p.13.

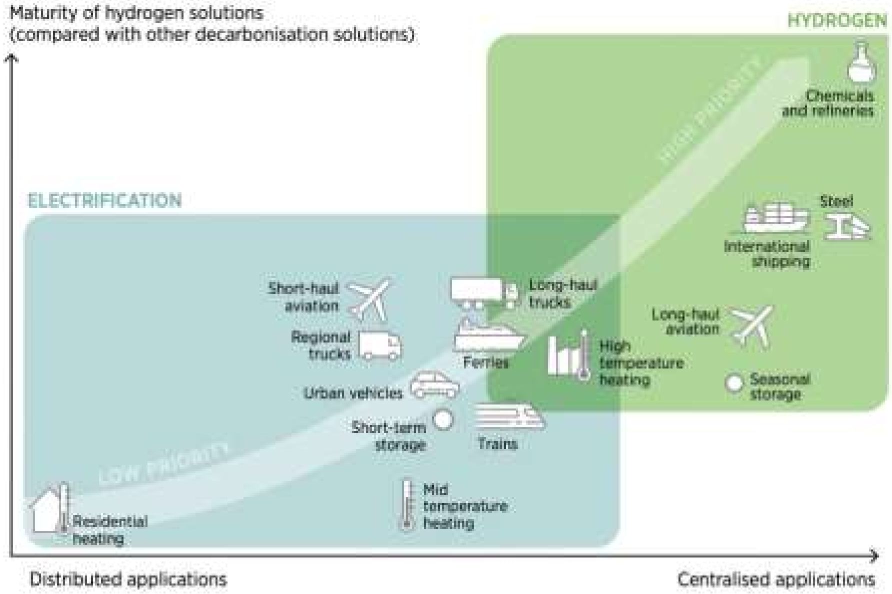

Figure 3.4 Hydrogen Usage Priorities in the World[77]

3.2.4.1 Transportation Sector

Hydrogen can technically decarbonize all transportation segments that are road, marine and aviation. The reason why electrification is not choosen and why hydrogen is the best solution is that batteries are too heavy for heavy trucks, maritime vessels and airplanes. And also there is a long charging time. Hydrogen can be used in fuel cells, in combustion engines and in derivative format like ammonia, kerosen and metanol. Hydrogen has an energy content which is similar with one galloon gasoil. For example, a car can go approximately 100 km with 1 kg hydrogen while it can go 10 km with 1 kg gasoil. Moreover, hydrogen can fill car tank in a short time like gasoil at the pump. Fuel cells are less heavy than internal combustion engines.

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[77] IRENA, Green Hydrogen for Industry, 2022, p.13.

Hydrogen cars are quite because there is less vibrations compared with internal combustion engines.[78]

3.2.4.2 Heavy Industry

Heavy industry accounts for approximately one-quarter of global GHG emissions. Sub sectors such as iron-steel and cement industries, each contribute 7% of global emissions. Traditional blast furnaces release roughly 1.8 tons of CO2 per ton of steel produced. Hydrogen-based direct reduced iron method could emerge as a competitive option compared with both conventional blast furnaces. The viability of hydrogen based steel relies on hydrogen production costs. To outperform blast furnaces, hydrogen costs need to fall within 1.8$–2.3$ per kg. Decarbonization of these sectors is crucial for global climate change efforts. Unlike in the power or mobility sectors where electrification may suffice, heavy industry can not be easily electrified due to their high structural reliance on carbon-intensive processes and materials.[79]

3.2.4.3 Feedstock

The refinery and fertilizer industries illustrate the critical role of hydrogen in existing industrial processes, while also highlighting the transformative potential of clean hydrogen in reducing emissions. These two sectors are currently the biggest consumers of hydrogen in the world. The refinery sector uses almost 40 million tons hydrogen per year. In refinery sector, hydrogen is used to lessen sulphury rate in oil. In fertilizer sector, hydrogen is the feed product of the ammonia. Almost 80% of the

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[78] US Department of Energy, Hydrogen's Role in Transportation, 2022, https://www.energy.gov/eere/vehicles/articles/hydrogens-role-transportation

[79] Hydrogen Council, Path to hydrogen competitiveness: A cost perspective, 2020, p.64.

produced ammonia is used in fertilizer sector. They mostly rely on grey hydrogen produced from fossil fuels, clean hydrogen has a significant potential to reduce their emission.[80]

3.2.4.4 Peak Shaving

Clean hydrogen is increasingly recognized as a promising solution for overcoming the limitations of conventional energy storage technologies, particularly in addressing the intermittency challenges of renewable energy sources. Long-term energy storage is not possible with traditional lithium-ion batteries. Hydrogen could accomplish long term storage with large-scale energy storage capacity.[81] Hydrogen energy storage provides high energy density, enables long-duration storage, and can be utilized in a variety of flexible applications.[82]

3.2.4.5 Heating

The integration of clean hydrogen into residential and industrial heating systems represents a vital pathway toward reducing GHG emissions. Burning hydrogen produces only water vapor while burning fossil fuels produce GHG. Switching to hydrogen for heating can significantly reduce CO2 emissions.[83] Hydrogen can be used directly for cooking, hot water production and space heating. Adopting green

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[80] Umair Yaqub Qazi, Future of Hydrogen as an Alternative Fuel for Next-Generation Industrial Applications;Challenges and Expected Opportunities, energies, 2022, p.19.

[81] Zhidong Chen et al. Thermodynamic and economic analyses of nuclear power plant integrating with seawater desalination and hydrogen production for peak shaving, *International Journal of Hydrogen Energy*, 2024, p.1386.

[82] Shenao Hou, Modeling and Simulation of Hydrogen Storage Technologies for Peak Shaving in Islanded Power Grids Based on Wind Power and Load Fluctuations, 4th International Conference on Green Energy and Power Systems, 2025, p.1.

[83] Kevin Knosala et al. The role of hydrogen in German residential buildings, Energy and Buildings, 2022, p.15.

hydrogen for heating presents several obstacles, chief among them being the substantial infrastructure investments required. It might be necessary to make changes to current heating systems in order to accept hydrogen, and new distribution networks will need to be set up.[84]

3.3 Hydrogen Finance

Although there is significant allocation of money to the hydrogen projects, they are not enough to cover 2030 targets. In the world, 1,572 projects were announced to be completed by 2030 and the total finance dedicated for hydrogen is 680 billion $ until 2030. There are also 75 billion $ which has been already spent for hydrogen projects. Europe has the largest number of projects with 617 ones and North America has the second largest project pipeline that is 280. EU has also the highest total investment announced that is 199 billion $ and the Latin America has the second largest one that is 107 billion $, the North America has the third one that is 96 billion $. Total announced 1,572 projects have a production capacity that is equivalent to 49 million tons by 2030.[85]

According to IEA, the world must use 70 million tons clean hydrogen by 2030 to meet 1.5 C global goal. There is roughly 20 million tons gap for 2030 when we consider announced hydrogen projects. There is also another crucial issue that only 297 projects have taken final investment decision while remaining only 337 ones are operational and the other roughly 938 ones are in demo or design stages. It shows us that there is a bigger gap to catch 2030 climate targets.[86]

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[84] Andrei David Korberg et al. On the feasibility of direct hydrogen utilisation in a fossil-free Europe, *International Journal of Hydrogen Energy*, 2023, p.2888.

[85] McKinsey and Company, Hydrogen Insights 2024, p.10.

[86] IEA, Hydrogen production Database, 2025

3.4 International Cooperation

International cooperation on hydrogen refers to the strategic use of hydrogen as an energy carrier in international relations, where states and organizations establish partnerships, trade agreements and policy frameworks to secure access to affordable and abundant clean hydrogen. There are many ways to increase cooperation. First one is bilateral agreements between governments. Main target of these agreements is to develop hydrogen supply chain infrastructures of potential exporter countries like Egypt and Australia and then export it to the demand centers like Germany and Japan.[87]

The second way for diplomacy is multilateral platforms. For example, Clean Hydrogen Partnership is a public private partnership supporting research and innovation activities in hydrogen technologies in Europe. The members are European Commission, hydrogen and fuel cell industries and research communities. This partnership plays a significant role in Europe to widen hydrogen solution to the economies.[88]

The other example is International Partnership for Hydrogen and Fuel Cells in the Economy. It is an intergovernmental partnership whose objective is to facilitate hydrogen development across globe. It is developing methods for calculating carbon intensity of hydrogen and provided standardized rules to define low carbon hydrogen. IPHE is not a regulatory body among states, it acted as a diplomatic coordinator.[89] The third example is Hydrogen Council which is found in 2017 at

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[87] Federal Ministry of Economic Affairs and Climate Action, Germany and South Africa sign cooperation agreement on green hydrogen, 2023, https://www.bmwk.de/Redaktion/EN/Pressemitteilungen/2023/06/20230627-germany-south-africa-cooperation-green-hydrogen.html

[88] Clean Hydrogen Partnership, Strategic Research and Innovation Agenda 2021 – 2027, 2022

[89] IPHE, Hydrogen Certification 101, 2024, pp.3-6.

World Economic Forum in Davos. It was the first initiative to become energy, transportation and manufacturing sectors together. It comprised 13 members initially, then now includes 140 multinational companies representing the entire hydrogen value chain. The founding members are Air Liquide, Alstom, Anglo American, BMW Group, Daimler, Engie, Honda, Hyundai, Kawasaki, Shell, Linde, Total and Toyota which are international business leaders in their sectors. Through the Hydrogen Council, investors, industry and public decision makers come together. The successes of the Council are many which have a significant effect in today's hydrogen development. Since 2017, studies and reports of the Council were used as a reference by international institutions, almost 40 national hydrogen plans have been announced, and hydrogen globally has taken off.[90]

3.5 Conclusion

This chapter examined the concept of clean hydrogen, which is increasingly regarded as a key solution to climate change. Although hydrogen is the most abundant element in the universe and its technologies are well established, it has not historically been utilized as a mainstream energy commodity. Today, however, hydrogen is emerging as one of the most promising options in energy transition. Its value lies particularly in sectors such as heavy industry and chemical production, where direct electrification is technically or economically unfeasible.

To evaluate the development of hydrogen across countries, it is necessary to examine it within the framework of the broader energy ecosystem. Unless all elements of this ecosystem are established in a coherent manner, any energy solution risks remaining fragmented and incomplete. The key components of this ecosystem include production, transportation, storage, and end-use applications

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[90] Hydrogen Council, Founding Story, 2017, https://hydrogencouncil.com/en/founding-story/

Technological advancements have been achieved across each stage of the hydrogen value chain to enable it play a significant role in the decarbonization of multiple sectors. Clean hydrogen holds considerable potential for reducing emissions in sectors such as peak power management, heating, industrial processes, transportation, as well as in refineries and fertilizer production. In conclusion, clean hydrogen has moved beyond being a niche concept; it is emerging as a tangible and increasingly important element of the global energy transition. Its successful deployment, however, will depend on addressing cost and infrastructure challenges, mobilizing sustainable sources of finance and fostering cross-border collaboration.

CHAPTER 4

UNITED STATES OF AMERICA

The USA has long been a leader in global energy landscape. With both domestic reserves and controlling power over foreign energy assets, it has been a global force throgh decades. The USA economy is one of the leaders in the world and behind this power, there have been coal, oil and natural gas over years. As of 2023, it is the biggest producer and consumer of oil and natural gas in the world. And also it became biggest LNG exporter. Energy geopolitics has been one of the core elements of the USA to control global order since decades. Now, clean energy transition is presenting new geopolitics and the USA should take an action not to lose power in that area. China, with its strong investments in clean technology and supply chains is a potential threat for the USA supremacy. The USA has been forced to develop these technologies especially clean hydrogen and published many governmental policy documents like Inflation Reduction Act.[91]

4.1 Energy Overview

The USA possesses one of the most complex and diverse energy systems in the world, marked by a vast array of energy sources, technologies, infrastructure, and policy frameworks. As the world's one of the biggest energy consumers and one of the top energy producers, the USA plays a critical role in shaping global energy markets and climate trajectories. The energy landscape in the USA is currently

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[91] Rainer Quitzow and Yana Zabanova, The Geopolitics of Hydrogen, 2025, pp.220-222.

undergoing a significant transition, driven by decarbonization goals, technological innovation, and shifting geopolitical and economic considerations.[92]

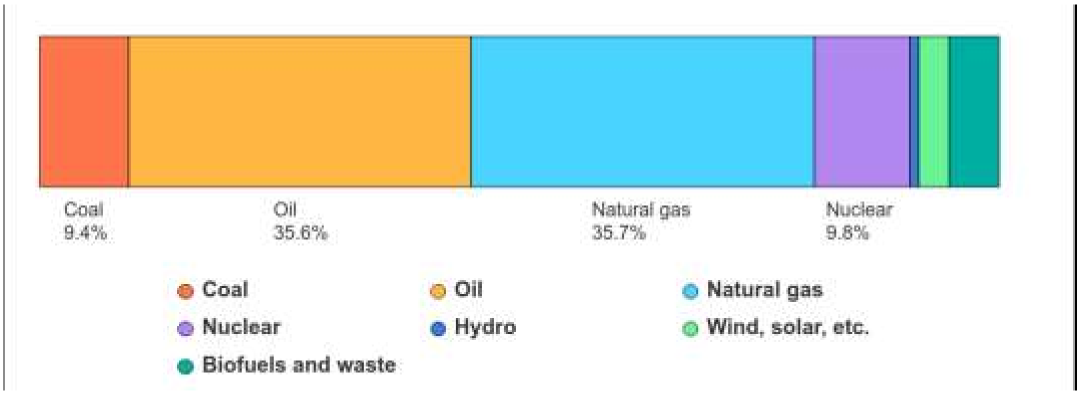

Figure 4.1 Total Energy Supply of the USA in 2023[93]

4.2 Energy Transition and Climate Pledges

The USA is the 1st economy in the world in terms of GDP accounting 25% of global economy. It is the 2nd largest energy consumer and GHG emitter in the world. At the same time, it is leader in technology and innovation, especially in clean technologies like renewables, battery, electrolyzer and electrical vehicles.[94] In the power sector, the USA is targeting to have 100% zero-carbon power production by 2035 using nuclear, wind, solar and geothermal. To reach this target, it is needed to set up a 2,000 GW of new clean electricity capacity by 2035. In the industry sector, the USA aims to decrease emissions 30% under the Industrial Decarbonization Roadmap for 2030. In the transport sector, the government set a target to make 50% of new cars and trucks to be zero emissions by 2030. In the building sector, the Blueprint for

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[92] IEA, United States, 2025, , https://www.iea.org/countries/united-states/energy-mix

[93] IEA, United States, 2025, , https://www.iea.org/countries/united-states/energy-mix

[94] IEA, United States 2024 Energy Policy Review, 2024, p.13. (IEA, United States 2024 Energy Policy Review 2024)

Decarbonizing Buildings is targeting to reach 65% reduction in emissions by 2035. Majority of annual total energy supply of the USA is still from fossil fuels. Largest sources are natural gas and oil with approximately 36% Fossil fuels are still dominant energy sources in the USA's energy portfolio. Coal, oil and natural gas compose of 81% of the primary energy supply in 2023. The picture was not so different from todays in 2000. Almost 85% of the portfolio was composed of fossil fuels in 2000. Total primary energy supply has decreased in the the US in last two decades. Renewable energy supply has increased 354% in last two decades but its share in portfolio increased limitedly from 1% to 3% only.[95]

In 2023, the USA emitted approximately 4.8 billion metric tons of CO_2 from energy-related sources. The breakdown by fuel type was as follows: natural gas is 1.76 billion metric tons, oil is 2.26 billion metric tons, coal is 781 million metric tons.[96]

The USA's alignment with the Paris Agreement is a discontinuous process. First time, the USA officially joined the Agreement in 2016 in Obama administration. Then Trump came to power and withdrew from the agreement. With the Biden, it became effective again in 2021. However, with the reelected Trump, the USA withdrew from the Agreement again in January 2025. This indicates that current climate ambitions in the USA are inherited from Biden administration, there is no clue from Trump era to support green transition.

The USA has announced its NDC during Biden era, targeted to reduce GHG 61%-62% below 2005 levels by 2035. Net-zero GHG emission target is 2050. This is a

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[95] IEA, United States, 2025, https://www.iea.org/countries/united-states/energy-mix

[96] Statista, Carbon dioxide emissions related to energy in the U.S. from 1990 to 2024, by fuel type, 2025, https://www.statista.com/statistics/489187/energy-co2-emissions-in-the-us-by-fuel/

significant target in terms of Paris Agreement goals. It means that the USA will have to decrease its GHG emissions by amount of 4 billion metric tons in 2035.[97]

4.3 Overview of the USA Clean Hydrogen

This section discusses the USA's political, technological, financial and international efforts to use clean hydrogen. It is evaluated that whether the USA will be able to achieve to meet the short-term climate targets by using clean hydrogen.

4.3.1 Policy and Strategy Documents

To start and enhance clean hydrogen ecosystem, US has published several incentives, grants and strategy documents.

First document is Bipartisan Infrastructure Law (2021) which is also known as Infrastructure Investment and Jobs Act, is one of the historical biggest supports of the USA into the infrastructure. It was signed by President Joe Biden in 2021. Support was announced as $1.2 trillion bill and it includes wide range of energy solutions like public electric charging stations, bus electrification, grid resilience and clean hydrogen generation. One of the biggest grants for clean hydrogen is establishing Regional Clean Hydrogen Hubs supported by Biden administration. The Project was announced in October 2023 by White House. In the USA, seven regional hubs were selected, and the total grant was announced as $7 billion which will be paid under Bipartisan Infrastructure Law. Selected hubs can be seen in figure below.[98]

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[97] The United States of America, Nationally Determined Contribution, 2025, p.2.

[98] The White House, Biden-Harris Administration Announces Regional Clean Hydrogen Hubs to Drive Clean Manufacturing and Jobs, 2023, https://bidenwhitehouse.archives.gov/briefing-room/statements-

Figure 2 USA Hydrogen Hub Plan[99]

The selected hubs also will catalyze $40 billion private investment bringing total public and private investment to $50 billion. The seven Hydrogen Hubs are projected to collectively generate over 3 million metric tons of clean hydrogen annually, representing about 30% of the USA 2030 production target. This initiative will reduce CO2 emissions by approximately 25 million metric tons per year equivalent to removing more than 5.5 million gas-powered vehicles from roads. With nearly $50 billion in funding, this program stands as one of history's most significant investments in clean energy manufacturing and workforce development.[100]

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releases/2023/10/13/biden-harris-administration-announces-regional-clean-hydrogen-hubs-to-drive-clean-manufacturing-and-jobs/

[99] Earthjustice, The Federal Hydrogen Hub Program, 2025, Access Date: 17.09.2025 https://earthjustice.org/feature/hydrogen-hub-program

[100] The White House, Biden-Harris Administration Announces Regional Clean Hydrogen Hubs to Drive Clean Manufacturing and Jobs, 2023, https://bidenwhitehouse.archives.gov/briefing-room/statements-

The second document is Inflation Reduction Act. It is an incentive act for clean energy. It is aiming develop hydrogen ecosystem via tax credit incentives. Inflation Reduction Act focuses on hydrogen production equipment production as well as hydrogen production. Moreover, there are strong incentives for fuel cell electric vehicles, and it shows us that USA is prioritizing decarbonization of transportation via fuel cell vehicles.[101]

Table 4.1 The USA Clean Hydrogen Tax and Credit Supports[102]

Incentive Name	**Explanation**
Advanced Energy Project Credit	30% investment tax credit for producers of fuel cell vehicle, electrolyzer
Carbon Capture and Sequestration Tax Credit	Enhanced tax credit for making carbon capture
Clean Hydrogen Production Tax Credit (45V)	$3 incentive for each kg hydrogen for 10-year production
Clean Vehicle Credit	$7,500 incentive for each fuel cell purchase
Energy Storage Credit	For hydrogen storage companies
Qualified Commercial Fuel Cell Vehicles	30% credit for commercial fuel cell electric vehicles capped at $40,000

The third document is The U.S. National Hydrogen Strategy and Roadmap. It assesses hydrogen's potential to support national decarbonization goals in various sectors. It was prepared by wide industry and stakeholder feedback, discussed by 50 organizations, with workshops and listening sessions. It was also contributed by

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releases/2023/10/13/biden-harris-administration-announces-regional-clean-hydrogen-hubs-to-drive-clean-manufacturing-and-jobs/

[101] US Department of Energy, US National Hydrogen Strategy and Roadmap, 2022, pp.1-7.

[102] Department of Energy, Financial Incentives for Hydrogen and Fuel Cell Projects, 2022, Access Date: 10.06.2025, https://www.energy.gov/eere/fuelcells/financial-incentives-hydrogen-and-fuel-cell-projects

executive office of President, so this report shows a complete behavior of USA to the hydrogen. This report helped all stakeholders and hydrogen players to show hydrogen's potential in USA. The adoption of clean hydrogen as a decarbonization pathway is guided by projected demand scenarios for 2030, 2040, and 2050, with strategic targets of 10 million metric tons (MMT) per year by 2030, 20 MMT annually by 2040, and 50 MMT annually by 2050. These projections are derived not only from the potential for domestic clean hydrogen production in the USA but also from anticipated demand across various sectors, contingent upon achieving market competitiveness in key applications. The utilization of clean hydrogen could contribute to an approximate 10% reduction in emissions by 2050 compared to 2005 levels, aligning with the objectives outlined in the U.S. Long-Term Climate Strategy. The USA targeted with this report a holistic approach into the hydrogen ecosystem. It focused all chains of the hydrogen; lower cost production, establishment of midstream infrastructure and developing end-use applications.[103]

According to report, there are three focus areas to take maximum benefit from hydrogen's decarbonization power. First is focusing high strategic areas rather than less strategic ones. It means hydrogen will focus on sectors whose decarbonization is hard to achieve with any alternative such as electrification etc. These sectors are chemical, steel-iron and heavy-duty transportation. Second focus is lowering cost of hydrogen in all chains. US has made it clear that not only technological advances will help to achieve lower prices, but also critical materials and supply chain vulnerabilities will be effective on hydrogen cost. The third one is focusing on regional networks. According to report, it will be achieved by Regional Clean Hydrogen Hubs. These hubs will enable economies of scale in production, distribution and storage of hydrogen. Moreover, long term offtake contracts,

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[103] US Department of Energy, US National Hydrogen Strategy and Roadmap, 2023, p.1.

jumpstart of domestic manufacturing industry and good-paying job opportunities will be enhanced.[104]

The Department of Energy launched the Hydrogen Energy Earthshot in June 2021 as part of its Energy Earthshots Initiative, marking the nation's first coordinated effort to accelerate innovation in clean hydrogen. The program's primary goal is to reduce the cost of clean hydrogen production to one dollar per kilogram within one decade (1-1-1 target), making it a competitive energy carrier for decarbonizing hard-to-abate sectors such as steelmaking, heavy transport and power generation.[105]

4.3.2 Production

USA has been a leader in blue hydrogen in terms of technology and scale. It is the first producer of blue hydrogen in commercial scale by capturing CO2 from steam methane reforming. In 2013, first commercial experiment of blue hydrogen production in the world was done by Air Products, at Valero Refinery complex, Texas. Firstly in the world, it was proved that hydrogen production from natural gas and integration of CO2 capturing technology together is feasible, commercial and a solution for decarboniztion.[106] There are five operational projects across the country.[107] According to Wu and Zhai, USA can increase blue hydrogen production

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[104] US Department of Energy, US National Hydrogen Strategy and Roadmap, 2022, p.27.

[105] US Department of Energy, Hydrogen Shot: An Introduction , 2021

[106] Carolyn Preston, The Carbon Capture Project at Air Products' Port Arthur Hydrogen Production Facility, *ieaghg,* 2018, p.i.

[107] IEA, Hydrogen Production Database, 2025

by tax incenties but in the short term it seems not feasible, compared with grey hydrogen.[108]

The USA has 347,924 tons clean hydrogen production annually. Moreover, there are many projects in design and feasibility phase. There are 163 projects which are expected to be online by 2030. Blue hydrogen project number is 55, green hydrogen is 54, pink hydrogen is 4 and remaining is from other clean technologies like biomass. Announced but not realized total capacity for 2030 is 4.5 GW which is 0.72 million tons per year, and it is still 8% of today's total production of the USA.[109] This number is still below government's target which is 10 million tons per year by 2030.[110]

Table 4.2 The USA Clean Hydrogen Production Operational Projects[111]

Operational Hydrogen Production	**Hydrogen Type**	**Production kg per year**
SoCalGas-NREL	Green	38,933
SunLine Transit Agency	Green	202,154
Coffeyville fertilizer plant	Blue	37,745,740
PCS Nitrogen-Geismar plant (LA)	Blue	21,965,953
Port Arthur	Blue	79,077,430
NEL-Champaign-Urbana	Green	134,769
Air Liquide	Biomass	3,280,899

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[108] Wanying Wu, Haibo Zhai and Eugene Holubnyak, Technological evolution of large-scale blue hydrogen production toward the U.S. Hydrogen Energy Earthshot, *Nature Communications*, 2024, p.10.

[109] IEA, Hydrogen Production Database, 2025

[110] US Department of Energy, US National Hydrogen Strategy and Roadmap, 2022, p.1.

[111] IEA, Hydrogen Production Database, 2025

Table 4.2. (Continued)

Olive Creek 1	Other	4,494,382
Long Beach Fuel Cell plant	Biomass	393,708
SunLine Palms Springs	Green	269,538
Cavendish NextGen Hydrogen Hub	Green	3.369.231
Great Plains Synfuel Plant	Blue	125,819,135
New Jersey Resources Howell	Green	27,253
SoHyCal	Green	1,010,769
Camden County (GA)	Green	5,390,769
Enid fertiliser	Blue	59,747,392
3 x 1250 kW projects in USA	Green	505,385
1 x 500 kW projects in USA	Green	67,385
18x180 kW projects in USA	Green	436,652
12 x 120 kW projects in USA	Green	194,068
Plug Power Charleston, Tenesse	Green	2,132,584
Plug Power Charleston, Tenesse	Green	1,148,315
Nine Mile Point Nuclear Plant	Green	134,769
Freedom Pines Fuels	Green	336,923

The USA is the 3rd country in the world in terms of hydrogen patents. Between 2011-2020, the USA took 20% of all hydrogen specified patents in the world while the EU and Japan took 28% and 24%. European Union is including Germany and

France. After Japan, it seems that the USA will be the driven force of hydrogen technology.[112]

Table 4.3 Hydrogen Patents in the World[113]

Countries	Share of Patents in Hydrogen	Hydrogen Production	Storage and Transmission	Industrial Applications
European Union	28%	28%	33%	27%
Japan	24%	20%	22%	28%
US	20%	19%	23%	19%
Germany	11%	10%	14%	12%
South Korea	7%	6%	5%	9%
France	6%	7%	9%	4%
China	4%	5%	3%	3%

4.3.3 Transportation

While the USA possesses commercially available hydrogen transportation technologies and infrastructure, large-scale in transportation sector remains contingent. Currently, the USA operates approximately 2,587 kilometers of dedicated hydrogen pipelines, 90% of it is concentrated in the Gulf Coast region, particularly in Texas, Louisiana and Alabama. The USA is the leader country in the world in terms of hydrogen transportation via pipelines. These pipelines primarily serve industrial clusters, including mostly refineries and fertilizer production facilities, reflecting hydrogen's historical use as an industrial feedstock rather than an energy carrier. A limited number of smaller pipelines exist outside this region, such as a 25-kilometer line in California**,** 22 kilometers in Indiana and other minor pipelines of less than 16 kilometers in various states. Although the USA can leverage

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[112] IEA, Hydrogen Patents for a Clean Energy Future, 2023, p.28.

[113] IEA, Hydrogen Patents for a Clean Energy Future, 2023, p.28.

its technological expertise, the lack of a national hydrogen transmission network hinders the integration of hydrogen rich production regions with demand rich centers. This infrastructure gap presents a significant barrier to achieving the scale envisioned in the National Clean Hydrogen Strategy, which targets the production of 10 million metric tons of clean hydrogen annually by 2030. Establishing a geographically expansive, interconnected hydrogen network is therefore critical to enable the widespread usage of hydrogen in the USA.[114]

One of the globally discussed methods to establish hydrogen transportation network is repurposing existing crude oil and natural gas pipelines. The USA has one example in that regard. In 1990s, Air Liquide company had converted two crude oil pipelines in Texas to carry hydrogen. From that time there has been no conversion in the USA. However, US Congress has announced that natural gas pipelines are well developed in the USA and they can be converted for hydrogen.[115] Although there is no example in natural gas pipeline conversion or blending, there are some research and development studies. For example, in November 2020, the National Renewable Energy Laboratory has made a study and concluded that hydrogen blending in natural gas pipelines has several inefficiencies and blending should be made according to specific pipelines.[116]

4.3.4 Storage

The USA possesses significant geological and infrastructural advantages for large-scale hydrogen storage, which is a critical enabler of a future hydrogen economy. The USA has already 36 gas storage caverns in the country. Among the most notable

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[114] IEA, Hydrogen Projects and Infrastructure Database, 2023

[115] US Congress, Pipeline Transportation of Hydrogen, Congressional Research Service, 2021, p.24.

[116] NREL, Hydrogen Blending in Natural Gas Pipeline Infrastructure, US Department of Energy, 2022, p.46.

advantages is the country's abundant salt dome formations, particularly in the Gulf Coast region, which are ideally suited for underground hydrogen storage. The Gulf Coast alone has the potential to store hundreds of terawatt-hours (TWh) of hydrogen in salt formations, positioning the region as a strategic storage and distribution hub. In addition, other geological formations such as depleted oil and gas reservoirs and aquifers are under study for their potential suitability in medium-to-long-term hydrogen storage, especially for seasonal balancing of variable renewable energy.[117]

4.3.5 Application

There are some initiations for clean energy transition. Office of Clean Energy Demonstration driven by state announced a support scheme. Under this scheme, industry actors submitted 110 clean energy transition projects and 33 projects have been selected for support. Total federal support is $6 billion. These projects' targets are deep decarbonization (50% less emission per project), timeliness (accelerate decarbonization in 10 years) and community benefits. Moreover, Cleveland-Cliff Steel Corporation has taken $500 million government support to install hydrogen ready melting furnace iron-steel infrastructure. And also SSAB company, has taken $500 million support for hydrogen fueled zero emission steel making.[118]

4.4 International Cooperation

Although the USA has made significant progress in technology and finance in domestic, it has an inefficient international cooperation structure in outside and has

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[117] US Department of Energy, Hydrogen Delivery, 2025, https://www.hydrogen.energy.gov/program-areas/production

[118] The Office of Clean Energy Demonstrations, Industrial Demonstrations Program Selections National Briefing, 2024, p.14.

international disputes with many potential partners. As we know from the previous chapters, the USA has an ultimate advantage in terms of hydrogen production potential and technology.[119] However, the USA undermines its global power of competitiveness in international scale. First, the USA has not placed in international hydrogen platforms like H2Global. Moreover, it has not engaged in diplomatic mechanisms to establish cross-border trade agreements, price guarantees or certification regimes. Moreover, the USA did not explain any ambition to export hydrogen in its national hydrogen documents. This reflects a largely inward-focused strategy that prioritizes domestic production rather than international ambition.[120]

The United States entered the LNG export market relatively recently, with large-scale shipments beginning in 2016 after the closure of Alaska's Kenai Plant in 2015. Since then, it has grown to become the world's leading LNG exporter. In the past year alone, U.S. LNG exports reached 86 million tons**,** supported by the launch of Calcasieu Pass LNG and the restart of Freeport LNG operations. Exports peaked in December 2023, hitting a record monthly volume of 8.6 million tons.[121]

The USA has also implemented LNG diplomacy, and this diplomacy has been decisive in unlocking LNG's potential in the USA. Many long-term LNG contracts have been made with European and Asian countries maintaining continuous flow of revenue. First, the USA focused on European markets to sell LNG. And one of the motivations has been ending Russia's natural gas hegemony with the USA LNG alternative. In 2024, the USA LNG to the EU has amounted 51 billion cubic meters and they were 13 billion $. The same strategic approach with LNG is crucial for hydrogen market ramp up in USA. There is strong hydrogen demand in the world

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[119] IEA, Hydrogen Projects and Infrastructure Database, 2023

[120] US Department of Energy, US National Hydrogen Strategy and Roadmap, 2022, pp.1-7.

[121] CSIS, U.S. LNG Export Boom: Defining National Interests, 2024, https://www.csis.org/analysis/us-lng-export-boom-defining-national-interests

which the USA can fill up. By replicating the strategy that enabled LNG's rise as a global commodity, an international hydrogen strategy could also mobilize similar flows of capital, infrastructure development and long-term trade agreements that benefit both domestic industry and international partners.[122]

Existing international conflicts also prevent the utilization of hydrogen ecosystem. For example, the USA has put in place extensive tariffs for Chinese products and China has introduced new export controls for rare earth metals. China is also leader in solar PVs and batteries. In 2024, 25% of the China's lithium-ion battery exports were for the USA and the USA is major importer for solar panels, solar cells and electric vehicles.[123] Moreover, the USA has a market problem with China and the EU. Inflation Reduction Act (IRA) entered operation in 2022 in the USA. The IRA is giving subsidies as tax credits and gives these credits on the condition of being the USA based and on sourcing from North America. Because of that China and especially the EU felt that they are attacked by the USA in energy transition rally. Following the IRA, the EU announced the counter plan, "Green Deal Industrial Plan". China also claimed that IRA subsidies are unfair trade measures and conflict with World Trade Organization. Moreover, China asserted that IRA pushes up the cost of energy transition.[124]

The USA has also international border and trade problems with neighbor countries. According to April 9, 2025, tariff decisions of Trump, Mexico and Canada had to

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[122] Anne Sophie Corbeau, Bridging the US-EU Trade Gap with US LNG Is More Complex than It Sounds, Columbıa Sıpa, 2025, Access Date: 20.08.2025, https://www.energypolicy.columbia.edu/bridging-the-us-eu-trade-gap-with-us-lng-is-more-complex-than-it-sounds/

[123] Ilaria Mazzocco, Analyzing the Impact of the U.S.-China Trade War on China's Energy Transition, 2025, https://www.csis.org/analysis/analyzing-impact-us-china-trade-war-chinas-energy-transition

[124] John Siciliano, US-China trade talks break down over Inflation Reduction Act energy tax credits, 2024, https://www.spglobal.com/commodity-insights/en/news-research/latest-news/electric-power/071624-us-china-trade-talks-break-down-over-inflation-reduction-act-energy-tax-credits

pay 25% tariff on products that do not comply with the USA-Mexico-Canada Agreement (USMCA) on free trade.[125] Mexico has a great advantage in terms of green hydrogen production potential. It has vast areas of deserts and significant solar potential. The targeted hydrogen price for 2030 is 2.5$/per kg which is a very competitive price in the world. However, existing trade and border disputes prevent the potential cooperation in hydrogen. The USA should set up a strong synergy with Mexico in terms of clean hydrogen by eliminating existing disputes.[126]

4.5 Conclusion

This chapter provides the USA's hydrogen framework focusing on ongoing investments, government incentives, technological developments, finance options and overal capacity to become hydrogen power.

The USA occupies a unique position in the hydrogen and energy transition. Domestically, it has taken decisive steps toward decarbonization, with policies such as the Inflation Reduction Act and significant federal funding programs that have stimulated investment in hydrogen. These measures signal a commitment to clean energy innovation and provide the financial foundation for hydrogen-based solutions. At the same time, structural challenges remain in the USA. The fluctuated nature of USA political support on renewable projects as we see in Trump era forms uncertainty for long-term planning.

Moreover, while the USA has significant power in terms of geography, finance, technology and has a chance to be hydrogen super power of the world, its international role in shaping hydrogen markets, certification schemes and trade

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[125] David Crisostomo, Carlos Pascual and Alejandra Leon, Can Mexico and the United States Take Advantage of their Energy Potential?, 2025, https://revista.drclas.harvard.edu/can-mexico-and-the-united-states-take-advantage-of-their-energy-potential/

[126] GIZ, Green Hydrogen in Mexico: towards a decarbonization of the economy, 2021, p.7.

partnerships is too weak. Compared to the Germany, which has actively pursued a global hydrogen diplomacy, the USA has so far placed greater emphasis on inward-looking industrial competitiveness. Nevertheless, the USA has the potential to play a decisive role in the global hydrogen economy. Its abundant renewable resources and strong technological base position it as a potential frontrunner in clean hydrogen production. If coupled with stronger international cooperation and resolution of emerging trade disputes, the USA could leverage its domestic power to into the global leadership.

In conclusion, the USA case illustrates both the strengths and limitations of a nationally driven approach to the hydrogen. Although there are significant domestic incentives and technical experience, the full potential of clean hydrogen will only be realized through international colloboration and institutionalized cooperation. The USA must implement more outward-looking strategy, ensuring that it contributes actively to shaping the rules, partnerships and institutions of the emerging global hydrogen economy.

CHAPTER 5

GERMANY

Germany has a distinct feature in terms of energy politics in energy history. Germany had a great ambition for coal and nuclear energy fifty years ago. However, with accidents and undsired effects, coal and nuclear power had become under skepticism. It went to decomissioning process in almost all coal and nuclear power plants in last decades. Moreover, government had announced Energiewende, energy transition policy, in 2011 and targeted to lessen fossil fuels' share from 80% to 20% by 2050. This was strengthened by Paris Agreement in 2016. When we came to the 2020s, Russian-Ukraine war was broke out and Germany- Russia natural gas ties have ended. A new energy crisis has emerged in Germany and some lessons have been concluded like supply security, energy sovereignty and maintaining cheaper energy prices. Clean hydrogen has been one of the leading long term energy solutions for Germany at that time.[127]

5.1 Energy Transition and Climate Pledges

Germany's Energiewende, literally "energy transition", is a comprehensive, long-term strategy to achieve a low-carbon, nuclear-free economy and climate neutrality by 2050, embedded within the European Union's Green Deal framework and Paris Agreement commitments. Originating from anti-nuclear and environmental considerations, it has evolved into a national transformation encompassing all

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[127] M.Loewe, C.Quittkat, M.Knodt, I.Ott, The Impact of the Russian War against Ukraine on the German Hydrogen Discourse, *sustainability*, 2024, pp.15-16.

economic sectors, with strong public support. Initially focused on the power sector, where renewable sources surpassed fossil fuels in generation share in 2020, the Energiewende combines the phase-out of nuclear energy and coal (scheduled by 2038, with an earlier exit likely) with legally binding sectoral emissions targets. Despite significant achievements, including stable electricity supply during the nuclear phase-out, persistent challenges remain in reducing emissions from road transport, accelerating grid expansion, enhancing energy efficiency, and mobilizing financial sector engagement, making sustained domestic reforms and international cooperation essential to its success. Overall, Germany energy policies are characterized by four elements; exit from nuclear power, ending dependency to Russian gas, coal phase-out and transition to renewable energy.[128]

Germany's energy transition is driven by ambitious national targets and reinforced by its obligations under European Union climate policy. While Germany achieved notable progress between 1990 and 2020, structural weaknesses in the energy sector and reliance on fossil fuels remain pressing challenges. Within the broader EU framework, Germany's strategy is closely aligned with the European ones and the This dual national and European approach highlights Germany's role as both a leading actor and a bound participant in shaping collective climate policy, underscoring the necessity of rapidly scaling up renewable energy and embedding climate action into economy.[129]

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[128] European Parliament, Germany's climate action strategy, Roadmap to EU climate neutrality – Scrutiny of Member States, 2024, p.3.

[129] Bundesministerium für Wirtschaft und Klimaschutz, Germany's current climate action status, 2022, pp.2-5.

5.2 Overview of the Germany Clean Hydrogen

This section discusses Germany’s political, technological, financial and diplomatically efforts to use clean hydrogen. It is evaluated that whether Germany will be able to achieve to meet the short-term climate targets by using clean hydrogen.

5.2.1 Policy and Strategy Documents

The initial document which was published by German Federal Ministry and Economic Affairs and Energy is National Hydrogen Strategy (2020). Germany has positioned hydrogen produced by renewable energy a core source for achieving GHG neutrality in line with the Paris Agreement. It outlines the full hydrogen value chain from production and infrastructure to use and certification and aims for rapid market adoption. What Federal Government of Germany has focused in clean hydrogen is just green hydrogen. Blue hydrogen can be used but just for transformation processes. This document was updated in 2023. This update clarified that Germany has a 10 GW domestic electrolyzer target by 2030. It is forecasted that 95-130 TWh will be needed and 70% of this demand will be imported. Germany is targeting to implement hydrogen ecosystem by 2030. Before that, according to Germany, necessary steps should be taken for a sucessful ecosystem. Necessary steps are as follows outlined in National Hydrogen Strategy.[130]

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[130] The Federal Government, National Hydrogen Strategy Update, 2023, p.6.

Table 5.1 Germany National Hydrogen Strategy Action Plan[131]

Actions for a Successful Hydrogen Ecosystem	**Target Area in Ecosystem**
Accelerated market rump-up:	Technology
Electrolyzer capacity is targeted to reach 10 GW by 2030	Production
Development of hydrogen infrastructure	Transportation-Storage
Implementation of hydrogen application in many sectors	Application
Germany will become the lead provider of hydrogen technologies by 2030	Technology
Formation of appropriate framework conditions:	Regulation

Approximately 50% to 70% of the demand will be covered by imports rather than domestic production. This number will increase after 2030 and Germany will be dependent on imported hydrogen more. To support National Strategy, Germany has published Import Strategy in July 2024. So, "Import Strategy for Hydrogen and Hydrogen Derivatives" document was published in July 2024 by Federal Ministry for Economic Affairs and Climate Action. It is a complementary document of National Hydrogen Strategy. It was announced because Germany domestic hydrogen production will not be enough to cover demand and there will be significant import need. Main method to secure import is making international strategic partnership with nations that have abundant green hydrogen production capacity like Chile, North Africa, Türkiye. Import of hydrogen is planned to be via ships at least until 2030. After 2030, imports of green methane, synthetic methanol and hydrogen via pipeline are forecasted. Germany has a target to use hydrogen derivatives like ammonia, naphtha, methanol instead hydrogen itself. Reason behind this strategy is that derivatives are easy to transport while molecular hydrogen transportation is harder via pipelines etc. Federal Government expects that derivatives can be

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[131] The Federal Government, National Hydrogen Strategy Update, 2023, p.2.

imported via ports instead of importing fossil fuels. This transition requires reengineering of ports.[132]

Table 5.2 Germany Hydrogen Import Strategy Actions[133]

Measures for the Ramp-Up of Hydrogen Import
Strengthening of Demand
Sustainable Import Infrastructure
Certification Procedures
Increasing International Supply of Hydrogen
International Partnerships
Support Research and Development

Also, infrastructure development was focused on this document. To transport hydrogen, both pipeline and maritime transportation methods are advised. For pipeline operations, repurposing of existing natural gas pipelines have been taken into the agenda. For the maritime transportation, Germany is planning to replace existing fossil fuel imports with green fuel imports like hydrogen derivatives. For example, for ammonia transportation, there are many projects, and they are expected to be online by 2030.[134]

5.2.2 Production

There are siginificant clean hydrogen investments in Germany but they are not enough to reach 2030 hydrogen production targets. Germany is currently one of the leading hydrogen-producing countries within the European Union and the World

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[132] The Federal Government, Import Strategy for Hydrogen and Hydrogen Derivatives, 2024, pp.3-4.

[133] The Federal, Import Strategy, p.17.

[134] The Federal Government, Import strategy, pp.14-15.

with a 2.2 million metric tons of hydrogen production but majority of it is from fossil fuel resources. However, only 0.03 million tons of hydrogen is produced in clean ways which comprise only 1.5% of the total production. Moreover, the expectation with National Hydrogen Strategy is to set up 10,000 MW electrolyser by 2030. Despite many efforts in terms of green hydrogen production, Germany has only 80 MW green hydrogen production capacity, which is 0.8% of the 2030 target.[135]

Table 5.3 Germany Operational Clean Hydrogen Production Sites[136]

Operational Productions	**Start Date**	**Electrolyzer Capacity (MW)**	**Annual Production Capacity (tons)**
Leuchtturmprojekt	2020	1.3	585
eFarm (5 production sites in North Frisia)	2020	1.125	506
PFI - Pirmasens-Winzeln	2019	2.5	1125
Windgas Haurup, 2nd phase	2020	1	450
Stromlückenfüller 2nd phase	2019	0.2	90
Falkenhagen STORE&GO	2018	1	450
Wind to Gas Südermarsch	2019	2.4	1080
H2ORIZON	2020	0.8	360
Windgas Haurup, 1st phase	2018	0.2	101

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[135] IEA, Hydrogen Production Database, 2025

[136] IEA, Hydrogen Production Database, 2025

Table 5.4 (continued)

Methanation at Eichhof	2018	0.05	23
MicroPyros, Altenstant	2018	0.001	1
Hassfurt	2016	1.2	563
HPEM2GAS (R&D)	2016	0.2	90
Hamburg - Schnackenburgallee	2016	0.1	83
Stromlückenfüller 1st phase	2015	0.02	9
Hanau, Wolfgang Industrial Park	2014	0.02	9
P2G plant Erdgas Schwaben	2013	1	450
MicrobEnergy GmbH, Schwandorf	2013	0.1	81
Refhyne	2021	10	4500
H&R Ölwerke Hamburg-Neuhof	2017	5	2250
Energiepark Mainz	2017	6	2700
Wunsiedel Energy Park (Phase 1)	2022	8.8	3960
HYPOS (several projects)	2019	1.3	585
Wuppertal refuelling station	2020	2.5	1125
SALCOS - WindH2	2021	2.5	1125
HRS Bremervörde - trains	2022	3.8	1753
Hydrogen Lab Bremerhaven (phase 1)	2023	1	450
Trailblazer - Siemens-Air Liquide	2024	20	9000
Fairfuel Atmosfair	2021	1.3	585
H2 Pilotanlage Lingen, phase 2	2024	4	1800

Clean hydrogen production in Germany remains economically uncompetitive with other fuels due to geographical constraints. Germany has not excess and abundant renewable energy potential which is must for green hydrogen generation. The country's renewable generation profile characterized by intermittent solar and wind limits electrolyzer utilization thereby reducing production efficiency and raising unit costs. Germany has made siginificant investments in last decades and became one of the leading nations benefiting from renewable energy. The installed renewable capacity has reached to 166,939 MW in 2023 which has been almost doubled since 2014.[137] Germany is heavily using green electricity to meet extensive decarbonization needs in industry, mobility and buildings. Moreover, ongoing coal and nuclear phase out development form a new demand for renewable electricity. Germany is planning nuclear and fossil fuel phase out. Coal phase out is planned to be completed by 2030 and nuclear phase out 2040. This indicates that Germany will need too much electricity from renewable power generation and there is a risk for hydrogen generation.[138]

There are also many efforts in Germany for green hydrogen market establishment. Since 2023, European Energy Exchange has been publishing the world's first market-based hydrogen index in Germany. It consists of Germany green hydrogen producers' and consumers' transactions. It is also crucial step for transparent price mechanism of clean hydrogen. In the early stages of market formation, such price mechanisms are critical for reducing information asymmetries, enabling investors, project developers and off-takers to benchmark long-term contracts. A transparent index also facilitates the structuring of financial instruments such as futures or contracts for difference that can hedge price volatility and lower perceived market

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[137] IRENA, Renewable Energy Capacity Statistics, 2025, p.4.

[138] Fabian Prager, Claudia Kemfert and Christian von Hischhausen, European energy infrastructure for 100% renewables, 2024, p.13.

risk, thereby improving bankability for large-scale electrolysis projects. By aligning producer and consumer expectations, the EEX hydrogen index can thus play a catalytic role in accelerating investment and scaling up Germany's clean hydrogen production capacity.[139]

5.2.3 Transportation

Transportation infrastructure has an important role in the ramp-up of the hydrogen ecosystem both in the the country and also in the international trade. Germany has a well-prepared pipeline transportation plan but companies cannot implement projects easily without seeing concrete hydrogen supply commitments. Most of the pipeline projects are in feasibility stage yet while only two ones took final investment decision. The pipeline projects that have taken investment approval are Energiepark Bad (19.4 km length) and Clean Hydrogen Coastline (316 km) projects. It is a very small number compared with total planned pipeline length, that is 4,783 km. It shows that only 1% of the total needed projects have taken approval. These pipeline projects are significant in terms of supply security. As Germany is planing to import majority of hydrogen from other countries, it is a necessity to disribute hydrogen inside the country via pipelines. So existing numbers of approved pipeline projects that is only 1% of the total needed show that there is a significant bottleneck to realize hydrogen ecosystem. However, the main reason behind the realization of pipeline infrastructure along the country is the lack of enough supply gurantees through imports. With the lack of hydrogen import deals, companies who are willing to invest in pipeline infrastructure are not able to see feasibility of the projects.[140]

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[139] EEX Hydrogen Index, 2025, https://www.eex-transparency.com/hydrogen

[140] IEA, Hydrogen Production Database, 2025

Table 5.4 Germany Hydrogen Pipeline Projects[141]

Pipeline Project	**Date Online**	**Project Status**	**Lengths**
doing hydrogen - 2026	2026	Feasibility	67 km
doing hydrogen - 2027	2027	Feasibility	122 km
Green Octopus Mitteldeutschland - 2026	2026	Feasibility	35 km
Green Octopus Mitteldeutschland - 2027	2027	Feasibility	142 km
Green Octopus Mitteldeutschland - 2028	2028	Feasibility	145 km
Energiepark Bad Lauchstädt	2025	FID	19 km
RHYn Interco-Phase I	2029	Feasibility	45 km
HyPipe Bavaria - 2027	2027	Feasibility	25 km
HyPipe Bavaria -2030	2030	Feasibility	187 km
HyPipe Bavaria - 2032	2032	Feasibility	128 km
Nordic-Baltic Hydrogen corridor	2030	Feasibility	10 km
Hamburg Hydrogen Industrial Network	2027	Feasibility	40 km
Hamburg Hydrogen Industrial Network (HH-WIN) Phase 1	2030	Feasibility	20 km
Hamburg Hydrogen Industrial Network (HH-WIN) Phase 2	2035	Feasibility	40 km
AquaDuctus-AquaPrimus	2025	Feasibility	20 km
AquaDuctus-H2ercules	2028	Feasibility	478 km
AquaDuctus	2030	Feasibility	200 km
AquaDuctus-Prolongation	2030	Feasibility	200 km

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[141] IEA, Hydrogen Production Database, 2025

Table 5.5 (continued)

MosaHYc (Moselle Sarre HYdrogène Conversion) -	2027	Feasibility	42 km
H2ercules Network North	2030	Feasibility	424 km
H2ercules Network West	2029	Feasibility	27 km
H2ercules Network North-West	2030	Feasibility	87 km
Delta Rhine Corridor H2 Germany	2030	Feasibility	148 km
H2ercules Network South-East	2030	Feasibility	131 km
H2ercules Network South-West	2030	Feasibility	223 km
HyPerLink 1&2	2027	Feasibility	328 km
HyPerLink 3	2028	Feasibility	190 km
HyPerLink 4	2027	Feasibility	77 km
HyPerLink 5	2027	Feasibility	174 km
Clean Hydrogen Coastline	2026	FID	316 km

Although the number of import deals is decisive in transportation projects, there are also other factors like insufficient finance, technical hurdles and regulatory problems but they pose small portion of the reason. Without solid deals and long-term off-take commitments, developers and investors hesitate to proceed pipeline projects. For example, Equinor, Norway energy company, halted blue hdrogen export pipeline project to the Germany because of the insufficient long term commitments of Germany.[142]

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[142] Reuters, Norway's Equinor scraps plans to export blue hydrogen to Germany, 2024, https://www.reuters.com/business/energy/norways-equinor-scraps-plans-export-blue-hydrogen-germany-2024-09-20

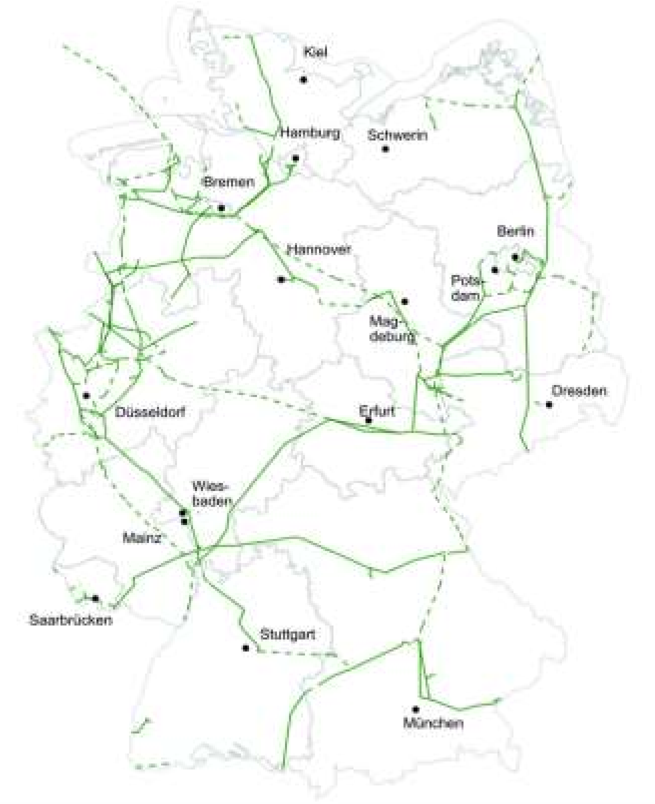

Figure 5.1 Germany Core Hydrogen Grid Pipeline Network[143]

To support future imports of hydrogen derivatives, Germany is developing import terminals at key ports. Major ports such as Hamburg, Wilhelmshaven, Stade and Brunsbüttel are actively planning infrastructure to accommodate derivatives like ammonia. Additionally, newly constructed LNG terminals in these ports are required to be designed with the capability for a future conversion to handle ammonia.[144]

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[143] Bundesnetzagentur, Hydrogen core network, 2024, https://www.bundesnetzagentur.de/EN/Areas/Energy/HydrogenCoreNetwork/start.html

[144] Mattis Körber, Clean Hydrogen Across the Atlantic, *American Council on Germany,* 2025, p.15.

5.2.4 Storage

Germany’s hydrogen storage infrastructure is evolving rapidly, with significant developments in both underground and above-ground technologies. Salt caverns are one of the solutions of large-scale storage. Germany has already one operational storage site called HyCAV mobil. There are also salt cavern projects, some of them are in FID stage while some of them are in concept design. They are expected to be online until 2027. Throuh these development efforts, very well-developed storage capacity of Germany will not only support its future hydrogen supply but also will help neighbour countries’ hydrogen demands.[145]

Table 5.5 Germany Hydrogen Storage Projects[146]

Project Name	**Online Date**	**Project Type**	**Project Status**	**Storage Type**
H2 Gronau-Epe	2027	New	FEED	Salt caverns
HYPOS-H2	2026	New	Under construction	Salt caverns
Krummhörn	2023	Repurposed	FID	Salt caverns
HyCAVmobil	2023	New	Operational	Salt caverns
H2CAST Etzel	2024	Repurposed	Feasibility study	Salt caverns
Bad Lauchstädt Energy park	2027	New	FID	Salt caverns
Jemgum Storage	NA	Repurposed	Concept	Salt caverns
Rehden	NA	Repurposed	Concept	Depleted gas field

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[145] IEA, Hydrogen Production Database, 2025

[146] IEA, Hydrogen Production Database, 2025

5.2.5 Application

There is a strong clean hydrogen demand from various sectors ranging from steel-iron to transportation in Germany. The companies like Linde, ThyssenKrupp explained their ambitions for clean hydrogen and are making necessary preperations for hydrogen future. For example, Salzgitter, which is a steel company, launched a tender to buy 120,000 tons per year green hydrogen for its Salcos steel production plant seeking supplies from 2027 and plans to connect German national hydrogen pipeline network. Moreover, another steel company, Stahl-Hoolding-Saar launched a tender in March 2024 to buy 50,000 ton per year green hydrogen for its Dillinger and Saarstahl plants in Saarland.[147]

Table 5.6 Hydrogen End User's Approach in Germany

Sector	**Companies**	**Method to Use Hydrogen**
Steel	Salzgitter	Green hydrogen in direct reduction[148]
Chemicals	Linde	Hydrogen Liquefaction[149]
Glass	BVGlass	Hydrogen as a fuel for furnaces[150]
Rail	Alstom	Hydrogen powered trains[151]
Heavy Road	FAUN	Hydrogen fueled trucks[152]

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[147] Thyssenkrupp, Thyssenkrupp Steel pauses German green hydrogen tender on high prices, 2025, https://eurometal.net/thyssenkrupp-steel-pauses-german-green-hydrogen-tender-on-high-prices/

[148] Thyssenkrupp, 2025

[149] Linde, Hydrogen in Leuna: The Success Story Continues, 2025, https://www.linde-engineering.com/products-and-services/success-stories/2024/hydrogen-in-leuna-the-success-story-continues

[150] BV Glass, BV Glass and GWI complete their HyGlass project. 2022. https://www.bvglas.de/en/detail/news/bv-glas-and-gwi-complete-their-hyglass-project

[151] Alstom, Alstom Corodia iLint, 2025, https://www.alstom.com/solutions/rolling-stock/alstom-coradia-ilint-worlds-1st-hydrogen-powered-passenger-train

[152] Faun Zoeller, Bluepower Alternative Fuel, 2025, https://faun-zoeller.co.uk/products/bluepower/

Although there are strong ambitions from industry to use hydrogen, existing high prices of hydrogen make it hard to use for companies. ThyssenKrupp which is one of the biggest iron-steel producers, launched a tender in February 2024 to buy 151,000 ton/year clean hydrogen in a 10-year contract period for the Duisburg facility. However, offered prices have been slightly higher than expected which make commercial operations harder. The average price in Germany is $10.1 per kg which is still higher for the industry. ThyssenKrupp emphasized on clean hydrogen's importance and also stressed on economic applicability claiming that they will only be able to use hydrogen if its price is affordable.[153] The another example is ArcelorMittal, which is a steel-iron company, revised its decarbonization strategy scaled back on hydrogen direct reduced iron (DRI) projects because of the slower than expected advancements in hydrogen cost.[154]

5.3 Finance

There are also financial supports for hydrogen end-use both from Germany itself and from EU. German companies participated in lots of subsidy and incentive programs of EU. For example, European Union has approved 2 billion Euros project, "tkH2steel" under IPCEI Hydrogen for Thyssenkrupp Steel Europe AG company. Thyssenkrupp will use this money to convert coal facility to hydrogen one.[155] In addition, Salzgitter took another EU fund under IPCEI which is 1 billion Euros to convert its coal-based system to hydrogen ones. German industry announced their ambition for decarbonization and choose hydrogen as a solution but they are still

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[153] Thyssenkrupp, 2025

[154] ArcelorMittal, ArcelorMittal fourth quarter report of 2024, 2024, p.4.

[155] Power, Thyssenkrupp receives 2 billion euros for H2 steel production, 2023, https://power-to-x.de/en/Thyssenkrupp-receives-2-billion-euros-for-H2-steel-production/

finding a way to lessen its cost. Even if they will convert existing coal-based plants to hydrogen with the help of EU funds, they will then face with domestically produced high cost hydrogen price which is at 7$ per kg range.[156]

5.4 International Cooperation

Germany has a strong technological readiness and extensive finance options but only international cooperations via sucessful partnerships is able to provide low cost and large volume hydrogen supply. Officially, Germany declared that demand for 2030 is approximately 3 million tons of clean hydrogen and 70% of it will need to be imported from outside. To cover this demand, Germany has made many bilateral cooperation with EU and non-EU countries. Main tools of Germany government have been bilateral agreements, electrolyzer projects and study- training programs.[157]

One of the partnerships is German-Chilean Energy Partnership which is an international cooperation ground for two countries. The partnership became operational in 2019. Partner institutions are German Federal Ministry of Economy and Climate Change and Chilean Ministry for Energy. Partnership has full-time secretariat in Santiago de Chile. It shows us that relations have an organizational structure. Hydrogen is a sub-subject in this partnership but has a strong background. Chile is one of the leader countries in the world in terms of renewable power potential especially leader in solar power. In 2021, two countries have formed “Hydrogen Task Force” to strengthen green hydrogen cooperation. Germany companies are active in Chile. In 2023, Siemens and HIF companies built a green hydrogen plant and then one hydrogen derivative, methanol from wind power. BMWE has funded the project which is totaled in 8.2 million Euros. Thanks to its abundant solar power

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[156] Steel Times International, Salzgitter acquires 1 billion $ fund decarbonization process, 2022, https://www.steeltimesint.com/news/salzgitter-acquires-eur1-billion-to-fund-decarbonization-process

[157] The Federal Government, Import Strategy for Hydrogen and Hydrogen Derivatives, 2024, pp.3-4.

potential, Chile will be able to produce green hydrogen 1.3 $ per kg by 2030. Adding shipping cost 0.9$ per kg from Chile to Germany, Germany can use green hydrogen in 2.2$ per kg price which is very advantegous compared with domestic production of Germany.[158]

Germany-South Africa energy partnership agreement was made in 2023 to support both country's energy demands. Germany has announced 30 million Euro support for South Africa. Cooperation will focus on renewable electricity production in South Africa and hydrogen production that later will be exported to the Germany.[159] South Africa has a siginificant potential to produce green hydrogen. According to Hydrogen Society Roadmap of South Africa government, targeted potential is to produce 500,000 tons clean hydrogen annually by 2030. It is a significant number and makes South Africa potential import candidate for Germany which has a demand target of 3 million tons hydrogen by 2030. South Africa also has a price advantage and can use it to become an exporter country. According to National Business Initiative, South Africa could produce green hydrogen for 1.6$ per kg by 2030. It is one of the lowest ones in the world and a great potential for Germany demand.[160]

Germany and Algeria's energy ministries signed a partnership agreement in 2024. Germany has explicitly claimed that Algeria has abundant renewable energy potential, and it will support hydrogen developments in this country with know-how and technical expertise. Moreover, hydrogen task force was set up between two countries to promote hydrogen. There is also SoutH2 pipeline project in the agenda

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[158] Energy Partnership Chilean-Alemania, Chilean-German Energy Partnership, 2025, https://energypartnership.cl/

[159] Federal Ministry for Economic Affairs and Energy, Germany and South Africa Sign Cooperation Agreement on Green Hydrogen, 2023, https://www.bundeswirtschaftsministerium.de/Redaktion/EN/Pressemitteilungen/2023/06/20230627-germany-south-africa-cooperation-green-hydrogen.html

[160] Department of Science and Innovation Republic of South Africa,Hydrogen Society Roadmap for South Africa, 2021, pp.41-51.

with Algeria. This pipeline is aimed to transport renewable hydrogen from Algeria to the Europe; especially to the Germany.[161]

Moreover, Australia and Germany signed an agreement which is valued 400 million Euro to support hydrogen production in Australia and then exporting to the Germany. They named this cooperation as Energy and Climate Partnership. According to Bowen, Australian Minister for Climate Change and Energy, Australia has enough sun and power potential to become a renewable energy superpower and leader exporter of hydrogen in near future. The relationship is able to start an international hydrogen trade.[162]

The Egyptian German Green Hydrogen Partnership, launched in 2023, seeks to advance Egypt's role in global hydrogen markets by fostering production capacity, industrial cooperation, and stakeholder engagement. Building on Egypt's abundant renewable energy resources and infrastructure, the partnership complements Egypt's Low Carbon Hydrogen Strategy, which targets capturing up to 8% of the tradable hydrogen market by 2040 through approximately $60 billion in investments. Germany's hydrogen strategy similarly emphasizes supporting partner countries in developing production sites as part of broader development cooperation. Within this framework, Egypt has introduced fiscal incentives, expanded renewable energy projects, and signed 23 memorandum of understanding at COP27 for over 8 GW of electrolyser capacity and at least 28 GW of associated renewable projects. Additionally, more than 26,000 km² of land, with potential for around 100 GW of renewable energy, has been allocated for such initiatives. These measures position

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[161] Federal Ministry of Economic Affairs and Energy, Germany and Algeria set up hydrogen taskforce, 2024, https://www.bundeswirtschaftsministerium.de/Redaktion/EN/Pressemitteilungen/2024/02/20240208-germany-and-algeria-set-up-hydrogen-taskforce.html

[162] Federal Ministry of Economic Affairs and Energy, Cooperation between Australia and Germany in the fields of energy and climate is being expanded, 2024, https://www.bundeswirtschaftsministerium.de/Redaktion/EN/Pressemitteilungen/2024/09/20240913-cooperation-between-australia-and-germany-in-the-fields-of-energy-and-climate-is-being-expanded.html

Egypt as a pivotal actor in the emerging green hydrogen economy, while simultaneously deepening its bilateral energy cooperation with Germany.[163]

Germany's hydrogen import strategy is a change in geopolitical map of energy security, but it does not erase the whole risks. Hydrogen itself has new geopolitics different from oil and gas ones. Hydrogen as an internationally traded product is competitive one and has an emerging market rather than a mature one. So early diplomatic engagement determines access to the most cost-effective and reliable sources in the world. Unlike in the oil and gas era, where market has a developed maturity level, spot purchases are applicable. However, hydrogen market rewards long-term relationship-building and infrastructure agreements. Without such diplomacy, Germany risks repeating the vulnerabilities of its gas dependency.[164]

From a neoliberal institutionalist perspective, Germany's hydrogen politics abroad demonstrates how international cooperation and institution-building are essential for managing the supply security in an emerging market. Hydrogen, unlike fossil fuels, lacks a mature supply and trading infrastructure or standardization that makes long-term agreements critical. Germany's extensive use of bilateral partnerships and cooperative task forces reflect the neoliberal institutionalist belief that diplomatic institutions enhance cooperation, reduce transaction costs and maintain security of supply. By embedding its hydrogen strategy within an international hydrogen strategy, Germany not only maintains supply security but also decreases the potential risks of political and economic fluctuations in partner countries.[165]

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[163] Federal Ministry of Economic Affairs and Energy, Egyptian German Green hydrogen Partnership, 2023, https://climateandenergypartnerships.org/partner/jcee-green-hydrogen-partnership/#:~:text=The%20Egyptian%2DGerman%20Green%20Hydrogen,within%20the%20Republic%20of%20Egypt.

[164] Dawud Ansari and J.Maria Pepe, Toward a Hydrogen Import Strategy for Germany and the EU, SWP, 2023, pp.15-18.

[165] Lentschig, Patonia ve Quitzow, Multilateral Governance, 2025

Germany also must resolve the international disputes to unlock hydrogen's potential. The main international problem that Germany face today is Ukraine-Russia war. When Ukraine-Russia war erupted in 2022, natural gas supplies were halted to the Germany and major pipeline, Nord Stream was suspended. Before that war, Germany had announced in 2022 that there are many places to import hydrogen like North Africa, Ukraine and even Russia. German-Russia Resource Forum which was set up by academics from each country claimed that Nord Stream 2 pipeline can transport green hydrogen from Russia. There is also a significant blue hydrogen production potential in Russia by having extensive natural gas reserves.[166]

Germany also can take more proactive action to stabilize countries in foreign affairs. For example, Libya has abundant solar power potential. Hydrogen produced in this country can be exported to the Germany via pipelines. However, the main obstacle is that Libya has not stable domestic political landscape to attract investment. There are civil conflicts and weak institutions. Germany can take a significant action, especially with the EU to stabilize this country and make it green hydrogen exporter to the Europea.[167]

5.5 Conclusion

This chapter discussed Germany's hydrogen framework, projects, import plans and contribution of the hydrogen into the short term hydrogen targets.

Germany represents one of the most ambitious states in the global energy transition. Through its Energiewende, launched in the early 2000s, Germany has sought to fundamentally restructure its energy system by phasing out nuclear power and coal, reducing dependence on fossil fuels and expanding renewable energy. This

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[166] Arunabha Ghosh ve Sanjana Chhabra, Case for a Global Hydrogen Alliance, CEEW The Council, 2021, p.26.

[167] Libya Review, Libya Explores Major Green Hydrogen Investment with H2 Global, 2025, https://libyareview.com/58348/libya-explores-major-green-hydrogen-investment-with-h2-global/

commitment has positioned Germany as a leader in both technological innovation and policy experimentation in the field of energy transition.

A central element of Germany's hydrogen pathway is its National Hydrogen Strategy, adopted in 2020 and updated in 2023. This strategy recognizes green hydrogen as core for reaching carbon neutrality by 2045. In that regard, there are many ongoing projects in green hydrogen and they are not only production ones but ranges from transportation to application ones. However, Germany's domestic green hydrogen production potential is limited. Even, announced hydrogen production capacities will not maintain the country's 2030 NDC and hydrogen targets. This indicates that clean hydrogen will not be able to meet Germany's short term energy transition goals.

However, for the long term, hydrogen can contribute more to the German economy. Although Germany has limitation in domestic side, it officially declared its need for hydrogen import in its Hydrogen Import Strategy. Germany's hydrogen strategy for now is much more outward-looking, relying on the development of international supply chains. There are also many bilateral agreements signed with countries in Africa, Latin America and the Middle East.

In conclusion, Germany illustrates a country's dilemma as having too much renewable ambition and limited renewable potential. While geographical limitations restrict its ability to be self-sufficient in hydrogen, Germany's international cooperations and institutional leadership allow it to exert influence far beyond its borders. By combining domestic action with international cooperation, Germany strengthens its position as a central actor in the emerging hydrogen economy. From the perspective of neoliberal institutionalism, Germany demonstrates how states can leverage institutions, partnerships and standards to maintain energy security and reinforce its own strategic interests.

CHAPTER 6

TÜRKİYE

Türkiye, by having abundant renewable energy potential, can meet its domestic energy demand, decrease GHG emissions and can become hydrogen exporter or even importer. As being closer to the potential hydrogen market, the EU, Türkiye can facilitate hydrogen production and exports via pipeline or shipping in future.[168]

Rather than becoming a exporter, hydrogen poses also a great alternative for Türkiye's energy supply security. Türkiye is dependent on imported fossil fuels in its economy. Almost 85% of fossil fuels; natural gas, oil and coal; are imported from different countries especially from Russia, Azerbaijan and Iran. This forms a risky environment in terms of geopolitics. Although Türkiye is not involved in Russian-Ukraine War, it was affected from price fluctuations too much. For example, one of the leading prices of natural gas, TTF price has fluctuated, before crisis, it was 6-9 per MMBtu in 2021 and when the war erupted, this rose to 70 $ level in March 2022. Hydrogen may present Türkiye an advantageous energy solution which has lower cost than fossil fuel and energy sovereignty as well as contributing climate pledges of the country.[169]

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[168] Daily Sabah, Germany eyes green hydrogen transport from Türkiye via pipelines, 2023, https://www.dailysabah.com/business/energy/germany-eyes-green-hydrogen-transport-from-turkiye-via-pipelines

[169] Market Voice, Data Spotlight, 2022, https://www.fia.org/marketvoice/articles/data-spotlight-ttf-gas-futures-see-record-trading-amid-russia-related-turmoil

6.1 Energy Transition and Climate Pledges

Türkiye is the 17th biggest economy of the world with its $1,024 billion GDP for 2023. Real GDP has a growth rate 5.4% between 2002 and 2022 and so total energy supply has also increased 107% between same period.[170]

Majority of primary energy consumption of Türkiye is met by fossil fuels (81%). Türkiye has an importer country on fossil fuels. The level of fossil fuel usage shows that there is high amount of dependency in terms of energy supply. Türkiye is also the 14th country in the world in terms of energy import. Caused by extended fossil fuel usage, Türkiye's GHG emission level is 552 million tons CO2 equivalent in 2023.[171]

Table 6.1 Türkiye GHG Emissions by Sectors in 2023[172]

Sectors	**GHG Emissions**
Energy (Power, Heat, Transport)	395.4 Mt
Industry	70.9 Mt
Agriculture	71.8 Mt
Other	14 Mt
Total	552 Mt

Türkiye signed the Paris Agreement in 2016 and completed its ratification in 2021. As an obligation of the agreement, Türkiye submitted its NDC pledges in 2023. Türkiye targeted 41% reduction in GHG emissions by 2030 and implemented net zero target by 2053. Some authorities like Climate Action Tracker found this target

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[170] World Bank Türkiye, Türkiye Genel Bakış, 2025, ttps://www.worldbank.org/tr/country/turkey/overview#1

[171] TÜİK, GHG Emissions by Sector, 2024

[172] TÜİK, GHG Emissions by Sector, 2024

of Türkiye as insufficient because announced NDC lacks enforcement mechanisms and coal phase-out plans.[173] Moreover, there is already no comprehensive climate law in Türkiye. However, Türkiye's existing economic integration with EU and EU's latest policies force Türkiye to implement more decarbonization efforts. One of the policies of EU that effect Türkiye is Carbon Border Adjustment Mechanism. That mechanism is an EU border carbon pricing tool for imported products into the EU. Türkiye, as a major exporter country to the EU, will be affected from this mechanism. In January 2026, exporters from Türkiye will have to report their carbon emissions and buy CBAM certificates equal with European emission trading carbon price. It shows that EU is trying to increase energy transition not just inside itself but also for its partners.[174]

Although Türkiye has not clearly stressed concrete precautions for climate change under the scope of Paris Agreement, it has realized a significant renewable energy investment in last decades. In 2024, Türkiye's total installed power capacity has reached 111 GW and 56 GW of it is coming from renewables which is almost 50% of total. Moreover, solar power and wind power capacities increased 17.9 GW and 14 GW. Türkiye has made clean manufacturing investments also. There are almost 75 solar module manufacturers and 3 solar-cell factories domestically. In wind power, there are 150 manufacturers and 65% of the wind power value chain is met by domestic production.[175]

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[173] Climate Action Tracker, Türkiye, 2025, https://climateactiontracker.org/countries/turkey/2024-11-12

[174] Türkiye Cumhuriyeti Ticaret Bakanlığı, AB Sınırda karbon Düzenleme Mekanizması, 2025, pp.3-4.

[175] Tracker, "Türkiye"

6.2 Overview of the Türkiye Clean Hydrogen

This section discusses Türkiye's political, technological, financial and international efforts to use clean hydrogen. It is evaluated that whether Türkiye will be able to achieve to meet short-term climate targets by using clean hydrogen.

6.2.1 Policy and Strategy Documents

One of the most important political documents is "National Hydrogen Technologies Strategy and Roadmap" which was published in 2023 by Ministry of Energy and Natural Resources. There are two main targets in this document. First one is reducing the cost of clean hydrogen less than 2.4$ per kg by 2035 and 1.2$ per kg by 2053. One of the main assumptions to meet this cost decrease target is that Türkiye has abundant renewable energy potential. And also it is asserted that cost decrease will be achieved by economies of scale, which by deploying electrolyzers in big scale. The second main target of the document is that electrolyzer installed power capacity to be 2 GW by 2030, 5 GW by 2035 and 70 GW by 2053. There are twenty proposed solutions in this roadmap to achieve above cost and production capacity targets. However, majortiy of these solutions, almost fifteen of them are not for settting up a large-scale, new energy ecosystem as wee see in the USA and Germany national plans. They rather for developing domestic technology activities. There are no detailed plan to decarbonize GHG emitters like industry and transportation. Although there is a target also for exporting hydrogen especially to the European markets, details are not clearly identified. Moreover, three types of clean hydrogen ar assumed to be used; green, blue and biofuel hydrogen. [176]

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[176] Republic of Türkiye Ministry of Energy and Natural Resources, Türkiye Hydrogen Technologies Strategy and Roadmap, 2023, p.1.

6.2.2 Production

Türkiye lacks large scale clean hydrogen production although it has significant potential due to its expanding renewable electricity base. The largest operational hydrogen facility is a 0.2 MW electrolyzer at Enerjisa's Bandırma plant, with additional micro-scale applications.[177] There is also South Marmara hydrogen Valley project that has taken EU grant, but it has not started operations yet. Those samples have very little production capacities compared with USA and Germany ones. Türkiye's clean hydrogen production is not in commercial stage yet.[178]

Studies estimate that Türkiye's renewable energy resources remain significantly underutilized. Wind power, for instance, has a considerable untapped capacity, only 12.6 GW has been installed out of a total estimated potential of 48 GW. The opportunity in solar energy is even more striking, with a technical potential of approximately 380 TWh per year, which could theoretically cover the country's entire current electricity consumption. Despite being the fourth-largest geothermal energy producer globally, Türkiye is utilizing just 38% of its estimated 4.5 GW geothermal potential. This comparison underscores that despite its favorable geographical conditions and abundant natural resources; Türkiye has implemented only a small portion of its renewable potential. Türkiye stands at a critical juncture in which renewable energy deployment could substantially strengthen its role in the global energy transition.[179]

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[177] FCV, Turkey: Enerjisa Üretim Started Green Hydrogen Production at Bandırma Energy Base, 2022, https://fuelcellsworks.com/news/turkey-enerjisa-uretim-started-green-hydrogen-production-at-bandirma-energy-base

[178] HySouth Marmara, Türkiye's First hydrogen Valley Project, 2025, https://hysouthmarmara.org/en

[179] Oguzhan Gulaydin and Monjur Mourshed, Net-zero Turkey: Renewable energy potential and implementation challenges, 2025, p.12.

According to Shura, Türkiye can produce up to 3.4 million tons green bydrogen by 2053. With using in domestic sectors like industry and transportation, domestic demand may reach to 1,9 million tons by 2050. After meeting domestic demand, Türkiye can export additional amount of production which is approximately 1.5 million tons. To reach that production level, Türkiye has to spend 3,4 billion $ every year until 2050 and the annual revenue expected for 2050 is 6-8 billion $.[180]

The realization of Türkiye's renewable energy potential into competitive hydrogen production will depend not only on domestic development but also on the degree of international cooperation in technology transfer, financing and market integration. Türkiye possesses abundant solar and wind resources, particularly in its southern and western regions, making it a natural candidate for green hydrogen production in future.[181] However, large-scale hydrogen production can only be started if hydrogen value chain elements have developed enough. Otherwise, any development in production stage would be useless. For now, Türkiye lacks advanced electrolyzers, hydrogen-ready grids and international certification schemes. In this context, cooperation with the international actors is critical.[182]

6.2.3 Transportation

Türkiye has already no operational hydrogen pipeline network and port facilities to export/import hydrogen. Compared to Germany and the United States, Türkiye's hydrogen transportation infrastructure remains at a nascent stage, underscoring its reliance on external cooperation for technical design and investment. Major development in terms of transportation of hydrogen in Türkiye is that natural gas

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[180] Shura, Türkiye'nin yeşil hidrojen üretim ve ihracat potansiyelinin teknik ve ekonomik açıdan değerlendirilmesi, 2021, p.8.

[181] Gulaydin and Mourshed, Net-zero Turkey, p.12.

[182] Shura, Türkiye, p.71.

transmission system operator of Türkiye, BOTAŞ has taken IPA-3 project of EU that is $3 million grant for a technical assistance project. Project name is “Boosting Green and Low Carbon Hydrogen in Türkiye”. Under the scope of the project, BOTAŞ natural gas pipelines will be analyzed to forecast whether they are suitable for hydrogen carrying or not. Moreover, hydrogen pipeline master network plan will be designed for Türkiye integrating potential customers and supply areas. Project implementation agenda is between 2026-2029.[183] There is also a pilot study of Gazbir-Gazmer on hydrogen blending in natural gas distribution pipelines. Distribution pipelines are smaller when compared with transmission lines which are bigger in size and pressure. Under study, successful results was handled in blending up to 20% hydrogen into the natural gas distribution pipelines is possible. This early-stage position means that Türkiye’s future hydrogen transport capacity will depend heavily on technology transfer, financing and standardization agreements with external partners, particularly within the EU framework.[184]

The EU also has many international hydrogen projects and Türkiye is one of the candidates to make such transportation projects in future. One example is H2med project which was designed to connect Iberian Peninsula and Northwest Europe. This initiative was launched by France, Spain and Portugal and has taken significant support from Germany. This international transportation project is scheduled to start by 2030. This project has also entered to the list of Projects of Common Interest of the EU in 2024. The other sample project for Türkiye is SoutH2 project which was designed to connect North African hydrogen production with Europe with a 3,300 km offshore hydrogen pipeline. The main importers will be Italy, Austria and

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[183] Republic of Türkiye Ministry of Foreign Affairs Directorate for EU Affairs, Boosting Green and Low Carbon Hydrogen in Türkiye, 2025, https://www.ab.gov.tr/boosting-green-and-low-carbon-hydrogen-in-turkiye_54071_en.html

[184] Anadolu Ajansı, Türkiye'nin İlk Hidrojen Köyü HyVillage Yolda, 2023, https://www.aa.com.tr/tr/ekonomi/turkiyenin-ilk-hidrojen-koyu-hyvillage-yolda/2799895

Germany. This project also accepted by EU under PCI list. All these projects are sign of the European countries to import and use clean hydrogen.[185]

6.2.4 Storage

In the hydrogen value chain, large-scale storage facilities function as strategic buffer between fluctuating production and demand. As renewable energy sources are intermittent in a day, it is crucial to store hydrogen and then service it to the end users when there is demand. In that regard, storage sites present seasonal balancing, supply security and price stability for countries. Türkiye has already no large-scale hydrogen site, but technical studies are ongoing. Under the scope of EU IPA-3 "Boosting Green and Low Carbon Hydrogen in Türkiye" project, there will be feasibility study for hydrogen storage in BOTAŞ' underground natural gas storage sites which are Salt Lake (salt cavern) and Silivri (depleted reserve). Conditions of hydrogen storage will be assessed technically and economically. Ideal parameters will be designed for an underground storage.[186]

6.2.5 Application

Türkiye also has some technology development projects in hydrogen. For instance, Karsan, which is a Turkish car company, has developed e-ATA hydrogen bus.[187] Otokar company has developed "KENT Hidrojen" bus which can go 500 km with one filled tank. Although there are significant developments in application in Türkiye, these technologies are not used in a wider respect because Türkiye lacks

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[185] H2Med, The H2Med Project, 2025, https://h2medproject.com/the-h2med-project/

[186] Republic of Türkiye, Boosting Green Hydrogen

[187] Karsan, e-Ata 10, 2025, https://www.karsan.com/tr/100-elektrikli/e-ata-10

clean hydrogen supply, refueling infrastructure and regulartory rules for the market. Transportation sector, especially long-distance transportation is of critical importance in Türkiye's international trade.[188] In industry, sector has shown their ambition for hydrogen but there is still no large scale usage but there are initial tests. For example, in 2024, Erdemir, which is a significant iron-stell producer, made a hydrogen injection test in steel-iron blast furnace. It was approved that hydrogen can be used in all Erdemir iron-steel facilities and that can reduce carbon emission by 15%. However these projects remain either at the prototype or single-site demonstration stage lacking industrial-scale manufacturing yet.[189]

The implementation of the EU's Carbon Border Adjustment Mechanism (CBAM) in 2026 represents not only a regulatory challenge but also a strategic opportunity for Türkiye's carbon-intensive industries to use clean hydrogen. CBAM places a carbon price on imports and eventually it fosters the energy transition. It is a beneficial tool to lessen carbon leakages, encourage technical advancement and makes money for green projects. It will be a force that attract Türkiye's industry to implement more renewable measures like hydrogen.[190]

6.3 International Cooperation

Türkiye's international cooperation on hydrogen is still in emerging phase. There are significant gaps when compared with other countries. Without resolving the disputes in foreign affairs, Türkiye's hydrogen potential can be locked. Maritime disputes in the Eastern Mediterranean, tensions with the EU over CBAM and customs union

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[188] Otokar, Kent Hidrojen, 2025, https://commercial.otokar.com.tr/otobus/sehir-ici-otobus/kent-hidrojen

[189] Erdemir, Erdemir'den Yeşil çelik için Dev Adım, 2024, https://www.erdemir.com.tr/kurumsal/medya/basin-bultenleri/erdemirden-yesil-celik-icin-dev-adim

[190] Taniya Choudhury, Anupam Tiwari and Rakshit Jakhar, Beyond Borders: CBAM's Revolutionary Potential and Challenges in Achieving Carbon Neutrality, 2024, p.14.

reform or frictions with regional neighbors create uncertainty for long-term investments. Solving the problems in outside and setting a more collaborative international frameworks will foster the hydrogen ecosystem in many ways.[191]

First, Türkiye has no binding offtake export agreement for hydrogen yet and successful international hydrogen policy can unlock it. There is a significant hydrogen demand especially in the EU. The EU has declared REPowerEU plan including the EU Commission's target for 10-million-ton domestic hydrogen production and 10 million tone hydrogen export by 2030 to replace fossil fuels.[192] To realize it, the EU is making significant efforts like setting a European Hydrogen Bank, giving grants for renewable hydrogen projects. Its main target is close the investment gap and enable Europe to use 20 million tons hydrogen by 2030. This bank not only concentrates on domestic production projects but also concentrates on import projects. Within this framework, Türkiye has a unique position to become an exporter to the EU.[193]

There are also many public and private finance options internationally and Türkiye can take them to finance its hydrogen ecosystem. For example, with a successful engagement and concrete projects, EU Hydrogen Bank and PCI grants can be taken. There are also other international institutions like World Bank and EBRD that finance energy transition projects. For instance, EBRD has prepared a report called "Low Carbon Hydrogen Economy in Türkiye" and assert that Türkiye has a better position than Germany and Finance in terms of hydrogen cost, and it can produce hydrogen with 2.9 Euro per kg by 2030. According to EBRD, Türkiye can use clean hydrogen to meet both domestic demand and to become an exporter. The positive

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[191] Arda Özkan and Levent Kırval, Continuity of Maritime Disputes in Turkish Foreign Policy in Retrospect, Uluslararası İlişkiler, 2023, p.17.

[192] European Union, REPowerEU Plan, 2022

[193] European Commission, European Hydrogen Bank, 2023, p.2.

studies about Türkiye's clean hydrogen position which were made by international funding institutions show that any project ranging from production to transportation have a great chance to take necessary financial support.[194]

Another element that international cooperations can utilize is technology and innovation. Türkiye has an ongoing scientific and technological improvement, but this is not enough as compared with other countries. Technology diplomacy refers to the international partnerships to gain access to the new technologies in electrolyzer, fuel cells, transportation, storage and green ammonia. Türkiye can sign bilateral agreements with technology leader countries in hydrogen like Germany, Japan, USA and Netherlands. In addition, it can take place in international frameworks like IEA's Hydrogen Technology Collaboration Program. With these ways, Türkiye can close the existing technological gap easily and become competitive in new energy geopolitics.[195]

To foster hydrogen ramp-up, Türkiye should resolve the existing international disputes with its potential partners. Although technical cooperation projects are ongoing such as IPA and Horizon Europe projects, there is stalled accession process and disputes over general EU reforms. As a result, the pace of cooperation is ongoing just on technical cooperation rather than long-term, trade-based cooperation. Relationships should be forwarded by export offtake agreements, certification schemes and standards development.[196]

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[194] EBRD, Low Carbon Hydrogen Economy in Türkiye, 2025, p.6.

[195] IEA, Technology Colloboration Programme, 2025, https://www.iea.org/programmes/technology-collaboration-programme

[196] European Parliament, Türkiye's EU Accession Process Must be Frozen, 2025, https://www.europarl.europa.eu/news/en/press-room/20250502IPR28215/turkiye-s-eu-accession-process-must-remain-frozen

Another candidate to cooperate in hydrogen is Iraq. The Iraq government announced that they will set up 12 GW electrolyzer by 2030, which will be supported by abundant solar potential of Iraq. Türkiye has an issue of Iraqi-Türkiye Crude Oil Pipeline problem that arises from the claims of the central government of Iraq and the Kurdistan region. In July 2025, Türkiye has announced the termination of the oil transportation agreement from this pipeline that will be valid in 2026. Resolution of problems may open a new page in terms of hydrogen cooperation with the Middle East countries like Iraq.[197]

6.4 Conclusion

In this chapter, Türkiye's energy transition targets and clean hydrogen potential were presented. Clean hydrogen framework in Türkiye was analyzed according to documents such as National Hydrogen Strategies and Technologies Roadmap, NDC and technical reports on hydrogen potential.

Türkiye has submitted its NDC, targeted 41% GHG reduction by 2030 and net-zero by 2053. Moreover, in hydrogen, it targeted to set up 2 GW electrolyzer by 2030. However, Türkiye has no large-scale hydrogen production projects but only has small capacity, pilot projects. This indicates that clean hydrogen will not able to contribute Türkiye's short term energy transition target.

Although Türkiye lacks clean hydrogen infrastructure for now, it has a significant potential for future. There is a significant number of untapped renewable energy capacity. Moreover, Türkiye's international cooperation on hydrogen is still in its early phase. Maritime disputes in the Eastern Mediterranean, tensions with the EU over the Carbon Border Adjustment Mechanism and other reforms form uncertainty

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[197] FCV, Iraq Explores Green Hydrogen Development in New Clean Energy Initiative, 2025, https://fuelcellsworks.com/2025/07/31/clean-energy/iraq-explores-green-hydrogen-development-in-new-clean-energy-initiative

for long-term investment. At the same time, the EU’s REPowerEU plan, which targets 10 million tons of hydrogen import by 2030, provides Türkiye a unique export opportunity. Instruments such as the European Hydrogen Bank, PCI grants, and funding from institutions like the World Bank and EBRD could help finance Türkiye’s hydrogen ecosystem.

In sum, Türkiye’s hydrogen landscape is based on strong natural potential, but its success will depend on overcoming international disputes, deepening cooperation with the partners like the EU and mobilizing international finance.

CHAPTER 7

CONCLUSION

The primary aim of this thesis is to investigate which factor plays the most decisive role in unlocking the potential of clean hydrogen in the global energy transition, through a comparative analysis of the USA, Germany, and Türkiye. Although significant progress has been made in political commitment, technological innovation and financial mobilization to make clean hydrogen feasible, affordable, and accessible, its maturity as a scalable solution remains limited compared to wind and solar energy. As a result, uncertainties persist regarding hydrogen's contribution to achieving global climate targets. While advancements in technology, finance, and regulatory frameworks are essential, this study argues that the most critical leverage for accelerating clean hydrogen deployment lies in international cooperation and the resolution of interstate disputes.

As indicated in the second chapter of the thesis, energy transition is a systematic change that affects the whole energy system and takes at least one or two decades in best case. Without an integrated development in all areas of the value chain, hydrogen may have a risk to be a niche solution. Moreover, there is an urgent need for faster decarbonization and transition to low carbon economy with the increasing threat coming from the climate change. In that regard, making hydrogen an affordable and sustainable energy solution is one of the immediate priorities of the world today. However, such transition cannot be realized through isolated national efforts. The successful integration of the energy transition solutions fundamentally depends on robust international cooperation, coordinated governance mechanisms like Paris Agreement and the resolution of geopolitical constraints that currently hinder cross-border collaboration.

The USA represents a case of both opportunity and limitation in the global hydrogen transition. Domestically, it has enacted significant policies, most notably the Inflation Reduction Act, and mobilized large-scale federal funding to accelerate investment in hydrogen technologies. These initiatives provide a strong financial and technological foundation for clean hydrogen development and demonstrate the country's capacity to drive innovation. However, the volatility of political support for renewable energy, evident during the Trump administration, forms uncertainty regarding the long-term stability of the USA decarbonization policies.

Despite its geographic scale, advanced technological capabilities and financial strength, the USA has thus far remained relatively inward-looking in its hydrogen strategy. Unlike Germany, which has proactively engaged in hydrogen diplomacy through bilateral partnerships and EU-led initiatives, the USA has emphasized industrial competitiveness and domestic deployment. Its limited engagement in shaping international certification schemes, trade rules, and cooperative governance frameworks weakens its influence in the emerging global hydrogen economy. Nevertheless, the USA has the potential to assume a leading role. With abundant renewable resources, world-class research institutions and advanced industrial capacity, the USA is well positioned to become a frontrunner in clean hydrogen production. To translate domestic progress into global leadership, however, it must adopt a more outward-looking approach. Strengthened international cooperation, participation in global governance institutions, and resolution of trade frictions are essential if the USA is to leverage its domestic advances into lasting international influence. In sum, the USA case highlights both the possibilities and the constraints of a nationally driven hydrogen strategy. While large-scale domestic incentives are indispensable, they are insufficient in isolation. The success of hydrogen as a cornerstone of the energy transition depends on institutionalized cooperation and multilateral engagement. The USA will therefore need to move beyond its domestic focus and actively contribute to shaping the partnerships, standards, and institutions that underpin the global hydrogen economy.

Germany provides an important case of both ambition and constraint in the global hydrogen transition. Through its Energiewende, launched in the early 2000s, Germany has pursued one of the most comprehensive national strategies for transforming its energy system by phasing out nuclear and coal, reducing reliance on fossil fuels, and expanding renewable energy. This long-term commitment has positioned Germany as a leader in climate policy innovation and technological deployment. Yet, despite this ambition, Germany faces clear structural limitations in achieving its near-term hydrogen and decarbonization goals. Even with announced capacities, domestic production will not be sufficient to meet its 2030 NDC and short-term hydrogen targets. Recognizing these constraints, Germany has placed international cooperation at the center of its hydrogen strategy. The National Hydrogen Strategy and the Hydrogen Import Strategy emphasize green hydrogen as a cornerstone of its pathway to carbon neutrality by 2045, while explicitly acknowledging the need for large-scale imports. Germany has already signed multiple bilateral agreements with countries in Africa, Latin America, and the Middle East and has been instrumental in shaping EU initiatives such as the European Hydrogen Backbone and certification schemes. These actions demonstrate how Germany compensates for limited domestic potential by leveraging its diplomatic and institutional leadership to embed itself at the center of the global hydrogen economy.

In conclusion, Germany exemplifies the structural dilemma of a highly ambitious country with insufficient renewable potential to achieve full self-sufficiency. While its domestic capacity is constrained, its proactive diplomacy, institutional influence, and integration into the European Union’s energy governance structures ensure that it remains a central actor in shaping global hydrogen markets. From a neoliberal institutionalist perspective, Germany illustrates how states can use partnerships, standards and institutions not only to safeguard energy security but also to extend their strategic influence beyond their own borders.

Türkiye represents a case where strong natural potential contrasts with limited current capacity in the hydrogen transition. National policy documents, including the Hydrogen Technologies Strategy and Roadmap and the updated NDC, outline targets of a 41% GHG reduction by 2030 and achieving net-zero emissions by 2053, alongside the installation of 2 GW of electrolyzer capacity by 2030. However, progress to date has been modest, with only small-scale pilot projects are underway and no large-scale hydrogen production in operation. As such, clean hydrogen is unlikely to make a substantial contribution to Türkiye's short-term energy transition goals. Looking forward, Türkiye's prospects are considerably stronger. The country possesses significant untapped renewable energy resources and a strategic geographical position between Europe, the Middle East and Asia. These advantages could allow Türkiye to become a future hydrogen center. Yet, its international engagement on hydrogen remains underdeveloped and is complicated by ongoing disputes in the Eastern Mediterranean, tensions with the EU over the Carbon Border Adjustment Mechanism and broader regional frictions. At the same time, the EU's REPowerEU plan, which includes an import target of 10 million tons of hydrogen by 2030, presents Türkiye with a major export opportunity. Financial instruments such as the European Hydrogen Bank, PCI grants and funding from international institutions like the World Bank and EBRD could play a crucial role in enabling Türkiye to realize this potential.

In conclusion, Türkiye's hydrogen pathway demonstrates the gap between resource potential and institutional capacity. While abundant renewables provide the technical foundation for hydrogen development, success will ultimately depend on overcoming geopolitical disputes, aligning more closely with the EU's energy framework and securing international finance. From a neoliberal institutionalist perspective, Türkiye's case underlines that clean hydrogen transitions in emerging economies require not only domestic ambition but also sustained participation in cooperative frameworks and multilateral governance structures.

The comparative analysis of the USA, Germany, and Türkiye reveals different approaches to hydrogen, shaped by each country's geopolitical positioning, institutional priorities and level of international engagement. Germany has proactively pursued international hydrogen partnerships with countries such as Egypt and Chile, reflecting its strategy to import hydrogen by 2030 while maintaining technological leadership and regulatory influence within the EU. Türkiye, with its strategic geography and growing renewable capacity, positions itself as a potential hydrogen production center however, its progress remains contingent on aligning with European energy frameworks, resolving regional political frictions and reaching international finance options. In contrast, the USA has largely focused on domestic production incentives through programs like the Inflation Reduction Act, but its limited international integration into emerging hydrogen value chains especially with potential partners such as the EU, Mexico, and China risks isolating it in the global hydrogen economy. This divergence underscores that international cooperation and conflict resolution are central determinants in the scaling of national hydrogen strategies.

The findings of this thesis suggest that countries must prioritize international relations, conflict resolution and international cooperation to fully realize clean hydrogen's role in the energy transition. National technological and financing efforts, while necessary, are insufficient in the absence of stable international frameworks that facilitate cross-border trade. Policymakers should shift from domestic strategies toward multilateral approaches that enable coordination among international hydrogen producers and consumers. This includes establishing bilateral and regional hydrogen agreements, supporting platforms like the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). For countries like Türkiye, aligning with the EU energy landscape and resolving regional disputes can unlock its potential as a hydrogen power. Moreover, Germany's existing hydrogen diplomacy demonstrates the value of early international action, while the USA should reassess its inward-looking focus to avoid marginalization from emerging international hydrogen scheme. To conclude, enabling clean hydrogen as a viable energy transition solution requires countries to treat it not just as a technology or an incentivized subject, but as a solution that must be enhanced internationally.

In conclusion, this thesis affirms that the future of clean hydrogen to become an energy transition solution is not solely a function of technological readiness or financial capacity but fundamentally a subject of international cooperation. As a globally tradable energy carrier, hydrogen demands cooperative governance structures. The comparative cases of the USA, Germany and Türkiye reveal that domestic ambition and developments, while necessary, is ultimately constrained and reaching 2030 Paris Agreement and national hydrogen targets by 2030 is too hard. From a neoliberal institutionalist framework, the success of hydrogen as a pillar of the global energy transition will depend on the formation of international cooperation, institutions and resolution of inter-state disputes. Without successful international relations, hydrogen will remain a fragmented solution and cannot decarbonize the energy system as expected from it.

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