Master's Thesis

Multi-Criteria Evaluation of Hydrogen Supply Paths

Multikriterielle Evaluation von Wasserstoffbereitstellungspfaden

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Abstract

According to Germany's National Hydrogen Strategy, hydrogen will be a key component of Germany's energy transition. As future demand will not be met from domestic production, an international supply chain has to be created. This thesis asks how Germany can prepare for an international hydrogen supply and how it is already doing so. With its financial capacity, international institutional network and reputation as a pioneer in the energy transition, Germany has power resources that it can draw on in the market ramp up. In the analysis of this paper these resources are structured along the Smart Power concept by Joseph S. Nye. A quantitative ecological and economic analysis of hydrogen supply paths from four energy partner countries shows how Germany is already building measures on these resources today and where these measures specifically address the supply chain. The results indicate that Germany is active at various levels to reduce costs and the ecological footprint. The energy partnerships are used as a platform to bring the different parties and players together and to support the partner countries in developing strategies. Furthermore, the analysis finds that the measures have repercussions on the power resources themselves and that they are reinforcing them.

Kurzzusammenfassung

Laut der Nationalen Wasserstoffstrategie wird Wasserstoff ein Schlüsselelement der Energiewende in Deutschland sein. Da der zukünftige Bedarf nicht aus heimischer Produktion gedeckt wird, soll ein internationaler Markt geschaffen werden. In dieser Arbeit wird der Frage nachgegangen, wie sich Deutschland auf eine internationale Wasserstoffversorgung vorbereitet und welche Maßnahmen darüber hinaus sinnvoll sind. Mit seiner Finanzkraft, seinem internationalen institutionellen Netzwerk und seinem Ruf als Vorreiter der Energiewende verfügt Deutschland über Machtressourcen, auf die es bei der Etablierung eines Marktes zurückgreifen kann. In der Analyse werden diese Ressourcen entlang des Smart Power Konzepts von Joseph S. Nye strukturiert. Eine quantitative ökologische und ökonomische Analyse von Wasserstoffversorgungspfaden aus vier Energiepartnerländern zeigt, wie Deutschland bereits heute Maßnahmen auf diesen Machtressourcen aufbaut und welche Aspekte der Bereitstellung von Maßnahmen adressiert werden. Aus den Ergebnissen ist weiterhin ersichtlich, dass Deutschland bereits auf verschiedenen Ebenen aktiv ist, um die Kosten und den ökologischen Fußabdruck zu reduzieren. Gleichzeitig, werden die Energiepartnerschaften als Plattform genutzt, um die Partnerländer bei der Gestaltung von Strategien zu unterstützen und Akteure aus der Wirtschaft zusammenzubringen. Darüber hinaus zeigt die Analyse, dass die Maßnahmen auf die Machtressourcen selbst zurückwirken und diese stärken.

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Aufgabenstellung
Master´s Thesis
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Multi-criteria evaluation of hydrogen supply paths

Multikriterielle Evaluation von Wasserstoffbereitstellungspfaden

Climate change mitigation and therefore the transition to a sustainable supply and use of energy is one of the greatest challenges of our time. In recent months, hydrogen has taken over the public debate and is now recognized as an essential pillar for the energy transition. As stated in the national hydrogen strategy of the German Federal Government, “hydrogen technologies should establish themselves as core elements of the energy transition”. As the energy carrier of the future, the demand for hydrogen is expected to increase strongly. Therefore, the supply will be an enormous challenge.

Within the scope of the master thesis, different supply paths of hydrogen are evaluated from a German perspective. The possibilities for Germany to prepare for a climate-neutral hydrogen supply are to be sorted and analyzed along the concept of smart power by Joseph S. Nye. The central component is a Life Cycle Assessment (LCA), but technical, economic and political criteria are also examined. Based on the analysis, measures and effects will be discussed.

In the course of the master thesis, the following research questions are answered through analysis in four use cases:

- How can Germany prepare for an advantageous hydrogen supply applying the smart power concept by Joseph S. Nye?
- What does smart power mean in the context of hydrogen supply and how do hydrogen dynamics affect Gemany’s smart power?
- What are the supply costs of hydrogen and what is the resulting cost structure?
- What is the ecological footprint of hydrogen? What are the main drivers?
- Which measures are and can be used to secure hydrogen supply by Germany?

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Declaration of Authorship

I hereby confirm that I have written the present thesis, submitted with the title

Multi-Criteria Evaluation of Hydrogen Supply Paths

independently. Thoughts and quotations which I have taken directly or indirectly from external sources are marked as such. This paper has not yet been submitted to any examination board in the same or similar form and has not been published yet. The work may be published by the chair of Energy Economy and Application Technology or the Research Center for Energy Economics (FfE).

_______________, _______________ ____________________

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Abbreviations

AnF annuity factor

AEL alkaline water electrolysis

ASU air separation unit

ATR autothermal reforming

CAPEX capital expenditure

CCfD carbon contracts for difference

CCS carbon capture and storage

EP energy partnership

EU European Union

EU ETS European Emission Trading System

FfE Forschungsstelle für Energiewirtschaft

FLH full load hours

GDP gross domestic product

GHG green house gas

GIZ German Agency for International Co-operation

GWP100 global warming potential with a time horizon of 100 years

HHV higher heating value of hydrogen

IPCEI Important Project of Common European Interest

IRENA International Renewable Energy Agency

IRESEN Moroccan Research Institute for Solar Energy and New Energies

KfW Germany's Development Bank

LCA Life Cycle Assessment

LCOE levelized costs of electricity

LCOH levelized costs of hydrogen

$LCOH_{deliv}$ levelized costs of delivered hydrogen

$LCOH_{prod}$ levelized costs of hydrogen production

LCOT levelized costs of hydrogen transport

LH_2 liquified hydrogen

LHV lower heating value of hydrogen

LHVa lower heating value of ammonia

LOHC liquid organic hydrogen carrier

NGR natural gas reforming

NH_3 ammonia

NHS National Hydrogen Strategy

ODA Official Development Assistance

OECD Organisation for Economic Co-operation and Development

OPEX operational expenditure

PAREMA German-Moroccan Energy Partnership

PEM polymer electrolyte membrane electrolysis

PSA pressure swing absorption

PV photovoltaic

RES renewable energy source

WGS water gas shift section

SMR steam methane reforming

SOEC solid oxide electrolyzer cell

UAE United Arab Emirates

UN United Nations

UNFCCC United Nations Framework Convetion on Climate Change

USA United States of America

WACC weighted average cost of capital

1 Introduction

"Hydrogen will play a key role in enhancing and completing the [German] energy transition." /BMWI-05 20/

The National Hydrogen Strategy (NHS) of Germany puts into words what the public debate of recent months suggests: hydrogen will evolve into the central energy carrier of a German climate-neutral society. This thesis asks how Germany can prepare for a secure international hydrogen supply using the concept of Smart Power by Joseph Nye /COFR-01 09/ and takes a comprehensive approach to analyze economic, ecological and institutional dimensions of hydrogen supply. In the course of this analysis, first, the implications for Germany's Smart Power through an emerging hydrogen economy will be discussed. Second, economic and ecological dimensions of hydrogen supply are analyzed quantitatively in four cases considering institutional aspects as well. Third, based on the results of the analysis, measures already applied by Germany are described and suggestions for further measures are outlined. This first chapter lays out the motivation and poses the research question, which will be answered in the course of this handwork. Further, the structure of this thesis is explained.

1.1 Motivation

In 2020, hydrogen not only reached the public awareness, but conquered the political agenda. In the NHS, the German government acknowledged the outstanding position of hydrogen in climate neutral societies /BMWI-05 20/. Germany is complying with the European Union (EU), which declared hydrogen as a "key priority" in the European Green Deal /EUROSTAT-03 20/. According to Hydrogen Europe, the energy carrier will replace fossil-based fuels and therefore will be promoted as Important Project of Common European Interest (IPCEI). A consensus is emerging in the political landscape that hydrogen will take on key tasks in many sectors, from energy production, storage and distribution to end-uses in transport, industry, heating and more /HEID-01 20/. This political support is in line with the energy industry. The energy industry news messenger Energate published more than 700 news related to hydrogen in 2020 /ENERG-01 21/. Hydrogen grew to an ubiquitous topic.

However, in Germany, hydrogen promises a path to climate neutrality with a big gap on the supply side. The think tank Agora Energiewende forecasts a demand of 268 TWh carbon-free hydrogen for a climate-neutral Germany in 2050, which corresponds to 15 % of the total primary consumption /AGORA-07 20/. The current hydrogen consumption in Germany is at 55 TWh /BMWI-05 20/. The supply chain today is mainly based on natural gas. In 2050 in contrast, only carbon free and green hydrogen can be combined with the concept climate neutrality. Therefore, a market for green hydrogen has to evolve from the scratch. It is not expected that this sharp growth in demand for green hydrogen can be met by hydrogen production only in Germany. Hence, international supply chains are supposed to cover the gap. /BMWI-05 20/

Germany has the unique opportunity to actively shape its future energy supply. In doing so, Germany can draw on resources it has already built up in the course of its energy transition. In the promotion of renewable electricity, Germany established a reputation as a pioneer in the energy transition /IASS-01 20/. Additionally, an international institutional framework was laid out in order to build partnerships in developing sustainable technology and harmonize a regulatory framework. Furthermore, Germany is ready to invest in significant orders of magnitude. Looking forward, Germany could use those resource of power in order to prepare for a sustainable hydrogen supply.

Conversely, hydrogen also offers Germany the opportunity to not only use its power resources, but also to expand and stabilize them. The relationship between hydrogen and Germany's power resources is not uni-directional. From power resources, effective measures can be derived in order to promote hydrogen technologies. But also the other way around, power resources could be strengthened by a successful implementation of a hydrogen economy.

This thesis argues that Smart Power by Joseph Nye /COFR-01 09/ is a useful concept to analyse Germany's measures to prepare for a hydrogen supply. The rise of hydrogen connects climate protection with economic opportunities and geostrategic deliberations. The concept of Smart Power bridges these dimensions and helps to evaluate possible supply pathways and measures. According to Joseph Nye, power is "the ability to influence the behavior of others to get the outcomes one wants" /NYE-01 04/. In the analysis of this thesis, the desired outcome is an international supply of green hydrogen by 2050, favorable for Germany. Germany as a key player intelligently combines the use of Hard Power and Soft Power, which corresponds to Smart Power, to approach the outcome as close as possible.

Hence, this work first draws the meanings of Germany's Smart Power in the context of its energy transition considering the new dynamics of hydrogen, second lays out data based techno-economical, institutional and ecological analysis, and third discusses concrete measures that are and can be used to secure hydrogen supply. In the course of this analysis following research questions are answered.

1.2 Research Question

To meet the enormous demand for hydrogen in 2050, many stops will have to be pulled out. Germany as a state can use a multitude of tools. To adequately address the complexity of hydrogen production pathways, this thesis structures the analysis along the Smart Power framework by Joseph S. Nye and addresses the following research question:

- How can Germany prepare for an advantageous hydrogen supply applying the Smart Power concept by Jospeh S. Nye?

The concept is setting the scene on a wide area. Therefore, a set of research sub-questions is formulated:

- What does Smart Power mean in the context of hydrogen supply and how do hydrogen dynamics affect Germany's Smart Power?
- What are the supply costs of hydrogen and what is the resulting cost structure?
- What is the ecological footprint of hydrogen? What are the main drivers?
- What measures are and can be used to secure hydrogen supply by Germany?

In order to answer these questions, first, terms and concepts of power are explained. The history of Germany's power resources in the energy sector is reviewed. This is followed by an analysis of how those resources are evolving under the dynamics of hydrogen. Second, four energy partnerships are selected in order to perform an economical and ecological evaluation on the possible supply paths. Third, based on the results, conclusions are drawn on the measures Germany is already taking and on those that might be taken in the future.

1.3 Thesis Structure

After presenting the research questions in section 1.2, this section introduces the structure of the thesis. The paper begins with an introduction to the concept of Smart Power. Within the concept, power resources are identified. Afterwards, the level of abstraction is changed. On a more detailed level, an institutional, economic and ecological knowledge base is built. On this basis, the arc is drawn back to Smart

Power. Implications for power resources are discussed and power measures are identified. The chapters are therefore interrelated as follows.

First, chapter 1 introduces the topic and presents the research questions. Second, the theoretical framework of Smart Power is introduced in Chapter 2. The discussion of power concepts and related terms over time are reviewed. Based on an understanding of power, the Smart Power concept by Joseph S. Nye is explained. Afterwards, Germany's power resource in the context of the energy transition is analyzed. This is followed by a discussion of how hydrogen affects those resources. Third, chapter 3 sets the technical scope of the analyzed hydrogen supply chain and explains basic technological terms relevant for the understanding of this thesis. Fourth, chapter 4 presents the methodology of the thesis and gives an deep-dive into the economic and the ecological methodology. Fifth, in chapter 5, the results discussing four use cases Chile, Morocco, Australia and Norway, are presented. Every case includes a review on the energy partnership with Germany, an economic overview of the cost analysis and an ecological evaluation. Sixth, chapter 6 connects the results of chapter 5 with the power resources identified in chapter 2. Last, chapter 7 concludes the analysis and provides an outlook.

2 Smart Power - Theoretical Basics and Development in the Context of the German Energy Transition

Green hydrogen will be a scarce commodity. The current national demand in Germany is at 55 TWh_{th} and is expected to grow up to 380 TWh_{th} in 2050 according to the NHS /BMWI-05 20/. On the supply side the German government plans to install electrolyzers with a capacity of 10GW until 2040 /BMWI-05 20/. This corresponds to an annual production of 28 TWh_{th} in 2040. Although the exact amount of domestic produced hydrogen remains to be unclear in 2050, the scientific community agrees with the NHS that a large share of hydrogen needs to be imported from countries with favorable conditions for renewable energies /WI-01 20/ /BMWI-05 20/.

As a big player in sustainable energy transitions, Germany is interested in shaping the market conditions. The Paris Agreement lays the foundation for increasing global commitments to climate neutrality and thus for increasing hydrogen demand. This development will put pressure on the currently non-existing market. Although the implications of an uncertain key market are not foreseeable yet, energy supply is a critical infrastructure and care must be taken to keep vulnerability to a minimum and security to a maximum. Furthermore, a quick and successful ramp-up of the market accelerates a global energy transition.

Hence, this thesis argues, that Germany could use what Joseph S. Nye has defined as Smart Power to take advantage of this opportunity and enable a favorable and secure hydrogen supply /NYE-01 04/. The following chapter first introduces the concept of Smart Power and second connects the dynamics of hydrogen to the concept with regard to Germany.

2.1 Basic Power Concepts and Terms

In social science, the concept of power is broadly discussed among scholars and goes back to Niccolò Machiavelli. A comprehensive discussion of all definition goes beyond the scope of this thesis. Hence, focus is on the necessary understanding of the concept regarding future hydrogen supply.

Multiple ideas of power have competed for almost a century. In 1922, Max Weber defined power as a "chance to enforce one's own will within a social relationship even against resistance, no matter on what this chance is based." /WEB-01 02/ This definition contains several important aspects. Power occurs in a social relationship between two players. Both do have a will, but actor A is able to impose his will independently of actors B's by applying power measures. The choice of those measures is not further specified. Similarly, the political scientist Robert Alan Dahl defines power to be a relational concept: "A has power over B to the extent that he can get B to do something that B would not otherwise do." /YU-01 57/ Dahl emphasis the relational character of power. He even states "power is a relation [...] among people". Power can therefore not exist without two parties in relationship with each other. This understanding called Relational Power Approach bears some difficulties in operationalization.

A significant problem of the Relational Power Approach is comparability. In order to measure or compare power, one has to take the difference of probability that actor B behaves in the will of actor A by applying A's power measures and by not applying them. If this difference is large, person A is powerful. A person for example standing on a street corner in Germany and saying "I want you all to drive on the right side of the street." is not perceived as powerful, if people followed his orders, because they would drive on the right lane anyway - independent of person A's order. In contrast, a person doing the same thing in Great Britain would have a great deal of power, if drivers followed his orders. In reality, the cases are more ambiguous. Dahl himself explains that operationalization and observation of power is very difficult. Rising the definition to a state level, the defects become even more obvious. The scholar hardly can observe whether state B would have acted this way anyway, independently of state A's measures. /CGS-01 13/

As response to the relational power concept, a National Power approach, also known as Power as Resource approach, emerged. In this neorealistic concept, power is seen as a capability. In this understanding, power is a tangible or intangible resource, such as nuclear weapons or an high gross domestic product (GDP). Morton A. Kaplan and Kenneth N.Waltz are two proponents, who have further developed this definition. Morton A. Kaplan criticized the conventional definition for its focus on attaining the goals, because it provided no independent measure of power /UO-01 57/. Kenneth N. Waltz referring to Kaplan, explained that power could be estimated by comparing the capabilities of states /UC-01 79/. With a good overview of the distribution of power, rank orders can be identified. Even recommendations for action and measures can be derived. Criticism was formulated trough the "paradox of unrealized power"

/UOC-01 79/. The paradox discloses the inability of the Nation Power approach to explain, why states with high capabilities sometimes do not reach their goals. Although the United States of America as an example of indisputably extraordinary military power, failed to achieve its objectives in the Vietnam war.

David A. Baldwin and Joseph S. Nye therefore refer to the Contextual Power approach in order to resolve the paradox. They argue that capabilities are the raw materials that underlie the power relationship. Whether the use of power capabilities lead to a desired result depends on context and interdependencies. Context contains the variable scope, which determines who influences whom and the variable domain, which tells what topic is involved. The idea of interdependency complements the Contextual Power approach. The interaction between two actors is defined as interdependence when omitting the interaction causes costs on both sides according to Keohane and Nye /PEAR-01 73/. In relationships with strong interdependencies situations can occur, in which A's power over B increases simultaneously with B's power over A. This is typically the case in trading partnerships. Furthermore, in the Contextual Power approach, Baldwin highlights the multidimensionality of political power. Comparing purchasing power to political power, money is the dimensions that weights the most. The more money the more purchasing power one has. In political power, more nuclear weapons grant more military capability to a state but may weaken the chance to get a citizen elected for Secretary General of the UN. Therefore, there is no direct proportionality between a power resource and power itself. That is, power is not equal to the capability /UOC-01 79/.

Here is a brief summary of the power concepts discussed so far:

- **Relational Power concept:** Power can only exist in a relation between two actors and is perceived as the ability to attain a goal against the will of actor B. Comparability is difficult.

- **National Power approach or Power as Resource approach:** Power is a capability and can be measured in absolute terms. Ranking orders are possible. The national power approach is not able to solve to paradox of unrealized power.

- **Contextual Power approach:** Actors have power capabilities. However, power capabilities are not the only decisive factor. Context and interdependencies explain whether specific capabilities lead to the preferred outcome.

Lastly, the difference between power resource and power measure shall be specified. Power resources are capabilities as defined earlier. But, the term power resource is used in the following. They refer to one national state. But in the understanding of the contextual power approach, it is not possible to rank different states by power resources. Power resources are rather comparable to poker cards. The cards are the initial potential for the course of the game. However, the actual success of the game is also determined by other factors, such as understanding of the game, skill, and so on. Power measures, on the other hand, have relational character. They are used by actor A to actually change B's will. All actions with the purpose to influence B are defined as measures. The success of those attempts depend on power resources, context and interdependencies between A and B.

In the analysis of this thesis, the Contextual Power approach serves as the basic understanding. Next, power resources and measures are structured along a dimension Joseph S. Nye introduced with the terms Soft Power, Hard Power and later Smart Power.

2.2 Smart Power - the Combination of Hard and Soft Power

The concept Smart Power was developed by Joseph S. Nye in 2003. Nye wanted to counter the misconception that Soft or Hard Power alone guarantees a successful foreign policy. Rather, it is the intelligent interplay of both that is most promising. He called this combination Smart Power /COFR-01 09/. This section introduces the concept, so that in the following the concept can be applied to the hydrogen market creation.

In order to understand Smart Power, one has to start with the definition Soft and Hard Power. Joseph S. Nye defines power as "the ability to influence the behavior of others to get the outcomes one wants" /NYE-01 04/. This definition is coherent with the contextual power approach and in the following it will always be referred to this definition. Basically, there are two types of influencing others behavior. First, in the Hard Power approach, one can change what others want. Changing the will of others means that the other person, which will be called (actor) B, already has his will, but (actor) A is able to influence B's will. Consequently, B rethinks and changes his mind. Second, in the Soft Power approach, one can shape what others want. In contrast to changing, in the process of shaping the will of others, B has not made up his mind yet and A accompanies B in the formation of will process. In the latter case, A is able to shape B's will in the manner, that B by his own wants the same as actor A.

Hard and Soft Power create a scale span in which power resources and measures can be classified (see Figure 2-1). A typical power measures of Hard Power is coercion. Military force for example is in classic realism the power resource that determines the international order. But economic inducement can also be a measure to actively change the will of others. The corresponding power resource to the measure economic inducement is money. On the other side of the spectrum, Soft Power relies on attraction. Intangible resources such as institutions, ideas, values and culture can shape others preferences indirectly. Putting specific topics on the agenda alone can make others deal with the issue and acquire a preferred opinion. In addition, narratives, in other words stories that convey values and emotions, can be appealing and can make a long-term impression on people.

Depending on the outcome, other measures of power are suitable. It is unlikely, for example, that human rights can be credibly conveyed through military intervention. On the other hand, the friendship between the US American basketball star Dennis Rodman and Kim Yong Un probably will not end the North American nuclear program. Smart Power is the intelligent combination of the toolkit presented by hard and Soft Power. The ability to identify a good selection of measures is called contextual intelligence. For policy makers, contextual intelligence is a "intuitive diagnostic skill" to create smart and therefore, successful strategies. /NYE-01 11/ /COFR-01 09/

With a clear concept of Smart Power in mind, the framework is applied to Germany's situation with regard to hydrogen market creation in the next section.

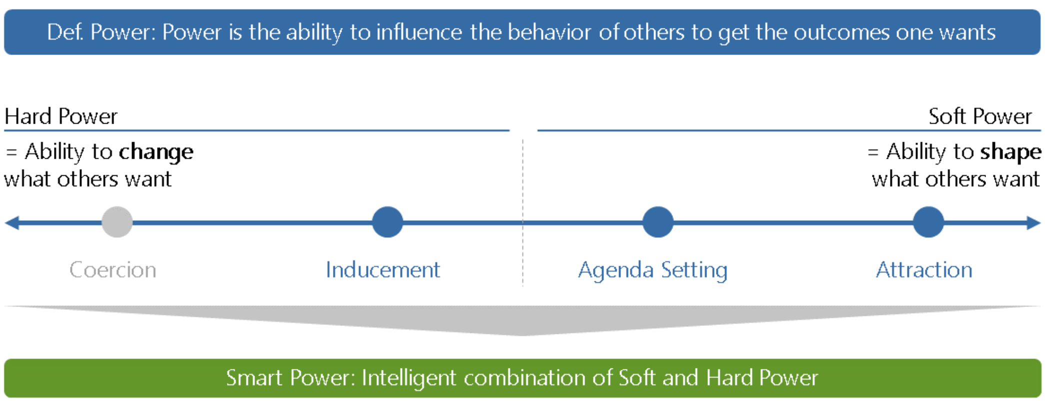


Figure 2-1: *Concept of Smart Power*

2.3 Development of Germany's Smart Power in Energy Foreign Politics

The analysis of this thesis builds on the theoretical basis of Smart Power explained in section 2.1 and 2.2 as a framework to approach and evaluates the emerging topic of hydrogen from a German perspective. In subsection 2.3.1, the practical relevance of the theoretical framework will be shown for the issue of hydrogen supply for Gemany. The following subsections tackle the first sub-research question (see section 1.2):

- What does Smart Power mean in the context of hydrogen supply and how do hydrogen dynamics affect Germany's Smart Power?

Therefore, subsection 2.3.2 reviews Germany Smart Power in energy transition in a pre-hydrogen era, in order to develop an understanding of Germany's existing power resources. Afterwards, in subsection 2.3.3 implications through the emergence of hydrogen for Germany's power resources are drawn.

2.3.1 Hydrogen Supply in the Framework of Smart Power

The analysis of this thesis aims to draws a broad spectrum of measures in order to promote a favorable hydrogen economy for Germany. Therefore, the Smart Power concept by Joseph S. Nye is applied. The concept sorts measures and resources along a scale between Hard and Soft Power. This section explains the theoretical structure of Smart Power and how it is understood in this thesis in the context of a hydrogen market creation with Germany as a key player.

First, some theoretical assumptions are made. In order to apply the Smart Power concept to Germany's hydrogen supply, we go back to the power definition by Joseph S. Nye: Power is "the ability to influence the behavior of others to get the outcomes one wants" /NYE-01 04/. Germany's goal and therefore its preferable outcome shall be a secure and favorable hydrogen supply. The contextual power approach, introduced in section 2.1, is based on a relational concept. Hence, the scope of the analysis is narrowed to four cases containing two actors: the state Germany as actor A and a counterstate as actor B. Therefore, four possible hydrogen export countries are chosen: Morocco, Chile, Australia and Norway (selection is explained in section 4.3.3). The domain includes only aspects affecting the hydrogen market creation on the supply side. The context considered for the relation is described trough the analysis of techno-economic and ecological dimensions.

The ability to prepare for a secure and favorable hydrogen supply depends strongly on power resources and associated measures. Those are structured along the spectrum of Hard and Soft Power (see Figure 2-1). Starting with Hard Power, it is import to clarify that military force is not considered as reasonable measure. Even if military force has always been an essential dimension in international analysis by means of power, Nye himself relativizes the importance of coercion with the introduction of the concept of Soft Power /CGS-01 13/. Moreover, it is currently politically unlikely that military force can be used in securing sustainable energy.

In the economic dimension of power, only measures of power are considered where the measure also originates from within the domain. Exporting countries, for example, shall not be induced to produce hydrogen by threatening to exclude them from the European trade zone. Instead, focus is placed on power in trade, rather than on power through trade /PU-01 06/. A power resource in trade, for example, can be the level of demand. The potential market size is a power resource and increases Germany's negotiation weight in bilateral agreements. Furthermore, Germany is a major donor of subsidies. Those could decrease costs and promote competitiveness of specific hydrogen production paths. One question to be investigated here is which process step generates high costs and whether subsidies have high leverage there.

Continuing with Soft Power, Germany has institutional resources to actively put hydrogen on the agenda. In particular, bilateral energy partnerships directly ensure continuous work on preferred topics. Quitzow states in /IASS-01 20/ that energy partnerships are a "power instrument" (power instruments are called power measures in this thesis). But it can be argued, that an existing network with established institutions and well-rehearsed partnerships are indeed cards which one holds in his hand and which one can draw. Especially, in the context of Germany's energy transition, the energy partnerships are already partly in place. Therefore, existing energy partnerships are seen as power resources. Setting hydrogen on the agenda in these partnerships would be an example for a referring measure.

With regard to attraction, an idea or rather a narrative has evolved in Germany, which is called *Energiewende* in literature /IASS-01 20/ /ECOFYS-01 19/. A narrative is a story transporting emotions and values. It makes others more prone to act in concert with Germany /COFR-01 09/. This narrative can be seen as a Soft Power resource of attraction and is described further in subsection 2.3.2.

The following subsections 2.3.2 and 2.3.3 delve into the resources already addressed in this section and describe their development in Germany's energy transition.

2.3.2 Germany's Smart Power in a Pre-Hydrogen Era

The global commitment to climate neutrality and the techno-economical rise of renewable energy led to major shift in international political economy of energy

/UOSUS-01 18/. Traditionally, foreign policy in terms of energy has focused on supply security by ensuring access to fossil resources. But the emergence of renewables created a new perspective on energy foreign policy. The low-carbon industry offered a divers landscape of economic opportunities. In the redistribution of power in the transformation process, actors were therefore seeking to exert influence not only for energy security, but also to create favorable economic conditions for domestic stakeholders /IASS-01 20/. In this perspective, Germany has risen to a new key actor and could establish new power resources.

Germany has a remarkable history in national climate policy, but at the international level it has only begun to actively engage in the last decade /GER-02 16/. Political scientists have since begun a discussion on how Germany harnesses the development of its own energy transition in international politics. This subsection reviews the narrative *Energiewende*, the economic attraction of Germany as a market as well as a donor and Germany's international institutional network.

Germany was able to establish itself as an pioneer for green energy. Over time Germany developed a common idea, which will be called *Energiewende* in the following and can be summarized as: the energy transition is economically necessary, technically feasible and will be economically lucrative. The idea evolved over time and resulted in a strategic narrative. As a Soft Power resource, a narrative can attract others on a Soft Power level and can be key for success /COFR-01 09/. The narrative *Energiewende* has its origin in the 1970s, when the oil crises questioned the central position of fossil fuels. In this time, an environmental and anti-nuclear movement emerged. Economic growth should no longer be dependent on uranium and oil. The nuclear accident in Tchernobyl gave the movement even more momentum. Politically the narrative arrived in the governing coalition of Social Democrats and Greens in 1998, when Germany first proposed the idea of a transition of German energy supply towards a sustainable system. The narrative included protection of the environment, reduction of carbon dioxide emissions, mitigation of nuclear risks, but also economic growth and job creation in new industries. In the 2000s, first far-reaching policies were implemented, but the narrative was not without controversies. Further events such as Fukushima or movements such as Fridays for Future as well as a successful market development for green technology strengthened the idea that an energy transition is necessary and at the same time offers economic opportunities. Germany is now trying to spread this narrative internationally and is using a multi-layered network to do so. /IASS-01 20/

Along with the social discourse, Germany managed to drive forward its energy transition in techno-economic terms. In the early 2000s, Germany's policy framework of feed-in tariffs and feed-in privilege for renewable electricity set a corner stone for the development of a lead market, which led to significant cost digression of renewable energy /GSEA-01 06/. This development had notable effect. On the one hand, Germany was able to constantly increase the share of renewable energy in its electricity mix /ECOFYS-01 19/. On the other hand, the positive development showed international observers as well as national opponents the fundamental feasibility of green energy. Internationally, this techno-economic development in combination with the inspiring narrative laid ground for further international engagement of Germany. The German government showed strong interest in further developing its international partnerships. /IASS-04 16/

Germany advanced its international co-operation on multiple levels. On the one hand, Germany established itself as one of the largest financiers in the climate protection by raising its Official Development Assistance (ODA). In 2016, only Japan spent more money into the energy sector /ECOFYS-01 19/. Secondly, Germany has built up a multi-layered network of international cooperation. Multilateral as well as bilateral, governmental as well as non-governmental initiatives were supported. Four ministries were in charge to place the topic of energy transition on platforms such as the United Nations (UN) Security Council, the United Nations Framework Convetion on Climate Change (UNFCCC), the G20 or G8/7 summits and promoted the German position in climate protection /GER-02 16/. Furthermore, Germany established own platforms such as the Petersberg Climate Dialogue or used existing summits in Germany to put focus on climate protection. As an example, the Munich Security Conference also covered climate change in recent years /GER-02 16/. In addition, Germany built a network of bilateral energy partnership (EP) with more than twenty states across the globe /BMWI-32 19/. Mutual learning, technological transfer, but also regulatory alignment are goals of these EPs. State owned institutions such as the German Agency for International Co-operation (GIZ) or Germany's Development Bank (KfW) carry out the organization of EPs or ODAs. But also in research, Germany had major influence. The International Renewable Energy Agency (IRENA) was founded in 2009 in Bonn on the initiative of Germany. Today, it is supported by more than 170 countries and makes a significant contribution to international climate research. /GER-02 16/ /IASS-04 16/

The narrative *Energiewende*, the international institutional network and the techno-economic experiences as well as the will to support green technology financially consolidate Germany's power resources in energy policy. The next subsection 2.3.3 deals with the question of how hydrogen dynamics impact Germany's power resources.

2.3.3 Germany's Power Resources and Measures with regard to Hydrogen Supply

The last subsection identified the narrative *Energiewende*, the international network and Germany's donor capacities as important power resources of Germany. Those power resources have been established in the course of Germany's energy transition. This subsection discusses the question of how these resources change with the emergence of hydrogen.

First, the narrative *Energiewende* can be broadened with a well established hydrogen market. Reviewing subsection 2.3.2, the narrative can be summarized as following: the energy transition is ecologically necessary and economically and technically feasible. Germany is perceived as a pioneer, but mainly in the electricity sector /ECOFYS-01 19/. Hydrogen offers a window of opportunity for Germany to establish itself as a pioneer to extend this narrative across the boundaries of the power sector. In the course of the Paris agreement, most states committed themselves to comprehensive climate neutrality. Hydrogen is indeed a key technology that will help achieve these ambitious goals. Promoting and improving the green character of hydrogen captures the zeitgeist of climate neutrality and complements the German narrative *Energiewende*. This idea encourages the willingness of other states to deal in the issue of energy transition with Germany and to push co-operation forward. Hydrogen must therefore prove to be technically feasible, ecologically meaningful and economically lucrative. Technically, hydrogen technologies are already seen as mostly possible, but not yet mature and established /IEA-05 19/ /AGORA-07 20/. In the ecological perspective, there is a strong discussion about the right color and supply path of hydrogen (see chapter 3.1). A variety of options in the choice of energy resources, transportation technologies and export countries complicates the debate. This is also where the quantitative analysis of this paper kicks in. Economic and ecological findings referring to the power resources are addressed again in the discussion (see chapter 6).

Second, Germany was able to establish an international multilateral and bilateral network as well as platforms. With regard to hydrogen, Germany can now take advantage of these already established platforms. The German NHS focuses particularly on bilateral relationships and explicitly states the following as a measure: "Integration of hydrogen into existing energy partnerships [...]" /BMWI-05 20/. Energy partnerships are designed to work together on policy issues relating to the energy transition /FRO-01 18/. It takes little effort to put the topic of hydrogen on the agenda. In GIZ's annual report, the topic of hydrogen was explicitly mentioned in eleven partnerships in 2019 /BMWI-32 19/. In contrast, hydrogen was only mentioned in the report on South Korea in 2017 /BMWI-18 18/. Further the German

NHS states: "We will strengthen the existing international activities, particularly in the context of the energy partnerships and of multilateral cooperation, [...] such as IRENA" /BMWI-05 20/. This measure also involves research institutes. The German, Norwegian, Chilean and Australian hydrogen strategies also refer to previous studies /BMWI-05 20/ /MFRL-01 20/ /GOC-03 20/ /COAG-01 19/. International cooperation at this early stage can help shape a hydrogen strategy. In addition, Germany is making great efforts to develop new structures. "Establishment of new partnerships" /BMWI-05 20/, especially with those, who have favorable conditions for hydrogen production, is also part of the tool set. The NHS states further, that international research is necessary in order to identify future countries with large trading potential. Moreover, the strategy aims to create a European hydrogen alliance. This alliance is already in place and open for stakeholders to participate /EC-05 20/. Here, as in the case of the energy partnerships, contacts are to be established so that interested parties from economy have an exchange platform to possibly form consortia.

Third, as in the past, when Germany was one of the largest donors in the energy sector /ECOFYS-01 19/, the German government has announced major financial support for hydrogen technology. More than 12 billion euros are reserved for a broad set of programs, from living labs for energy transition (0.6 billion euros for 2020 - 2023), up to basic research on renewable hydrogen (0.3 billion euros for 2020 - 2023) /LBS-01 20/. Within the framework of the strategy and the Corona stimulus package, 7 billion euros were allocated for the hydrogen market ramp-up and 2 billion euros for international cooperation /BMWI-05 20/. All in all, Germany has a solid financial foundation, which it is already willing to invest. Furthermore, Germany has more financial measures to induce competitiveness for green hydrogen. On the one hand, operational costs could be reduced, including lowering taxes and fees. On the other hand, costs of carbon emission could be increased. In addition, a foundation H2 Global has been founded to manage part of the 2 billion euros for international cooperation. The foundation agrees on prices with consortias and covers the difference between the conventional and renewable hydrogen through carbon contracts for difference (CCfD). Lastly, there is a high demand in Germany. A clear commitment to the demand for green hydrogen arouses the interest of countries willing to export and gives them investment security.

In summary, Germany has built up power resources in the course of the energy transition within the last decades. These power resources are now helping Germany to prepare for a hydrogen supply. On the one hand, the energy narrative is known throughout the world and is gaining more and more supporters. On the other hand, Germany's network within the energy industry spans the globe at various levels. But the relationship between these resources and Germany is not a one-way street. With the emergence of the hydrogen issue, these resources continue to develop. The narrative, for example, can become more compelling and the energy partnerships can deepen.

In order to identify measures based on these power resources that prepare for hydrogen supply and to gain insights into the repercussion of hydrogen on power resources, the quantitative analysis for four energy partnerships examines the hydrogen supply paths based on economic and ecological criteria. Therefore, the remainder of this paper continuous to look at energy partnerships. The costs of selected pathways will be calculated. Statements are made which paths are economically more sensible and at which points there are major levers. In addition, the question is raised, if green hydrogen import makes ecological sense, and if so, which technologies are suitable for this purpose. In chapter 6, the findings are again placed into the picture of power resources and power measures are derived. In order to prepare for this analysis, the next chapter sets technical assumptions and explains the most important technologies. The following chapter introduces the methodology for the economical and ecological analysis.

3 Technical Basics

The path from the primary energy source in foreign countries to hydrogen available in Germany is long and has several ramifications. Hydrogen can be obtained from various resources. An overview is given in section 3.1. Section 3.2 sets the scope and discusses the assumptions made along the supply chain. Within the scope of this master thesis, only green, grey and blue hydrogen will be discussed. This means that renewable energy source (RES) and natural gas reforming (NGR) are considered as primary energy resources. For both resources, the hydrogen production technologies, electrolysis and gas reformation, are explained in section 3.3. In order to import the hydrogen to Germany, long distances have to be overcome. Depending on external circumstances, it can be reasonable to convert hydrogen into a hydrogen carrier. Those are described in section 3.4.

3.1 Hydrogen Production Pathways and Color Theory

Hydrogen is the smallest element and stands with the atomic number one at the beginning of the periodic system. It occurs very frequently in nature and is a component of many molecules, most prominently in water H_2O and Hydrocarbons C_xH_y. Accordingly, there are several ways to obtain hydrogen. These are usually arranged in colors. This section gives an overview of the color theory.

Generally, hydrogen can be produced in thermochemical, biological and electrochemical processes /WUL-01 17/. The colors, however, do not refer only to the classification of the production process, but also to the energy carrier used for the production of hydrogen. Up to now, by far the most hydrogen has been produced thermochemically by steam reforming in Germany (see subsection 3.3.2). This technically matured production process is called "grey". Blue hydrogen is closely related to grey hydrogen. It is produced in the same way and the same energy carrier is used. The difference, however, is that carbon dioxide emissions are captured afterwards. A third method of extracting hydrogen from natural gas is pyrolysis named turquoise hydrogen. In this method, the methane is split with the addition of heat and a catalyst. The carbon dioxide is materially bound, for example as graphite. Graphite can be easily stored and therefore, turquoise is also considered climate-friendly. /BDI-01 20/

A well known electrochemical technology to produce hydrogen is electrolysis. Water is split into hydrogen and oxygen with the use of electric energy. The electrical energy can be obtained from any energy source. If the electricity were obtained from natural gas, the hydrogen would be called grey as well. But this is to be avoided, because reformation is a more efficient way. If the electricity is used from the grid, however, a corresponding proportion of fossil resources is involved, depending on the energy mix. In the color theory, therefore, mainly two resources are considered. On the one hand, hydrogen obtained from nuclear power, which is labeled as red or pink hydrogen and on the other hand, hydrogen produced with RES, called green hydrogen. Green hydrogen can also be produced by biological or thermochemical processes on the basis of biomass. However, the capacities are not considered to be very scalable and are therefore not taken into account in the following.

Lastly, hydrogen known as white hydrogen also occurs as an element in some African regions. These deposits can be extracted by fracking methods. Those resources are estimated to be very small and therefore not part of the further analysis. Table 3-1 lists the production paths discussed in this section /ESWG-01 20/.

Table 3-1: *Color theory and overview of hydrogen production processes (/WUL-01 17/, /BMWI-05 20/ and /CYUT-01 17/)*

Source		**Technology**	**Color**
Fossil fuels	Hydrocarbon	Reforming	Grey
		Reforming + CCS	Blue
		Pyrolysis	Turquoise
Nuclear Power	Water	Electrolysis	Red/pink
Renewable sources	Biomass	Biological processes	Green
		Thermochemical processes	
	Water	Electrolysis	
Natural occurrence		Fracking	White

3.2 Supply Chain of Hydrogen

The color theory in section 3.1 structures hydrogen along resources and production technology. The entire supply path, however, includes production and transportation (see Figure 3-1). The process chain is long and has several alternatives in each step. Therefore, this chapter goes through the process and discusses general assumptions made in this thesis.

- **Production:** The scope of this thesis includes green hydrogen as well as blue hydrogen and grey hydrogen. For green hydrogen, solar and wind power is considered, which is transformed into hydrogen via PEM or AEL electrolysis (see subsection 3.3.1). The plant is directly connected to the electrolyzer. No energy storage facility is used in between. It also follows that the installed capacity for the electrolyzer is assumed to be the same as the installed capacity of the wind or solar farm. Supply paths for green hydrogen is evaluated for Chile, Australia and Morocco. Grey and blue hydrogen is evaluated in Norway (see explanation in section **??**). Furthermore, in the cost analysis, no differentiation is made between SMR and ATR. In contrast, the ecological analysis considers both production methods due to different possibilities of carbon capture and storage (CCS).

- **(Re-)Conversion:** Depending on distance and transmission technology, different hydrogen carriers are used (see section 3.4). In this thesis, only compressed hydrogen for pipeline transmission and liquified hydrogen as well as ammonia for ship transmission is considered. It is assumed that the conversion takes place at the same location as the hydrogen production. Therefore, the electrical demand for conversation is produced by the wind or solar plant in the case of green hydrogen. Reconversion has to take place in Germany. Therefore, the electricity is also taken from the German electricity mix.

- **Transmission:** In terms of transmission technologies, hydrogen can be used in pipelines, ships and trucks. Since only international supply is considered in this paper, trucks are excluded and only pipelines and ships are considered.

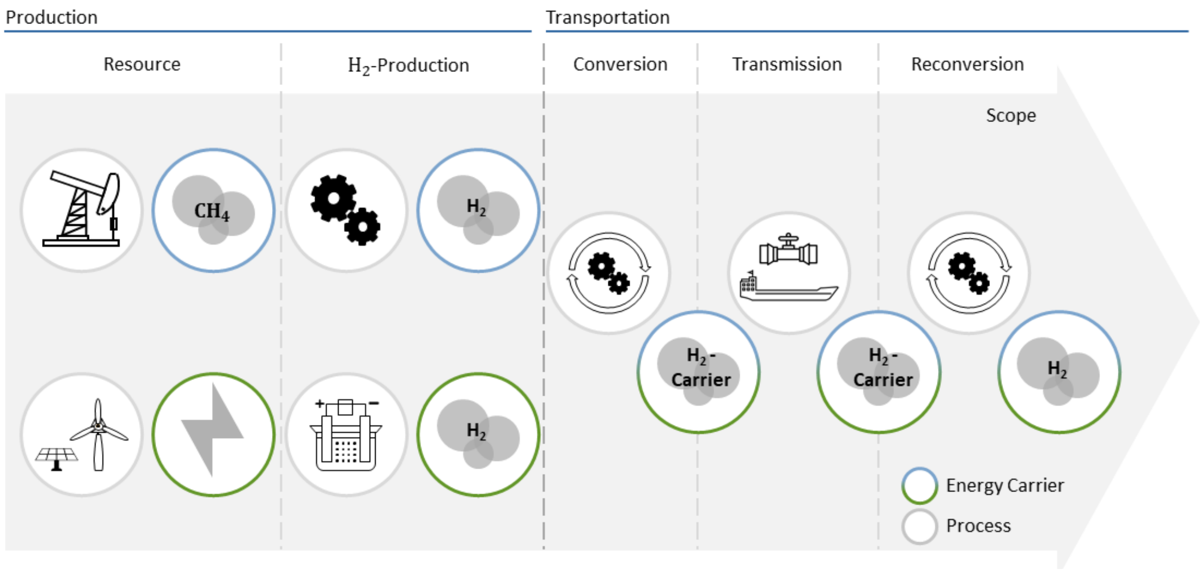


Figure 3-1: *Visualization of the supply chain of grey and green hydrogen*

3.3 Production Technologies

This section considers and explains the production technologies considered in this thesis.

3.3.1 Production Technology of Green Hydrogen

The green hydrogen, which is considered in this master thesis, is produced by electrolysis and renewable energy from PV and wind plants. In the following, the most important representatives of electrolyzers are briefly presented.

AEL: The alkaline water electrolysis (AEL) is a mature technology that is already widely used. The name comes from the KOH solution that embeds the electrodes as an electrolyte. It is currently the cheapest variant and offers a lifetime of 30 to 50 a. The efficiency, however, is the lowest of the two variants presented and lies at 68 % (see Table A-2). A weakness of interest for this master thesis is the load range. The minimum load of AEL is at 10 to 40 % of nominal hydrogen production capacity. The analysis in this thesis assumes a plant that has no intermediate storage. In order to avoid energy losses, the PEM electrolysis explained in the next paragraph is considered more suitable. /BUTT-01 17/

PEM: The name polymer electrolyte membrane electrolysis (PEM) indicates that a proton exchange membrane separates the electrodes. Those are attached directly to the membrane and no electrolyte is used. The purity level of the hydrogen is very high and the efficiency is slightly higher than that of the AEL. Furthermore, the manufacturers do not specify a minimum load. However, the plants are more expensive and usually have a lifetime of 20 a (see Table A-2). /BUTT-01 17/

3.3.2 Production Technology of Grey and Blue Hydrogen

The grey and blue hydrogen obtained from natural gas reforming (NGR) is also considered. There are two established technologies that are used for grey and blue hydrogen production, which are presented in this subsection.

SMR: Steam methane reforming (SMR) is the state of the art technology for grey hydrogen. The production process consists of four phases. First, the feedstock containing long-chain hydrocarbons is decomposed into methane and syngas. In a second phase, methane and steam are converted into hydrogen and carbon monoxide in a endothermic reaction (reaction 3-1). A external furnace heated with natural gas provides the activation energy. In a third exothermic phase, the resulting carbon monoxide reacts with water to hydrogen and carbon dioxide in the water gas shift section (WGS) increasing the total hydrogen yield (reaction 3-2). A technology called pressure swing absorption (PSA) is used in a last phase to extract hydrogen from the syngas and to purify the product.

$$CH_4 + H_2O \longrightarrow 3\,H_2 + CO \qquad \Delta H^\circ_{298\,\mathrm{K}} = 206\,\frac{\mathrm{kJ}}{\mathrm{mol}} \tag{3-1}$$

$$CO + H_2O \longrightarrow CO_2 + H_2 \qquad \Delta H^\circ_{298\,\mathrm{K}} = -41.1\,\frac{\mathrm{kJ}}{\mathrm{mol}} \tag{3-2}$$

ATR: ATR is a second established reforming technology. The chemical process follows the same pattern as in the process of steam methane reforming (SMR). In contrast to SMR, an ATR plant does not require an external furnace in order to cover the activation energy of reaction 3-1 due to an partially oxidization of methane within the vessel. Therefore, pure oxygen has to be injected to the vessel. Air could be used also, but to avoid contamination pure oxygen is preferred.

CCS: In hydrogen production via SMR, carbon dioxide is formed in two sources - approximately 60 % in the reforming and shift process and approximately 40 % in the external furnace. In the production via ATR, 100 % of the resulting carbon dioxide is contained in the syngas. Hence, pre-combustion capture technologies such as the amine-based absorption avoid most of carbon dioxide emissions in a ATR plant, but captures only 60 % of all emission in a SMR plant.

3.4 Hydrogen Carrier

The competition for the best hydrogen carrier has not yet been decided. Hydrogen itself has a low energy density and a high volatility. Storage and transportation of gaseous hydrogen is therefore more challenging and expensive than fossil fuels. Hence, it is discussed to convert hydrogen in hydrogen based fuels or feedstocks. Those can be used directly or reconverted back to hydrogen. Each of the hydrogen carriers has advantages and disadvantages. The following section provides an overview over the most relevant potential hydrogen carrier. The analysis of this thesis, however, focuses on liquid hydrogen (LH_2) and ammonia (NH_3).

LH_2: In order to increase the energy density, hydrogen can be converted to liquified hydrogen by cooling down to −239.96 °C and compressing to 1.3 MPa. This process is very energy consuming. Theoretically the required energy is at 1.1 kWh/kg_{H2}, but can increase further in real liquefaction processes /UOTOK-01 20/. In the analysis for this thesis a energy consumption of 6.1 kWh/kg_{H2} is assumed (see Table A-4) /IEA-06 19/. A further challenge is the cooling and heat leakage during transportation and storage. A boil-off of about 0.1 - 0.3 % can occur /SMU-01 18/. Transmission infrastructure is at an early development phase. However, a first purpose-built liquified hydrogen carrier was demonstrated in the HESC-Project /COAG-01 19/.

NH_3: Ammonia (NH_3) is a colorless, toxic, corrosive alkaline and a compound of nitrogen and hydrogen. In the conversion process, first, nitrogen needs to be extracted from the air in an air separation unit (ASU) and second, ammonia is synthesized from hydrogen and nitrogen. For this process, energy consumption is specified from 2 up to 18 % of the thermal energy of hydrogen /SMU-01 18/, /BBU-01 20/, /IEA-05 19/. The reconversion process on the other hand consumes 11.2 kWh/kg_{H2} taking the purification process also into account, which corresponds to 29 % of the thermal energy of hydrogen /IEA-06 19/. Due to its toxicity transportation and storage have to be handled with caution, but easy detection at low concentration rates simplify a controlling system. Furthermore, ammonia can be liquefied at a low pressure of about 0.87 MPa, which makes infrastructure less expensive. It might be stored in current available tanks /SMU-01 18/ and transported in a commercial liquefied petroleum gas tanker /EWI-01 20/. /UOH-01 18/ /UOTOK-01 20/

LOHC: As the name suggests, liquid organic hydrogen carrier (LOHC) are liquid organic substances that can absorb hydrogen in an exothermic process with the aid of a catalyst. The basic molecular form does not change in this process. In reverse, with the addition of heat and catalyst, hydrogen can be released afterwards. As an advantage, LOHC can store hydrogen without losses, even for a long time. Furthermore, the existing fuel infrastructure can be used to transmit LOHC /UOH-01 18/. Due to low research maturity, the technology is considered relatively new, although it has been discussed since the 1970s. Anyway, levelized costs of hydrogen (LCOH) molecules need to be shipped back in order to reuse them /IEA-05 19/.

Hydrocarbon based fuels: With carbon dioxide extracted from the atmosphere, hydrogen can be converted climate-neutral to methanol, methane or liquid hydrocarbons. Natural gas, which corresponds to methane, is a common fuel for which infrastructure and end-use facilities exist in many regions. Hence, synthetic methane can be used directly as substitutes for fossil fuels. The efficiency, however, is lower than the efficiency of its competitors. Furthermore, the production costs are higher. This is mainly due to the immaturity and inefficiency of carbon dioxide extraction from the atmosphere. /IEA-05 19/ /UOH-01 18/

Table 3-2: *Hydrogen carrier overview /IEA-05 19/, /SMU-01 18/, /UOH-01 18/*

	LH_2	NH_3	LOHC	Methane
Conversion Efficiency in %	82	82 - 98	60 - 98	79.5
Reconversion efficiency in %	–	71 - 80	70 - 97	–
Losses	high	low	low	medium

4 Methodology and Data

Germany's challenge of carbon free hydrogen supply exceeds the capacity of an one-dimensional analysis, in which the interdependency as well as the importance of other dimensions would be neglected. Therefore, this thesis takes a new approach by looking at the issue from a power perspective. Chapter 2 explained the theoretical background and placed the challenge of hydrogen supply in the framework of Smart Power. Subsection 2.3.3 concludes that Germany created power resources in energy foreign energy, on which it can rely now: (1) an institutional network, (2) narrative *Energiewende* and (3) reputation as donor. In order to identify power measures and draw conclusions about the development of power resources, the level of abstraction is changed in the following analysis.

Four case studies quantitatively explore energy partnerships, examine the cost of the hydrogen supply and determine the environmental footprint. As described in subsection 2.3.3, energy partnerships play an essential role in promoting hydrogen technologies. Therefore, four partner countries are selected from the broad institutional network, which on the one hand have high chances to become an export country for hydrogen and on the other hand, whose cases promise interesting findings. The selection is explained in section 4.3.3. In these four cases, the institution of energy partnership and its interaction with the topic of hydrogen is first examined in a qualitative analysis. Second, an economic study of hydrogen is conducted to determine the cost distribution. This cost distribution is expected to serve as a basis for conclusions as to whether the partner country is economically competitive, but also which levers for subsidies are most attractive. Third, a Life Cycle Assessment is executed in order to allocate a global warming potential with a time horizon of 100 years to the different supply paths as well as to the specific processes. Hence, it can be examined which path is most likely to support the narrative of the energy transition by being most climate-friendly and which measures could be taken to improve the carbon footprint of hydrogen.

The methodological approach shown in Figure 4-1 is designed to analyze four cases of international hydrogen supply in the context of Smart Power. First, the four cases are selected on the basis of several criteria, which are described in section 4.3.3. Second, the resulting cases are evaluated economically, ecologically and institutionally. Third, the findings from the cost breakdown along the process chain, as well as results gained from the LCA are sorted and discussed within the Smart Power concept. Chapter 6 discusses the impact of the findings on existing power resources and discusses measures based on the findings.

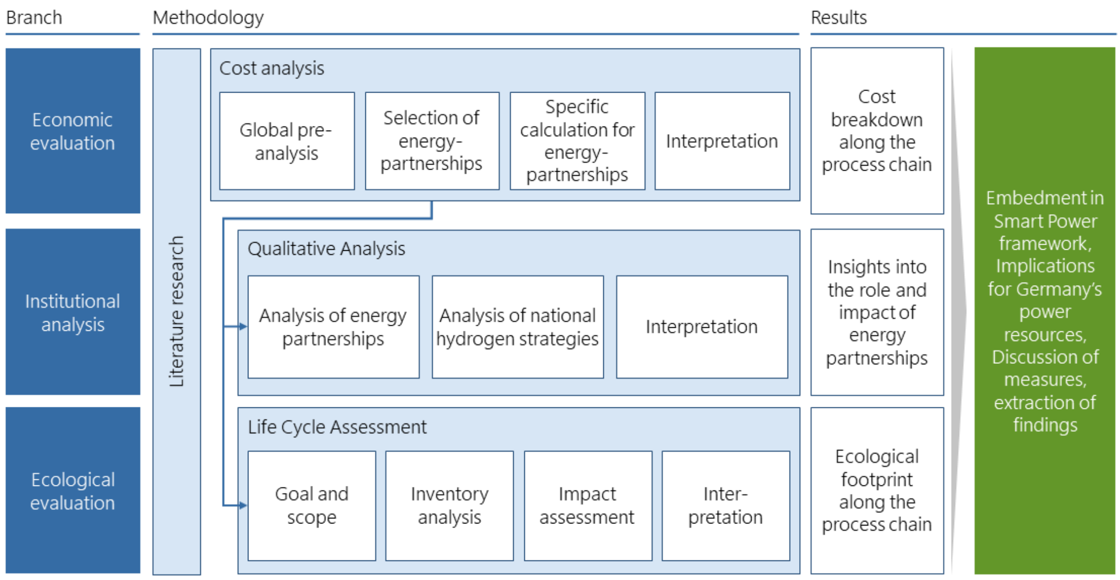


Figure 4-1: *Methodological approach*

4.1 Selection of Cases

Hydrogen supply depends on many variables, such as RES, transmission distance, or political support, which all differ between production sides. This thesis aims to analyze a wide range of dimensions, such as economic, ecological and institutional aspects. Hence, such wide range in scope requires narrowing the field of application. Therefore, four cases are selected in this section. The cases studied are the countries Australia, Chile, Morocco and Norway. The following are the criteria on which those cases were selected:

- **Economic competitiveness:** Good conditions for RES are the basis for competitive green hydrogen export. Therefore, naturally some countries are able to produce green hydrogen less expensive than others. In order to identify these countries with the most favorable conditions, the maps in Figure 4-2 were created following the methodology from subsection 4.3.1 and 4.3.3. The upper map in Figure 4-2 visualizes production costs of hydrogen (later called $LCOH_{prod}$), based on an off-grid system containing no storage capacities for electricity powered by wind energy. The bottom map shows the production costs of hydrogen using the same technical assets powered by solar power. Coastal areas of northern Europe, Greenland and especially southern Chile stand out on the wind map. Whereas, good solar conditions lead to low hydrogen production costs in

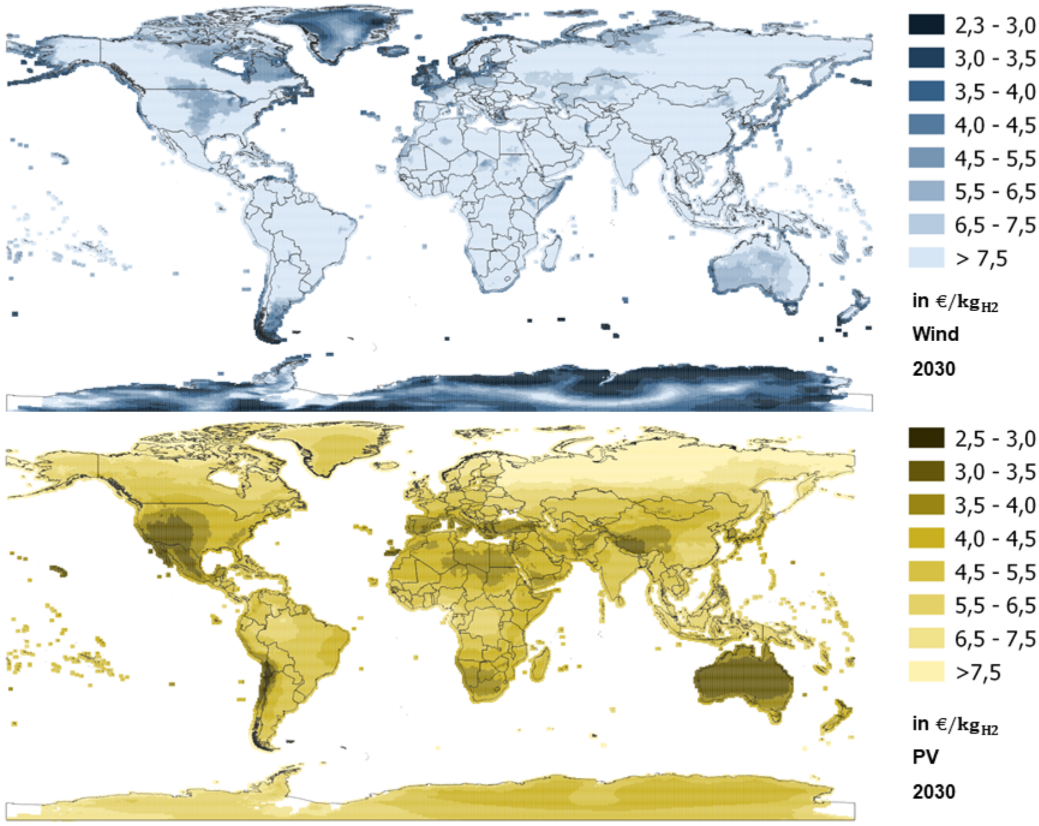


Figure 4-2: *Levelized costs of green hydrogen production worldwide*

Australia, in the United States of America (USA), in the Mediterranean region and once again in Chile - this time in the north. High full load hours (FLH) of RES lead in those areas firstly to low levelized costs of electricity (LCOE) and secondly to higher utilization rate of the electrolyzer. As a result, the capital expenditure (CAPEX) of the electrolyzers is spread over more quantity of hydrogen, which leads to lower cost per quantity of hydrogen (see equation 4-8).

- **Distance between partner country and Germany:** Critical to hydrogen import is the distance between the export country and Germany. The costs visualized in Figure 4-2 do not include transportation costs. In order to compare the distance aspect, the selection of cases shall represent states with long transmission routes, as well as states close to Germany.

- **Existence of diplomatic ties with Germany with focus on hydrogen:** One of Germany's institutional resources are the EPs that have been established in the course of the energy transition. In selecting the case studies, care was taken to ensure that the selected countries are in an existing energy partnership with Germany, as it is expected that this institution will have a major impact on whether a hydrogen supply pathway is established from this country. In addition, attention was paid to whether a NHS has been adopted so that a broader source base can be used in the analysis of EP. Table 4-1 gives an overview of all states having an EP with Germany, which has an focus on hydrogen /BMWI-32 19/.

Table 4-1: *Selection of countries /LBS-01 20/, /BMWI-32 19/ (chosen states printed in bold)*

State	EP in hydrogen	Status of NHS	Export/Import	Color
Australia	Existing	Available	Export	Green
Canada	Existing	In preparation	Export	Green
Chile	Existing	Available	Export	Green
Morocco	Existing	In preparation	Export	Green
Norway	Existing	Available	Export	Grey/blue
Russia	Existing	In preparation	Export	Grey/blue
South Africa	Existing	Not available	–	–
South Korea	Existing	Available	Import	–
UAE	Existing	Not available	Export	Green
USA	Existing	Available	Export	–
Japan	Existing	Available	Import	–

- **EU membership:** members of the EU are not in the scope of this thesis.
- **Willingness to export:** the German NHS clearly states import interests of hydrogen. Hence, only states with export interest are considered as potential cases. South Korea and Japan are therefore excluded /LBS-01 20/ (See table 4-1).
- **Color of hydrogen:** the scope of this thesis includes three colors of hydrogen: green, grey and blue. Therefore, the selection of states should represent all three colors of hydrogen.

Considering the listed aspects, Australia, Chile, Morocco and Norway are chosen to be the four cases. Figure 4-2 shows that Chile and Australia have extraordinary renewable potential. Morocco has favorable renewable energy conditions and is close to Germany, which could have positive affects on its competitiveness. As a non-member of OECD, higher weighted average cost of capital (WACC) were used for Morocco in Figure 4-2. Lastly, Norway as a potential supply path for grey and blue is chosen over Russia, because Norway has already published a NHS.

The next section describes the approach taken in the institutional analysis of the energy partnerships and which sources of information were mainly referred to.

4.2 Analysis of Energy Partnerships

The energy partnerships are the institutional link in the energy sector between Germany and the partner country. The goal of this analysis is to make conclusions about the power resource of agenda setting and to potentially derive power measures from this resource. In addition, it will be determined how the energy partnerships themselves are developing within the topic of hydrogen. In contrast to the cost analysis and the LCA, this is a qualitative analysis.

Sources of information are GIZ reports, the National Hydrogen Strategies of the partner countries and other internet sources that describe achievements or projects of the energy partnerships in more detail. Secondary literature was also used.

Norway has a special energy partnership with Germany due to its proximity to the European single market. This energy partnership is not managed by GIZ and was therefore not analyzed in the same depth as the other three partner countries.

The next section explains the economic approach, which has been used already to create Figure 4-2 and which will further be used to lay out a detailed economic analysis including production and transportation costs of the chosen cases.

4.3 Economic Assessment - the Costs of Hydrogen

This chapter presents the approach and the operationalization for the economic assessment, pursued in this thesis. The analysis aims to calculate levelized costs of hydrogen (LCOH). In general, levelized costs are the total costs related to a specific quantity of a good /ZAPF-01 16/. Equation 4-1 illustrates the definition, where total costs C_{total} are divided by mass of hydrogen m_{H_2}.

$$LCOH = \frac{C_{total}}{m_{H_2}} \tag{4-1}$$

The good, to which the research questions refer, is hydrogen as an energy carrier. Total costs C_{total} include all costs incurred along the process chain, such as costs for the wind plant, maintenance costs of the same, costs for the electrolyzer, transport costs, etc. The unit for hydrogen, which is referred to as functional unit, is chosen to be $\mathrm{kg_{H_2}}$ and therefore, is in this analysis always in the denominator.

The choice of the functional unit for hydrogen needs to be discussed a bit further. The quantity hydrogen can be operationalized as mass m_{H_2}, which corresponds to $\mathrm{kg_{H_2}}$, or as thermal energy E_{th}, which leads to $\mathrm{kWh_{th}}$ as functional unit. Both are in a linear relationship via lower heating value of hydrogen (LHV) or higher heating value of hydrogen (HHV) depending on whether the enthalpy of water is taken into account. If the LHV is used when converting m_{H_2} into E_{th}, the efficiency of the electrolyzer $\eta_{electolyzer}$ must also be related to the LHV when the electrical energy E_{el} in $\mathrm{kWh_{el}}$ is calculated. Not being specific about the use of LHV and HHV is often a cause of misinterpretation of data. Hence, a clear choice and labeling is necessary. Therefore and for the sake of better comparability with other literature, this work uses $\mathrm{kg_{H_2}}$ as the functional unit and efficiencies based on LHV. Equation 4-2 describes the relation between the variables mass m_{H_2}, thermal energy E_{th} and electrical energy E_{el}. /STE-02 14/

$$m_{H_2} = \frac{E_{th}}{LHV} = \frac{\eta_{electrolyzer,LHV} * E_{el}}{LHV} \tag{4-2}$$

The economic assessment is conducted in two steps. As already stated, LCOH contain all costs along the process chain. In this sense, the term LCOH is ambiguous. It is not clear, if the process chain includes hydrogen transmission to Germany. Therefore, in the following the terms levelized costs of delivered hydrogen (LCOH$_{deliv}$) and levelized costs of hydrogen production (LCOH$_{prod}$) are used. According to equation 4-3, LCOH$_{deliv}$ is subdivided in LCOH$_{prod}$ and levelized costs of hydrogen transport (LCOT):

$$LCOH_{deliv} = \frac{C_{production} + C_{transmission}}{m_{H_2}} = LCOH_{prod} + LCOT \tag{4-3}$$

In the first step, LCOH$_{prod}$ are calculated based on the geographical RES-potential. In combination with an analysis of LCOT, the result of the first step served as decision criteria in the selection of four cases (see. section 4.3.3). Second, the LCOH$_{deliv}$ of the four cases are analyzed in detail, with a closer look on cost distribution. The cost distribution serves later as data basis in an analysis for economic inducement measures for Germany.

According to /PRO-02 20/, LCOH$_{prod}$ of PtX-products inclcude (1) Energy costs (electricity and heat), (2) raw material costs (water supply costs), (3) facility costs and (4) operating costs. LCOT consider the costs for ship or pipeline transport, costs for conversion of hydrogen into a hydrogen carrier and costs of import or export terminals, where storage and berthing costs are included. In subsection 4.3.1 and 4.3.2 the calculation behind the variables LCOH$_{prod}$ and LCOT are explained further.

4.3.1 Levelized costs of Hydrogen Production

In general, hydrogen can be produced in various ways. Typically, they are sorted and named by colors. Section 3.1 gives an overview of the variety of hydrogen colors. The scope of this thesis comprises green, blue and grey hydrogen. Hydrogen produced with RES and electrolyzers is assigned the color green. Whereas, hydrogen based on fossil fuels is called grey hydrogen. The grey production path including CCS is known as blue hydrogen.

Hence, there are two paths, which need to be considered in order to calculate LCOH$_{prod}$. First, the green production path and second, the grey/blue production path, which are explained next.

Levelized Costs of Green Hydrogen Production For LCOH_{prod} of green hydrogen, electricity costs, facility costs and operating costs are considered. The supply costs of water are neglected. Therefore, in equation 4-4 the calculation of LCOH_{prod} (from equation 4-3) is further evolved. The formulary contains costs for electrolyzer $C_{electrolyzer}$, which includes facility costs and operating costs, as well as electricity costs $C_{electricity}$. /FFE-113 20/

$$LCOH_{prod,green} = \frac{C_{production}}{m_{H_2}} = \frac{C_{electrolyzer} + C_{electricity}}{m_{H_2}} \tag{4-4}$$

Splitting the equation 4-4 into two halves, equation 4-6 takes a closer look into the costs for electrolyzer $C_{electrolyzer}$. Often, facility and operating costs are given as specific CAPEX and operational expenditure (OPEX) in EUR/kW. In order to get absolute costs, one has to multiply the specific costs with the peak capacity of the respective installation, which can be calculated by the division of the converted energy E_{el} and the full load hours FLH. It is important to consider that the basis for FLH, as well as OPEX, is one year. Hence, CAPEX including WACC must also be allocated from the lifetime lt to one year. This is done via annuity factor (AnF), which is defined in equation 4-5 /PFWA-01 18/. WACC used in the analysis and corresponding AnFs are listed in table A-1 /STEF-01 20/. Inserting equation 4-2 into equation 4-1, the electrical energy is eliminated as seen in equation 4-6.

$$AnF = \frac{(1 + WACC)^{lt} - 1}{(1 + WACC)^{lt} * WACC} \tag{4-5}$$

$$\frac{C_{electrolyzer}}{m_{H_2}} = \frac{(CAPEX/AnF + OPEX) * \frac{E_{el}}{FLH}}{\frac{\eta_{LHV} * E_{el}}{LHV}} = LHV * \frac{(CAPEX/AnF + OPEX)}{\eta_{LHV} * FLH} \tag{4-6}$$

The second part of equation 4-4 are electricity costs, which are looked at in equation 4-7. Given LCOE in EUR/(kWh), the equation simplifies as following.

$$\frac{C_{electricity}}{m_{H_2}} = \frac{LCOE * E_{el}}{m_{H_2}} = \frac{LCOE * E_{el}}{\frac{\eta_{LHV} * E_{el}}{LHV}} = LHV * \frac{LCOE}{\eta_{LHV}} \tag{4-7}$$

Combining equation 4-6 and 4-7 in equation 4-4, the resulting formula is given in equation 4-8. /FFE-113 20/

$$LCOH_{prod,green} = LHV * (\frac{CAPEX/AnF + OPEX}{FLH * \eta} + \frac{LCOE}{\eta}) \tag{4-8}$$

The data necessary for those calculations is firstly listed in table A-2 for the electrolyzer. Sources are /PRO-02 20/, /BUTT-01 17/ and /IEA-06 19/. Secondly, calculated global LCOE are taken from the Dynamis project /FFE-12 17/, which is based on weather data from 2012, 2015, 2017 and 2019 /NASA-01 19/.

Levelized Costs of Grey and Blue Hydrogen Production The levelized costs of production of grey hydrogen consists of facility and operating costs of the reformation unit $C_{reformation}$, costs for NGR C_{NGR} and costs related to carbon dioxide $C_{CO_2-related}$ (see equation 4-9). Latter costs can occur due to emitted carbon dioxide and payed though the European Emission Trading System (EU ETS) or due to captured carbon dioxide, which has to be transported and stored.

$$LCOH_{prod,grey/blue} = \frac{C_{production}}{m_{H_2}} = \frac{C_{reformation} + C_{NGR} + C_{CO_2-related}}{m_{H_2}} \tag{4-9}$$

Analogous to the transformation of the equations 4-4 to 4-8 for the costs of green hydrogen, equation 4-10 and 4-11 is obtained for gas reformation from equation 4-9.

$$LCOH_{prod,grey} = LHV * (\frac{CAPEX/AnF + OPEX}{PA * 8760\,\mathrm{h}} + \frac{P_{NGR}}{\eta}) + m_{uc} * P_{CO_2} \tag{4-10}$$

$$LCOH_{prod,blue} = LHV * (\frac{CAPEX/AnF + OPEX}{PA * 8760\,\mathrm{h}} + \frac{P_{NGR}}{\eta}) + m_{cc} * P_{CS} + m_{uc} * P_{CO_2} \tag{4-11}$$

The plant availability PA is a factor between 0 and 1 corresponds multiplied with 8760 h to the FLH for RES. Furthermore, P_{NGR} is the price for NGR in EUR h/kW, P_{CO_2} is the price for a certificate at the EU ETS in EUR/t and P_{CS} are the costs for transport and storage of captured carbon dioxide also in EUR/t. The variables m_{uc} and m_{cc} are the mass of uncaptured and captured carbon dioxide in t. Data for those calculations is listen in Table A-3. /EWI-01 20/

The approach for the calculation of LCOH$_{prod}$ has been explained in this subsection. In order to have the full LCOH$_{deliv}$, one has to add the costs for transmission. The approach to calculate those is described in the next subsection.

4.3.2 Levelized Costs of Hydrogen Transport

International hydrogen transport remains to be a major issue. Hydrogen infrastructure locally exists already, but in the international context new paths must be taken. Just one hydrogen carrier ship has been built yet and boarder crossing pipelines technically are only suitable for transporting natural gas at the moment, but can be retrofitted to transport hydrogen. Hence, tackling by considering this issue, LCOT are calculated in detail in this thesis.

In general, LCOT contain specific costs for conversion c_{conv}, reconversion c_{reconv}, for export terminal c_{expte}, import terminal c_{impte}, which include storage and berthing facilities and transportation via ship or pipeline c_{transp} (see equation 4-12). The costs for transportation via ship or pipeline depend on distance d.

$$LCOT = c_{conv} + c_{expte} + c_{transp}(d) + c_{impte} + c_{reconv} \tag{4-12}$$

In this analysis LH_2 and NH_3 are considered as energy carrier. For both, the same calculation approach has been taken, but with different data. The data is taken from /IEA-06 19/, /EWI-01 20/ and summarized in Table A-4 and A-5. The next paragraphs go through every summand of equation 4-12 and explain them.

Import and Export Terminals At import and export terminals infrastructure is necessary in order to store hydrogen or the respective hydrogen carrier and in order to load the ship. Those facilities have CAPEX and OPEX. Furthermore, the tanks, in which LH_2 or NH_3 is stored need to be cooled and therefore, have electrical energy consumption E_{electr}, which is multiplied by the local electricity price $P_{electr.}$, which is assumed to be LCOE of the related RES plant except for hydrogen from Norway. In Norway an industrial electricity price of 0.05 EUR is assumed. In addition, depending on the hydrogen carrier boil-off losses have to be considered during the time at the terminal. Hence, a boil-off rate bo multiplied by LCOH_{prod} is added to the calculation.

$$c_{expte/impte} = (CAPEX/AnF + OPEX) + P_{electr.} * E_{electr}(+bo * LCOH_{prod}) \tag{4-13}$$

Transmission via Pipeline or Ship Over long distances hydrogen can either be transmitted via pipeline or ship. In equation 4-14 the costs for pipelines are given. Pipelines can transport compressed hydrogen or ammonia. According to /UOC-01 07/, losses as well as hydrogen compression are included in OPEX.

$$c_{transp-pip} = (CAPEX/AnF + OPEX) * d \tag{4-14}$$

In transmission costs by ship, boil-off losses bo (given in %/d) and fuel use FU_{H2} (given in in $\text{kg}_{\text{H2}}/\text{t}/\text{km}$) depend on distance d and travel time d/v_{ship}. They are not included in OPEX. This is why the costs for the boil-off losses and for fuel use are added to CAPEX and OPEX of the ship. The data given in Table A-4 and A-5 for CAPEX and OPEX is referred to the capacity of one ship. But the actual quantity of hydrogen transported by the ship is smaller than the nominal capacity of the ship due to losses and fuel use on the way. Hence, CAPEX and OPEX need to be adjusted by the term $(1 - bo/24\,\text{h/d} * d/v_{ship} - FU_{H2} * d)$. Further, a ship does more than one route in a year, which is why the capacity in the denominator is multiplied by the number of trips $\frac{8760\,\text{h}}{2*(d/v_{ship}+t_b)}$. Berthing time is referred to as t_b and ship velocity as

v_{speed}.

$$c_{transp-ship} = \frac{(CAPEX/AnF + OPEX)}{(1 - bo/24\,\mathrm{h/d} * d/v_{ship} - FU_{H2} * d) * \frac{8760\,\mathrm{h}}{2*(d/v_{ship}+t_b)}} + (bo/24\,\mathrm{h/d} * d/v_{ship} + FU_{H2} * d) * LCOH_{prod} \tag{4-15}$$

Conversion and Reconversion This analysis considers liquified hydrogen and ammonia as hydrogen carriers. At the start of every transmission processes hydrogen is converted into a hydrogen carrier. Conversion costs include plant CAPEX and plant OPEX, as well as the costs for electrical energy E_{electr}, which is consumed by the conversion process. It is assumed that the conversion takes place directly at the production side of hydrogen. Therefore, LCOE are taken a electricity price $P_{electr.}$. The reconversion process is located in Germany. Therefore, electricity prices for 2020, 2030 and 2050 are taken from /FFE-144 19/.

$$c_{conv} = (CAPEX/AnF + OPEX) + P_{electr.} * E_{electr} \tag{4-16}$$

The next subsection presents further explanations referring to the economical analysis.

4.3.3 Further Technical Assumptions and Data

LCOH$_{deliv}$ are mapped in section as an pre-selective method. Global LCOH$_{prod}$ of green hydrogen are visualized. This is done by using MERRA-2 data /GMAO-01 18/ in order to create a worldwide net of cells. Only off-grid systems with a direct connection between RES and electrolyzer were considered. The data for global LCOE is taken from the Dynamis Project /FFE-12 17/, which took weather data for 2012, 2015, 2017 and 2019 from MERRA-2 /GMAO-01 18/.

Since not all locations are suitable for hydrogen production, the data is filtered along following criteria (The selection is visualized using the example of PV in Chile in Figure 4-3):

(a) the data are assigned to the respective countries (see Figure 4-3a)

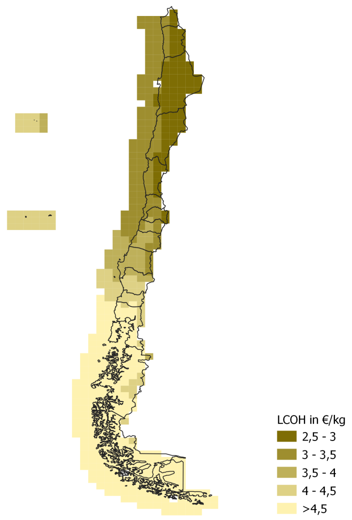
(b) Protected area is excluded from the country's data pool. Data for protected area is taken from /UNEP-01 14/ (see Figure 4-3b)

(c) the data are assigned to provinces in the state, offshore cells are also excluded in this step (see Figure 4-3c)

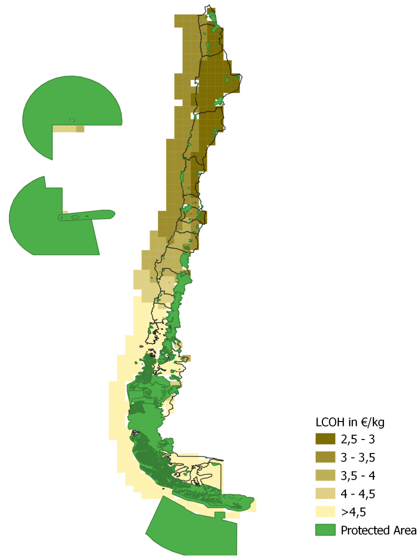
(d) best 10 % of remaining cells is taken for further analysis described in section 4.3 (see Figure 4-3d). Hydrogen production facilities would only be built in favorable locations.

The visualization in Figure 4-3 takes Chile as an example, but the same approach is taken for Australia and Morocco, too. Furthermore, this section refers to the data tables in the appendix. Table A-8 presents general data and assumptions. Data for transportation is listed in Table A-4 and A-5.

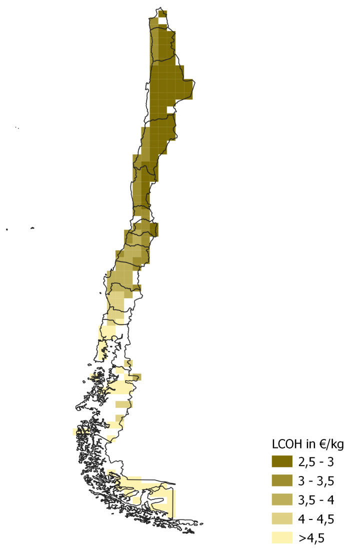
The next section of this chapter introduces the methodology of LCA.



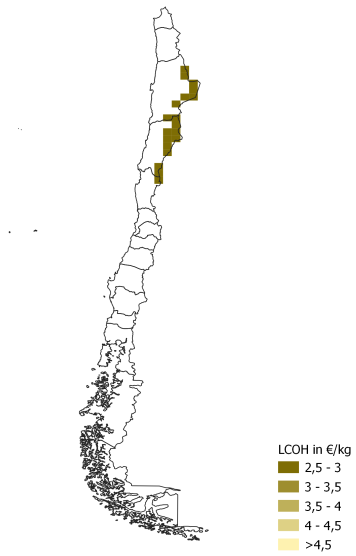
(a) *Entirety of Merra cells in Chile*



(b) *Exclusion of protected areas*



(c) *Assignment of Merra cells to provinces / exclusion of offshore data*



(d) *Selection of the best 10 % the values*

Figure 4-3: *Data selection using the example of $LCOH_{deliv}$ in Chile (PV, PEM, 2030)*

4.4 Life Cycle Analysis - the Footprint of Hydrogen

The main cause of hydrogen use in future energy systems arises from climate change. The global community committed themselves to develop into a climate neutral society. Therefore, the ability of hydrogen to be produced without any green house gas (GHG) emissions placed the energy carrier in the front row. Green or blue hydrogen is supposed to become an energy carrier without any emissions.

The goal of climate neutrality is the main motivation for states to promote hydrogen. Furthermore, this characteristic can lead to a strengthening of Germany's soft power with regard to the frontrunner position in the energy transition. In order to quantify the climate neutrality and to be able to derive measures for the improvement of climate friendliness, an LCA is carried out in this master thesis. The methodology is laid out in this chapter.

Generally, a LCA analyses the totality of the environmental influences and aspects of a product throughout its entire lifecycle. The assessment can assist in identifying measures to improve environmental footprint, in informing stakeholders, or in underpinning a green marketing strategy. The most relevant principle is transparency. Only with clear understanding of the setting of a LCA, the results can be discussed reasonably. As stated in ISO 14040:2006 /DIN-02 06/ and further explained in ISO 14044:2006 /DIN-03 06/, the approach consists of four phases:

- *Goal and scope definition phase:* in the first phase, goal and scope of the assessment are defined. Furthermore, boundaries and level of detail are set.
- *Inventory analysis phase:* in the second phase, data necessary to meet the goals are collected.
- *Impact assessment phases:* in the third phase, an indicator for the environmental impact is defined.
- *Interpretation phase:* in the final phase, results are discussed and summarized.

The following subsections go through the first three phases and explain the procedure according to ISO 14044 /DIN-03 06/. The last phase will be included in the analysis of chapter 5.

4.4.1 Goal and Scope

The Life Cycle Assessment in the thesis performs a process-based, attributional analysis of the environmental impact for possible hydrogen supply paths. The results shall put different paths in perspective, identify the main drivers within the ecological footprint and lay a basis for a discussion whether hydrogen, more specifically, which hydrogen paths, can contribute to Germany's reputation as green frontrunner. Therefore, the GWP100 according to /IPCC-02 13/ is calculated along the supply process and is related to the functional unit kg_{H_2}, which is also chosen in the economic analysis. The reason for the decision explained in section 4.3 also applies to the LCA. In addition, a consistent choice of units within this thesis contributes to a better understanding.

In order to properly perform these analyses, it is important to define the scope. This provides the necessary transparency and puts the significance of the results into a suitable framework. The results of this analysis are intended for comparison between pathways within the thesis. In comparing the results with other study caution is necessary due to different depth and width of the scope. However, the analysis in this thesis concentrates on the cases defined in section 4.3.3. Those include green, grey and blue hydrogen. Figure 4-5 and Figure 4-4 show flow charts for hydrogen supply paths of green and grey/blue hydrogen. The flow chart represents the supply path described in section 3.2 and is therefore not further described.

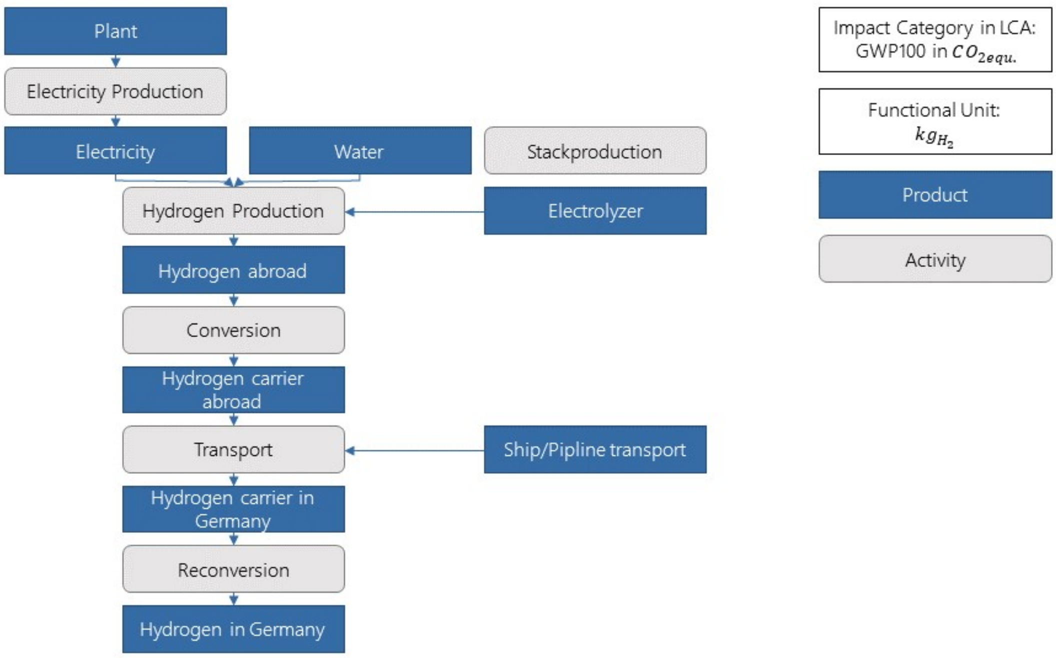


Figure 4-4: *Flow chart and system boundaries of green hydrogen*

Having goal and scope defined, the following subsection gives an overview of the inventory analysis phase.

4.4.2 Inventory Analysis

In the Inventory Analysis Phase all data is collected. In this thesis a software built upon Brightway2 /PSI-01 17/ called Activity Browser is used as calculation tool to

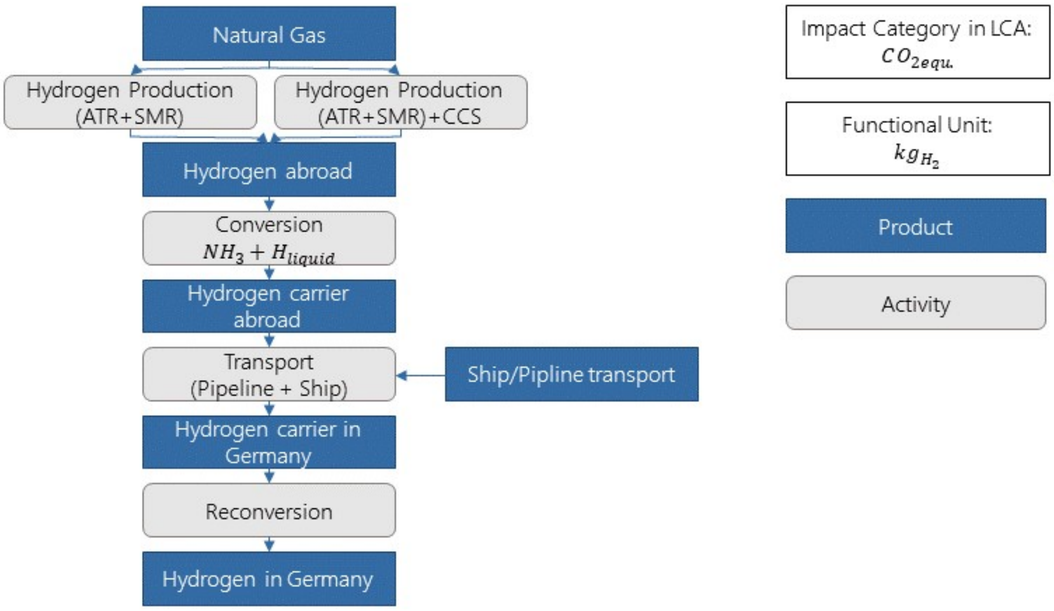


Figure 4-5: *Flow chart and system boundaries of grey and blue hydrogen*

develop a coherent LCA. The data used in the calculation is taken from the ecoinvent database v3.6, system model "allocation, cut-off by classification" /ECOINV-01 19/ and from complementary literature, which is then labeled.

The structure of the LCA follows the flow charts in Figure 4-4 and 4-5. Activities are defined determining inputs and product. The products themselves are input parameters in the next activity.

The most important activities and their relation between input and product are listed here:

- **Activity:** green electricity production - template from /ECOINV-01 19/
  Modified input: RES plant (wind turbine or PV plant), network connection

$$fraction_{plant} = \frac{1}{lt * FLH_{avg} * C_{plant}} \tag{4-17}$$

  where: $fraction_{plant}$ is the fraction of a wind turbine or a PV plant corresponding to $1kWh$ produced electricity over its lifetime, lt is the lifetime the plant, FLH_{avg} is the average full load hour at the geographic location based on weather data from /NASA-01 19/, and C_{plant} is the installed capacity of the plant;
  Assumptions: A open ground installation with a installed capacity of 570 kWp with a lifetime of 20 a.

- **Activity:** green hydrogen production

Table 4-2: *Plant fraction values for solar /BUTT-01 17/, /PRO-02 20/, /IEA-06 19/*

Location	FLH_{avg}	$fraction_{PVplant}$	$fraction_{AEL}$	$fraction_{PEM}$
Australia	1790.1 h	4.9×10^{-8}	1.40×10^{-8}	2.79×10^{-8}
Chile	2201.6 h	3.98×10^{-8}	1.14×10^{-8}	2.27×10^{-8}
Morocco	1808.5 h	4.85×10^{-8}	1.38×10^{-8}	2.77×10^{-8}

Table 4-3: *Plant fraction values for wind /BUTT-01 17/, /PRO-02 20/, /IEA-06 19/*

Location	FLH_{avg}	$fraction_{windplant}$	$fraction_{AEL}$	$fraction_{PEM}$
Australia	3056.8 h	5.45×10^{-9}	8.18×10^{-9}	1.63×10^{-8}
Chile	5076.7 h	3.28×10^{-9}	4.92×10^{-9}	9.85×10^{-9}
Morocco	3929.0 h	4.24×10^{-9}	6.36×10^{-9}	1.27×10^{-8}

Input: water, electricity, electrolyzer

$$m_{H_2O} = \frac{m_{molarH_2O}}{m_{molarH_2}} * m_{H_2} = \frac{18.02\,\mathrm{g/mol}}{2.016\,\mathrm{g/mol}} * 1\,\mathrm{kg} = 8.94\,\mathrm{kg} \tag{4-18}$$

$$E_{electr.} = \frac{LHV}{\eta_{electrolyzer}} \tag{4-19}$$

$$fraction_{AEL/PEM} = \frac{1}{lt * FLH_{avg} * C_{AEL/PEM}} \tag{4-20}$$

where: m_{H_2O} is the mass of water needed to produce 1 kg of hydrogen, m_{molarH_2O} and m_{molarH_2} are the molecular mass of hydrogen and water, $E_{electr.}$ is the electrical energy demand to produce 1 kg of hydrogen, $E_{electr.}$ is calculated from the quotients of the LHV and the electrolyzer efficiency $\eta_{electrolyzer}$, which is based on the LHV

analogously calculated to equation 4-17, the plant fractions $fraction_{AEL/PEM}$ are listed in Table 4-2 and 4-3 **Notes:** the data for electrolyzers is taken from /FFE-55 18/ and the input value is calculated according to equation 4-17

Table 4-4: ***Activity:*** *hydrogen production - Assumptions /PRO-02 20/, /BUTT-01 17/, /IEA-06 19/*

Technology	Year	$\eta_{electrolyzer}$	$E_{electr.}$
AEL	2020	68 %	49.0 kWh
	2030	69 %	48.3 kWh
	2050	71 %	46.9 kWh
PEM	2020	71 %	46.9 kWh
	2030	72 %	46.3 kWh
	2050	75 %	44.4 kWh
SOEC	2020	73 %	45.6 kWh
	2030	75 %	44.4 kWh
	2050	79 %	42.2 kWh

- **Activity:** grey and blue hydrogen production (SMR and ATR inkl. CCS)-template taken from /ETH-03 20/

- **Activity:** ammonia production /BBU-01 20/
  Input: hydrogen, water, electricity, nitrogen, ammonia catalyst

$$m_{H_2} = \frac{3}{2} * \frac{m_{molarH_2}}{m_{molarNH_3}} * m_{NH_3} = \frac{3}{2} * \frac{2.016\,\mathrm{g/mol}}{17.031\,\mathrm{g/mol}} * 1\,\mathrm{kg} = 0.177\,45\,\mathrm{kg} \quad (4\text{-}21)$$

$$m_{N_2} = \frac{1}{2} * \frac{m_{molarN_2}}{m_{molarNH_3}} * m_{NH_3} = \frac{1}{2} * \frac{27.0134\,\mathrm{g/mol}}{17.031\,\mathrm{g/mol}} * 1\,\mathrm{kg} = 0.7931\,\mathrm{kg} \quad (4\text{-}22)$$

  where: m_{H_2} and m_{N_2} the minimum masses of hydrogen and nitrogen needed to produce 1 kg of ammonia, /BBU-01 20/ states $m_{N_2} = 0.874\,\mathrm{kg}$, m_{molarH_2}, m_{molarN_2} and $m_{molarNH_3}$ are the molecular mass of hydrogen, nitrogen and ammonia, $E_{electr.}$ is the electrical energy demand to produce 1 kg of ammonia is taken from /BBU-01 20/

- **Activity:** ammonia reconversion /SMU-01 18/
  Assumptions: According to /UO-01 21/, SMR plant can be used as a basis for a ammonia cracking plant. Hence, the activity of SMR from /ETH-03 20/ is used and modified. **Modified input:** ammonia, electricity /IEA-06 19/,

$$m_{NH_3} = \frac{2}{3} * \frac{m_{molarNH_3}}{m_{molarH_2}} * m_{H_2} = 5.635\,\mathrm{kg} \quad (4\text{-}23)$$

  where: m_{NH_3} is the mass of ammonia needed to produce 1 kg of hydrogen

- **Activity:** liquefaction of hydrogen /SMU-01 18/
  Input: hydrogen, electricity /SMU-01 18/

- **Activity:** sea tanker for liquefied hydrogen /IEA-06 19/
  Assumptions: activity tanker for liquefied natural gas from /ECOINV-01 19/ is taken as a template
  Modified input: tanker and maintenance $fraction_{sh/m}$ (Table A-6), fuel (fuel)

m_{fuel}, losses m_{losses} /IEA-06 19/

$$fraction_{sh/m} = \frac{1}{lifetime * total\_Capacity\_per\_year * total\_distance\_per\_year} \tag{4-24}$$

$$= \frac{1}{lt * C_{ship} * (1 - (\frac{bo}{24\,\mathrm{h/d} * v_{ship}} - FU_{H2}) * d) * (\frac{8760\,\mathrm{h}}{2*(d/v_{ship}+t_b)})^2 * 2d} \tag{4-25}$$

$$m_{fuel} = FU_{H_2} \tag{4-26}$$

$$m_{losses} = \frac{bo}{24\,\mathrm{h/d} * v_{ship}} * d \tag{4-27}$$

where: lf is the lifetime of a tanker, C_{ship} is the capacity of a tanker, bo is the daily boil-off rate, d is distance, v_{ship} is the velocity, FU_{H2} is the fuel use and t_b is the berthing time; data is taken from /IEA-06 19/ and listed in Table A-4 and and A-6;

- **Activity:** sea tanker for ammonia
  Note: analogously to sea tanker data for liquefied hydrogen is stated in Table A-5 and A-6 /IEA-06 19/

- **Activity:** Pipeline /IEA-06 19/ /ITUL-01 13/
  Assumptions: a activity for natural gas pipeline from /ECOINV-01 19/ serves as the template
  Modified input:

$$fraction_{pip} = \frac{1}{lifetime * r_u * Q * distance} \tag{4-28}$$

$$losses = 2\,\%/10\,000\mathrm{km} * 1\,\mathrm{t\,km} = 0.002\,\mathrm{kg_{H_2}} \tag{4-29}$$

where: lt lifetime, Q is Design throughput of a pipeline, r_u is utilization rate and d is distance (see Table A-7)

4.4.3 Life Cycle Impact Assessment

The LCA is used as a tool to quantify the environmental impact on climate change of hydrogen supply paths. Therefore, the global warming potential with a time horizon of 100 years (GWP100) according to /IPCC-02 13/ is used as indicator. With this metric, the environmental impact of all green house gases can be normalized taking their radiative efficiencies and their lifetimes in the atmosphere into account. The reference gas is carbon dioxide, which is why the GWP100 is given in $\mathrm{kg_{CO_2-e.}}$.
This concludes the explanation of the methodology. In the next chapter, the results of

the ecological, economic and institutional analysis are presented in the context of the four case studies.

5 Discussion of Cases

Germany is preparing for an advantageous hydrogen supply. After the description of the power resources in section 2.3, on which Germany can base its measures, four cases are selected in section 4.3.3 to describe how Germany uses measures to ensure a hydrogen supply. This chapter presents the economic and ecological analysis for each of the cases. The results of the analysis are used as a basis for further discussion on possible measures. The cost structure for example indicates big levers for subsidies to make hydrogen more competitive. The ecological contribution analysis shows to what extent hydrogen supports the development of the narrative *Energiewende* in terms of climate neutrality. Thereby following research questions are answered in the following:

- What are the supply costs of hydrogen and what is the resulting cost structure?
- What is the ecological footprint of hydrogen? What are the main drivers?
- What measures are and can be used to secure hydrogen supply by Germany?

The first two of this questions are tackled in the following sections for Chile, Morocco and Australia. Furthermore, it is discussed, what measures are already used in those states with special focus on energy partnerships. Afterwards, chapter 6 continuous to tackle the third of the given research questions by summarizing which measures are already in place and discussing further options in section 6.2. Norway is presented first and serves as a reference point to better classify the values from the other three countries. Fact sheet with the most important figures for each state can be found in appendix A.2.

5.1 Norway

In international hydrogen supply, Norway is labeled as a "frontrunner" /FRO-01 18/. Hydrogen has been on the political agenda for several years and technologies needed for blued hydrogen such as CCS are strongly promoted /IEA-102 17/. For European countries, Norway also offers itself as an trading partner through its geographic location. Pipeline infrastructure for example is already in place that could be retrofitted at low cost. Furthermore, Norway is closely tied to the European Market and therefore, for Germany an uncomplicated trading partner. This also gives the energy partnership a special character. The partnership exists /AUS-02 19/, but is not overseen

by GIZ, as it is not mentioned in the annual reports /BMWI-33 19/, /BMWI-18 18/, /BMWI-32 19/.
Besides geographical proximity and close economic ties to EU, the conditions for hydrogen production in Norway are favorable. Norway has significant wind potential that is well suited for green hydrogen production (see Figure 4-2). The electricity sector is almost 100 % covered by hydro power /IEA-102 17/. Hence, the chance is relatively low that additional utilization of the renewable potential would lead to the detriment of the local energy transition.

In the following, however, Norway's green potential is not considered. Rather, attention will be paid to the supply path of grey and blue hydrogen. Norway is a major fossil fuel exporter and could continue to be so in the coming decades. Only one-third of estimated gas resources have been produced as of 2016. Furthermore, Norway has laid out ambitious policies supporting CCS technology /IEA-102 17/. Despite this suitable conditions, Norway does not mention blue hydrogen export as an explicit goal in its NHS. At the moment, no business case is feasible, but work is continuing to establish long-term competitiveness /MFRL-01 20/.

Generally, the NHS, published in May 2020, does not present a detailed plan with a specific set of goals and measures. It is rather a summary of the technical status and the political discussion in Norway /LBS-01 20/. The export of blue hydrogen is estimated to be more competitive compared to green hydrogen. With regard to transport, it is proposed to export natural gas itself to the EU and then take back the carbon dioxide and store it in Norway. The development of hydrogen infrastructure is only worthwhile once a certain export volume is reached. /MFRL-01 20/

The following two subsections are intended to present a reference point for future green hydrogen from Chile, Australia, and Morocco. Therefore, both grey and blue hydrogen with a hydrogen infrastructure will be considered.

5.1.1 Economic Overview

The Norwegian NHS argues that blue hydrogen cannot yet compete with grey hydrogen /MFRL-01 20/. This subsection presents the result of the economic assessment, which followed the approach introduced in section 4.3.

First, general price development of hydrogen from Norway is discussed. Figure 5-1 gives an overview. On the one side, grey hydrogen starts at 1.5 EUR/kg_{H2} in 2020. This result corresponds to the literature, which gives a span of 1 to 2 EUR/kg_{H2} for hydrogen based on NGR without CCS /HEID-01 20/. In following decades, costs increases up to 2.7 EUR/kg_{H2}. On the other side, blue hydrogen starts higher at

1.8 EUR/kg_{H2} and continues at the same level. As early as 2030, the cost of blue hydrogen will be lower than the cost of grey hydrogen.

Both, the prices for grey and blue hydrogen include costs for transportation in new hydrogen pipelines. Assuming a retrofitted net of pipelines, the costs decrease by 0.4 EUR/kg_{H2}. The fourth bar in Figure 5-1 corresponds to the average cost of green hydrogen calculated for the corresponding year from the other three countries. On the technical side, the use of a PEM and the transport as LH2 was assumed in this calculation. As can be seen, this value for green hydrogen is far higher than that of grey and blue hydrogen. Even after significant cost reduction, the difference is more than 2 EUR/kg_{H2}. This difference is not in Germany's political interest. There are two ways to lower this difference. Either the cost of fossil-based hydrogen increases or that of green hydrogen decreases. The options for cost reduction of green hydrogen are discussed in more detail in the following sections. In order to discuss the possibilities for reducing the cost of grey hydrogen, the cost structure is discussed in the following.

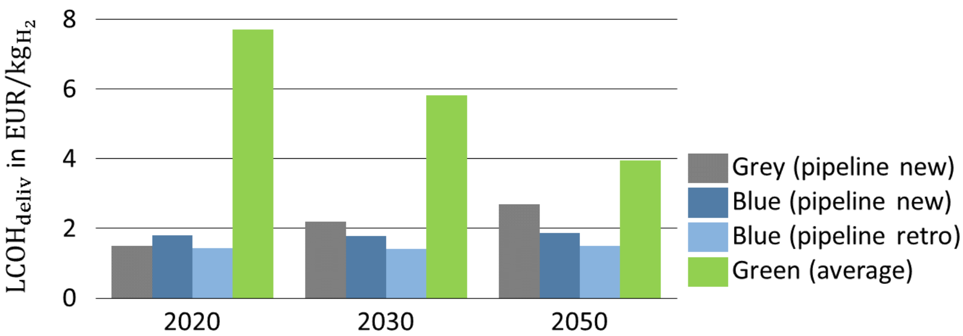


Figure 5-1: *Cost competitiveness with focus on Norway, levelized costs of delivered hydrogen in* EUR/kg_{H2} *('Green' corresponds to average costs of green hydrogen produced via PEM, transported as* LH_2*)*

Second, Figure 5-2 shows the cost structure of grey and blue hydrogen. While the costs for transportation remain stable, the slightly decreasing costs for the reformation process are offset by the slightly increasing production prices of natural in Norway. The sharp increase in the cost of grey hydrogen is due exclusively to rising prices in the EU ETS. The EU ETS is also responsible for the slight increase in the cost of blue hydrogen. It should also be noted that a capture rate of 90 % was assumed for this calculation. This corresponds to an ATR plant with CCS. For an SMR plant, where only 60 % of the carbon dioxide is captured, a stronger increase in costs is to be expected.

Resuming the cost analysis of grey and blue hydrogen from Norway, following key messages can be formulated:

- The cost of natural gas-based hydrogen paths over time is significantly lower than that of green hydrogen paths

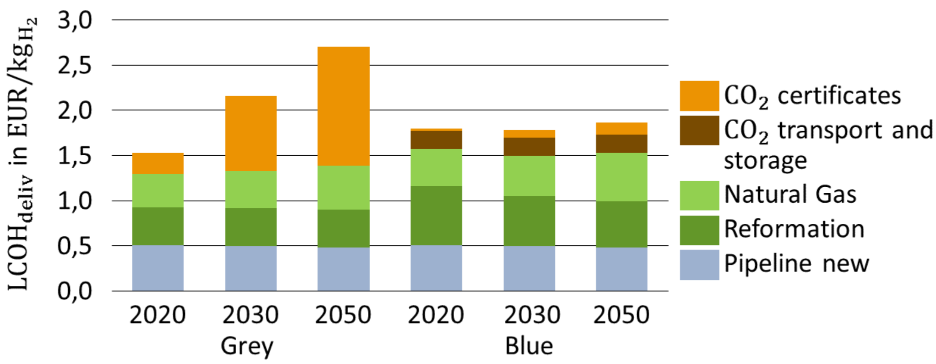


Figure 5-2: *Cost structure of grey and blue hydrogen from Norway, levelized costs of delivered hydrogen in* EUR/kg$_{H2}$

- EU ETS is a central instrument to influence the costs of grey and blue hydrogen
- Using retrofitted Pipelines reduces the LCOH$_{deliv}$ by 0.4 EUR/kg$_{H2}$
- Blue hydrogen can become competitive with grey hydrogen in the short term

Data for the analysis is mainly based on /IEA-06 19/. Estimations for certificate prices of the EU ETS are taken from /EWI-01 20/. The cost of natural gas was taken from Forschungsstelle für Energiewirtschaft (FfE) internal expert knowledge.

Grey hydrogen is expected to be displaced in the future market due to its carbon footprint. The next chapter considers the results of the life cycle analysis of the gas-based production pathways.

5.1.2 Carbon Footprint

Almost the entire demand of the current hydrogen in Germany is covered by grey hydrogen. This is expected to change in the next decades due to the high carbon dioxide emissions /BMWI-05 20/. This subsection discusses the results of a contribution analysis of the GWP100 according to the methodology explained in section 4.4. Thereby, the results of blue hydrogen are related to those of grey hydrogen.

Figure 5-3 shows that grey hydrogen has a total GWP100 of about 10.9 kg$_{CO_2-e.}$/kg$_{H2}$. Blue hydrogen produced in an SMR plant is about half of that and blue hydrogen produced in an ATR plant is about a quarter. The main components of the footprint consist of NGR supply, the process of reformation including CCS, and transportation via pipeline. The contribution of the natural gas supply and transportation is about the same for each path. Essential reduction happens in the reformations process. As explained in subsection 3.3.2, the carbon capture rate in ATR plant reach 90 %, whereas SMR plant only reach about 60 %. This has huge effects on the resulting carbon footprint. However, the electrical energy demand increases with captured carbon dioxide. Its contribution is also clearly shown in Figure 5-3.

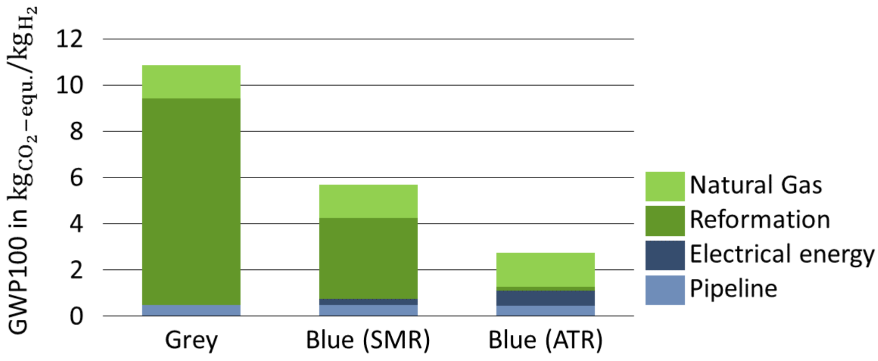


Figure 5-3: *Contribution analysis of GWP100 for grey and blue hydrogen in* $kg_{CO_2-e.}/kg_{H2}$

The following statements can be made under the assumptions of the analysis:

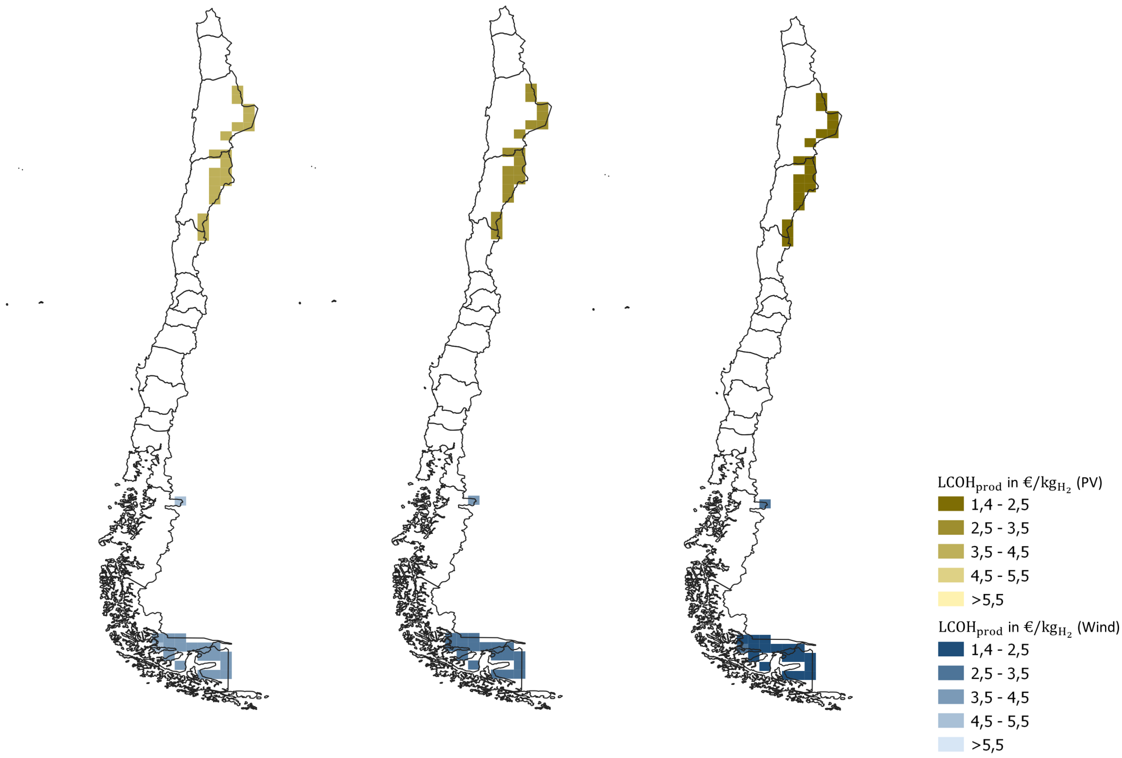
- CCS reduces the GWP100 of grey hydrogen by half (SMR) or even by a quarter (ATR).
- Blue hydrogen is not equal to blue hydrogen in terms of GWP100. The technology must be taken into account.

The green hydrogen considered in the following sections in Chile, Morocco and Australia is expected to be well below the grey hydrogen. For better comparability, the values from this section (grey as well as blue via ATR) are intended to relate the results of the following sections and are therefore also shown in the other graphs.

5.2 Chile

The first case for green hydrogen is regarded as a "hidden champion" /FRO-01 18/. Chile has an enormous potential of renewable energy. In the north the annual solar yield stands at 2500 kW h/m^2. In the south the FLH for wind energy exceed 5000 h. In total the renewable potential is 100 times higher than the actual energy demand of Chile /BMWI-32 19/. These special conditions are also reflected in the global analysis of the LCOH$_{prod}$ in Figure 4-2.

However, this potential has not yet been exploited. Hydrogen offers a unique opportunity to unlock the volume of RES in Chile. With the help of GIZ, Germany has been able to accompany Chile on its way so far. This partnership is described in subsection 5.2.3 in more detail. But first, the costs and ecological footprint of an possible Hydrogen supply paths from Chile to Germany are presented in subsection 5.2.1 and 5.2.2.



(a) *LCOH$_{prod}$ in 2020 at best 10 % of locations in Chile* **(b)** *LCOH$_{prod}$ in 2030 at best 10 % of locations in Chile* **(c)** *LCOH$_{prod}$ in 2050 at best 10 % of locations in Chile* **(d)** *Legend*

Figure 5-4: *Development of LCOH$_{prod}$ over time at best 10 % locations in Chile*

5.2.1 Economic Overview

As already mentioned, Chile has major potential of solar power in the north in the regions Antofagasta and Atacama, as well as high potential of wind power in the south, especially in the region Magallanes y de la Antártica Chilena. Figure 5-4 gives an overview of the best locations for hydrogen production and a first indication of cost development of green hydrogen production until 2050. LCOH$_{prod}$ start between 4.5 and 5.5 EUR/kg$_{H2}$ and decrease to a level of 2 EUR/kg$_{H2}$ by 2050. The data of those location is used for further analysis.

LCOH$_{prod}$ do not correspond to the actual costs of a supply path. Transport costs complement the LCOH$_{prod}$ resulting in LCOH$_{deliv}$ and are often seen as a more critical component. Therefore, Figure 5-5 visualizes the LCOH$_{deliv}$ of green hydrogen produced with solar and wind energy in Chile in comparison with the average LCOH$_{deliv}$ of all three green use cases and the LCOH$_{deliv}$ of grey and blue hydrogen from Norway. It is notable that green hydrogen from Chile is less expensive than the average of green hydrogen. According to those calculation green hydrogen produced with solar energy has the same costs as grey hydrogen in 2050. Further, hydrogen produced with solar power has lower costs than hydrogen produced with wind power and the cost reduction is higher. This can be explained as follows. FLH of wind mills in Chile are higher than the FLH of PV plant. According to equation 4-8, CAPEX are divided by FLH. Thus, declining CAPEX have a higher impact at lower full load hours. This can also be observed in Figure 5-6. In Subfigure 5-6a, it was visualized which renewable energy was the more favorable choice at which location at the electrolyzer costs according to /IEA-06 19/,. Further, in Subfigure 5-6b, CAPEX for the electrolyzers was expected to fall sharply according to /AGORA-11 19/ (see Table A-2). The better locations for PV extend very far south. However, with decreasing CAPEX, they are almost completely displacing wind plants.

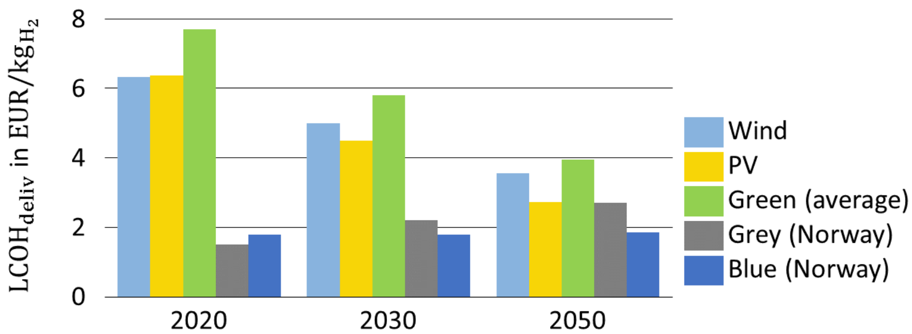
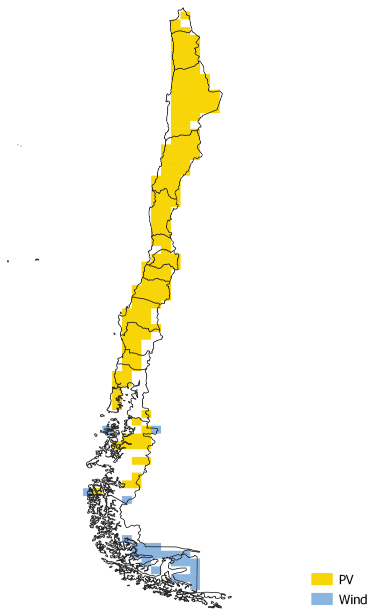
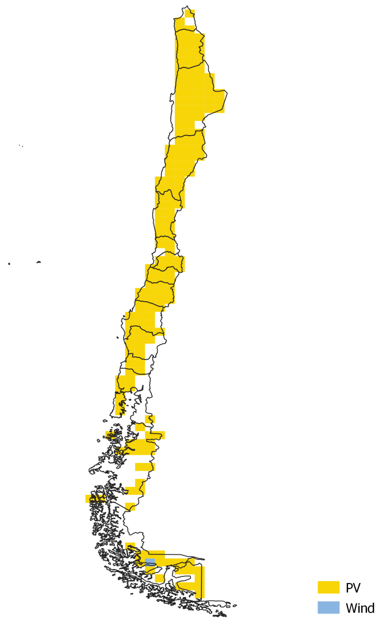


Figure 5-5: *Cost competitiveness with focus on Chile, levelized costs of delivered hydrogen in* EUR/kg_{H2} *('Green' corresponds to average costs of green hydrogen produced via PEM, transported as LH_2), 'Grey' and 'Blue' is taken from figure 5-1 and corresponds to grey and blue (ATR) hydrogen transported via pipeline*

In addition to the choice between wind and solar energy, different electrolysis and hydrogen carrier technologies also have an impact on $LCOH_{deliv}$. Figure 5-7 shows the cost structure of hydrogen produced via AEL and transported via LH_2, hydrogen produced via PEM and transported via LH_2 as well as hydrogen produced via AEL and transported via NH_3. First, one can notice that the costs for the electrolyzer (CAPEX, as well as OPEX) are significantly higher using PEM instead of an AEL electrolysis. This is due to the lower investment costs and longer lifetime of the AEL electrolysis. Nevertheless, the PEM will be used as the default in the following calculations because, as in section 3.3 explained, it can better handle power variations. Second, comparing LH_2 and NH_3 as hydrogen carrier, the resulting $LCOH_{deliv}$ is the same. Contrary, the structure differs. Both conversion processes are expensive, but on the one hand, the transmission process as well as the import terminal is more expensive using LH_2 due to high boil-off losses. On the other hand, reconversion of NH_3 is very energy consuming and therefore, very costly. Therefore, no clearly more favorable technology can be determined for Chile. In Australia's case, LH_2 becomes more expensive as more boil-off losses occur on the long distance. Then NH_3 gains competitiveness. In addition, depending on the end user, it is not necessary to



(a) *Comparison with conservative CAPEX for electrolyzer (see Table A-2)*



(b) *Comparison with low CAPEX for electrolyzer (see Table A-2)*

Figure 5-6: *Best choice of wind or solar as RES for LCOH$_{deliv}$ with conservative and low CAPEX for electrolyzers according to /AGORA-11 19/*

reconvert NH_3.

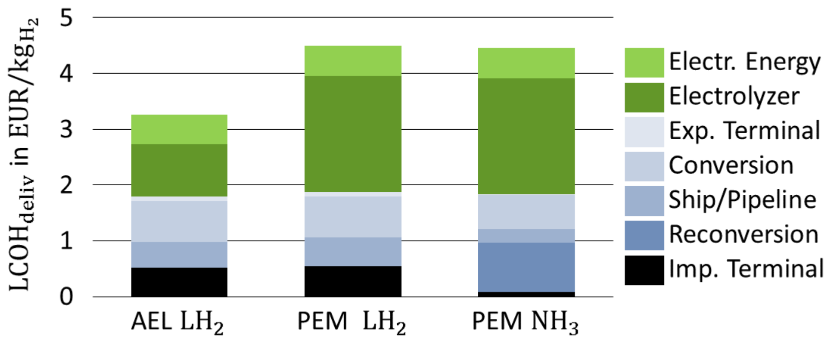


Figure 5-7: *Cost structure of green hydrogen produced with solar power from Chile in 2030, Comparison between AEL and PEM, LH$_2$ and NH$_3$, levelized costs of delivered hydrogen in* EUR/kg$_{H2}$

By analyzing the hydrogen supply paths, the following statements could be concluded:

- LCOH$_{deliv}$ of green hydrogen from Chile is lower than the average green hydrogen
- Declining CAPEX have a higher impact at lower full load hours
- AEL is less expensive than PEM, but PEM is more flexible

- NH_3 and LH_2 as hydrogen carrier in the case of Chile equally expensive, but with longer distances NH_3 is more favorable compared to LH_2
- No reconversion would discount NH_3 as a hydrogen carrier by more than 50 %

In order to be able to evaluate the pathways from Chile in terms of climate neutrality, the results of the LCA for Chile will be presented in the next subsection.

5.2.2 Carbon Footprint

Germany's goal is to import climate neutral hydrogen as part of the energy transition. Therefore, it is important to consider all aspect of climate impact along the supply pathways. In this chapter, the GWP100 of the same pathways are presented, which were also the subject of the economic analysis in subsection 5.2.1.

Figure 5-8 compares wind and solar based hydrogen as well as LH_2 and NH_3 transport in 2030. Thereby, the values of blue and grey hydrogen give a reference point. Several conclusions can be drawn. First, electricity produced via PV has a GWP100 of 51 $g_{CO_2-e.}$/kWh. In contrast, electricity from wind mill has a carbon footprint of 15 $g_{CO_2-e.}$/kWh. This gap goes back to the energy consuming production process of PV-panels. With regard to the carbon footprint of hydrogen, however, this difference results in a GWP100 of 3.2 $kg_{CO_2-e.}/kg_{H2}$ for solar power based hydrogen and 1.2 $kg_{CO_2-e.}/kg_{H2}$ for wind power based hydrogen. Even blue hydrogen has a lower value than solar power based hydrogen. Second, the energy consuming reconversion process of NH_3 add 5.6 $kg_{CO_2-e.}/kg_{H2}$ to the GWP100. The energy for this process is based on the electricity mix for the year 2030 from the Dynamis project /FFE-144 19/. The energy required for the conversion process in the partner country, on the other hand, is covered entirely by the renewable energy generated and is therefore not as significant.

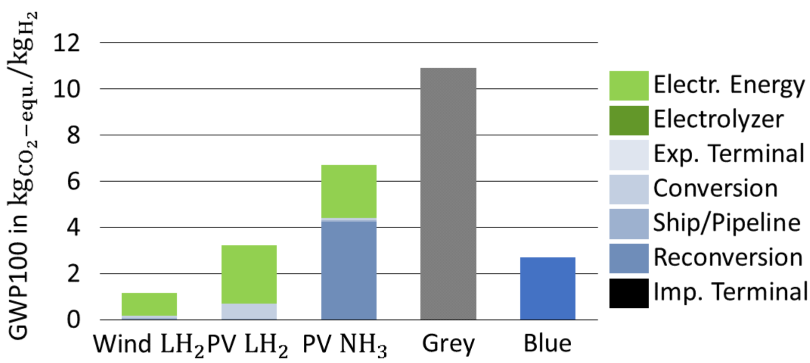


Figure 5-8: *Contribution analysis of GWP100 for green hydrogen from Chile in 2030 in* $kg_{CO_2-e.}/kg_{H2}$*; comparison between AEL and PEM, LH_2 and NH_3*

The results from Figure 5-8 allow the following statements to be made:

- With the assumed electricity mix in Germany, the emissions caused by the re-conversion of ammonia are of significant importance.
- With the assumptions made, solar-based hydrogen has a higher GWP100 than wind-based hydrogen and even blue hydrogen
- Especially, wind-based hydrogen has a low GWP100

Chile actually offers green hydrogen, which has a GWP100 starting with the right choice of technology at 1.2 $kg_{CO_2-e.}/kg_{H2}$. This would support the narrative of the energy transition. In the following subsection, a closer look is taken at the partnership between Germany and Chile.

5.2.3 Energy Partnership

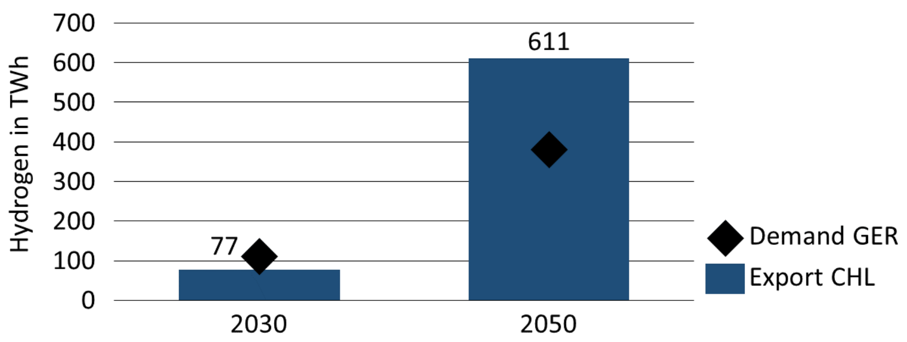


Figure 5-9: *Comparison of Chile's export and Germany's import efforts in* TWh */BMWI-05 20/, /GOC-03 20/*

Chile and Germany agreed to enter in a energy partnership in 2019 and is therefore one of three newcomers. The partnership identifies three key priorities, which are renewable energy, phase-out of coal and hydrogen /BMWI-32 19/.

Looking at the partnership from a German perspective, there are two major interests. First, Germany has an interest in securing its hydrogen supply. Second, Germany wants to open up foreign markets for German technologies /BMWI-05 20/. Both interests can be met by Chile.

Hence, Chile itself has two major interests. First, Chile wants to transform its own energy system socially compatible towards a carbon free system. Therefore, Chile decided in 2019 to phase out coal and projects, that the goal of reaching 70 % of electricity generation with renewable energy by 2050 will be reached before 2030 /GOC-04 20/. Second, Chile wants to sell domestic renewable energy resource in the international market. Hydrogen opens an unique window of opportunity for Chile. In November 2020, Chile published its National Green Hydrogen Strategy

/GOC-03 20/. Figure 5-9 compares Chile's planned export with Germany's demand for hydrogen and indicates that Chile export alone could cover Germany's demand.

German diplomacy directly participated in Chilean interest formation. In a first interinstitutional roundtable, in which Chilean key stakeholder discussed and formed a "common vision for the development of green hydrogen in Chile" /GOC-03 20/, the GIZ was the only foreign institute at the table. Furthermore, in the Plan of Phase-out and/or Reconversion of Coal Units /GOC-04 20/, as well as in the the National Green Hydrogen Strategy /GOC-03 20/, the GIZ is mentioned and thanked for its "constant support". Hence, the GIZ not only manages the energy partnerships, it also actively participates in the process of decision-making.

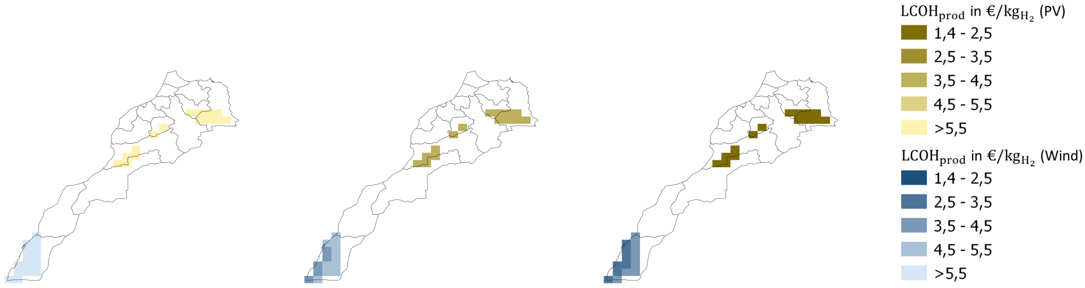
The Haru Oni project can be highlighted as a real success. Green hydrogen produced in the south of Chile will be transported as efuel to Germany by 2020. The project will start in 2022 with a capacity of 130 000 liters (about 1.2 GWh) and will reach a volume of 550 million liters (about 5.5 TWh) in 2026. A consortium was formed including Chilean, German and Italian companies (AME, ENAP, Enel, Siemens Energy and Porsche). Financially, the project has a volume of 35 million euros. The German government is supporting the project with 8.2 million euros from the pot earmarked for the NHS. This project can be seen as the first success of international efforts. Lessons learned from this project will be very helpful for further projects. /SIE-01 20/

5.3 Morocco

Due to the proximity to Europe and the favorable renewable potential, Morocco is in the center of the public debate about hydrogen supply. In the north of the country, solar power is particularly favorable. Wind power has favorable conditions in the south of the country (see Figure 5-10). In addition, Morocco's infrastructure is connected to the European one. Gas pipeline network extends across Spain to Morocco. The electricity grids are also connected. In 2019, Spain imported electricity from Morocco for the first time. These close ties in the energy sector give Morocco a prominent position in the debate. In /FRO-01 18/, Morocco is referred to as "hyped potential". One critical aspect is its political dependence. But even in Figure 4-2, Morocco is not particularly favorable for either solar or wind power. This situation is examined in more detail in this chapter.

5.3.1 Economic Overview

North African countries are always in the debate as possible energy exporters for Europe. Hydrogen has given this debate new momentum. This subsection



(a) *$LCOH_{prod}$ in 2020 at best 10 % of locations in Morocco* **(b)** *$LCOH_{prod}$ in 2030 at best 10 % of locations in Morocco* **(c)** *$LCOH_{prod}$ in 2050 at best 10 % of locations in Morocco* **(d)** *Legend*

Figure 5-10: *Development of $LCOH_{prod}$ over time at best 10 % locations in Morocco*

comparatively describes Morocco's marginal costs to other supply paths.

Figure 5-11 shows the $LCOH_{deliv}$ compared to the green average costs from Chile, Australia, and Morocco and to grey and blue hydrogen from Norway. In this graph, LH_2 was assumed as the hydrogen carrier transported by ship for all paths. Also from Morocco this hydrogen is transported to Germany by ship (Pipeline transport is considered in Figure 5-12). Several points stand out. First, in the preliminary analysis in Figure 4-2, it was already evident that the $LCOH_{prod}$ in Morocco did not highlight. The $LCOH_{deliv}$ are also in the average range. Second, as well as in the case of Chile, the costs for green hydrogen based on solar power decrease more sharply due to lower FLH. Third, the cost of green hydrogen from Morocco remains significantly higher than the cost of blue hydrogen from Norway. A major reason for higher LCOH is interest rates, which are assumed to be higher in non-Organisation for Economic Co-operation and Development (OECD) countries (see Table A-1).

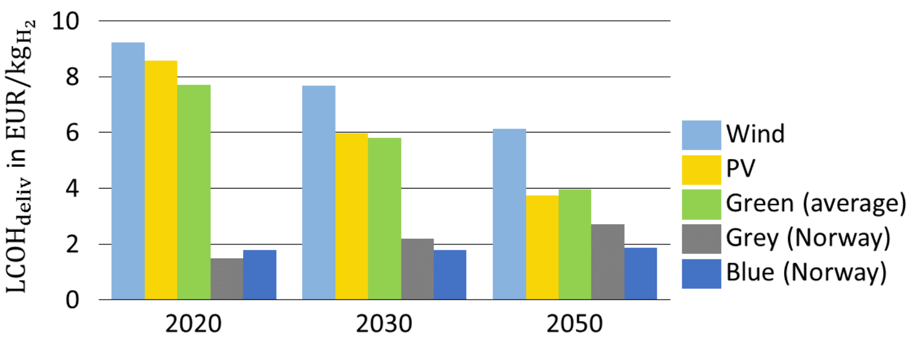


Figure 5-11: *Cost competitiveness with focus on Morocco; levelized costs of delivered hydrogen in* EUR/kg_{H2} *('Green' corresponds to average costs of green hydrogen produced via PEM, transported as LH_2), 'Grey' and 'Blue' is taken from Figure 5-1 and corresponds to grey and blue (ATR) hydrogen transported via pipeline*

Morocco has a clear locational advantage due to its proximity to Europe. Therefore, the assumption of ship transport in Figure 5-11 may not be realistic. Hence, Figure 5-

12 takes a closer look on different option of hydrogen transport and their implication on $LCOH_{deliv}$. Before discussing the transportation options, it should be noted that the high FLH of wind again affect the electrolyzer costs. The cost of electrical energy is due to the significantly higher LCOE generated by wind power in Morocco. Generally speaking, it can be said that pipeline transport is cheaper than ship transport for short distances. After a certain distance, ship transport becomes more expensive. In the case of Morocco, it makes more sense to rely on pipelines. Even newly built pipelines are cheaper than ship transport in terms of $LCOH_{deliv}$ due to less expensive conversion costs. If the existing pipeline network is retrofitted for hydrogen, the costs are about 1 EUR/kg_{H2} less.

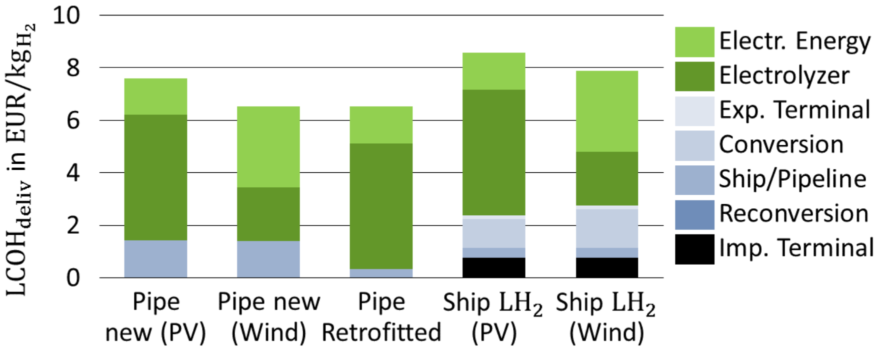


Figure 5-12: *Cost structure of green hydrogen from Morocco in 2020; comparison between new, retrofitted pipeline and ship transport; levelized costs of delivered hydrogen in* EUR/kg_{H2}

Therefore, the following can be concluded:

- For the same transport modes, $LCOH_{deliv}$ are in the global midfield. By using pipelines, however, the costs could be reduced by approx. 2 EUR/kg_{H2}
- High WACC compensate Morocco's good RES potential

With favorable financing and suitable infrastructure, the $LCOH_{deliv}$ from Morocco are therefore quite competitive. The next chapter takes a closer look at the ecological footprint.

5.3.2 Carbon Footprint

This subsection briefly assesses the environmental impact of hydrogen from Morocco. Figure 5-13 compares the GWP100 of hydrogen supply paths via pipeline with hydrogen supply paths via ship. As in Figure 5-12, it also distinguishes between hydrogen produced with solar power and hydrogen produced with wind power. Ship transport has a slightly higher GWP100 due to the energy-intensive conversion. However, this is not very significant, because the hydrogen is liquefied with the renewable electricity on site. If the Moroccan electricity mix were used, the GWP100 would be significantly higher. As in Figure 5.2.2, the difference between hydrogen produced with solar power and hydrogen produced with wind power is clearly higher. Since panels from the world market were deposited in the LCA, this also has the same reason of the environmentally harmful production of the panels.

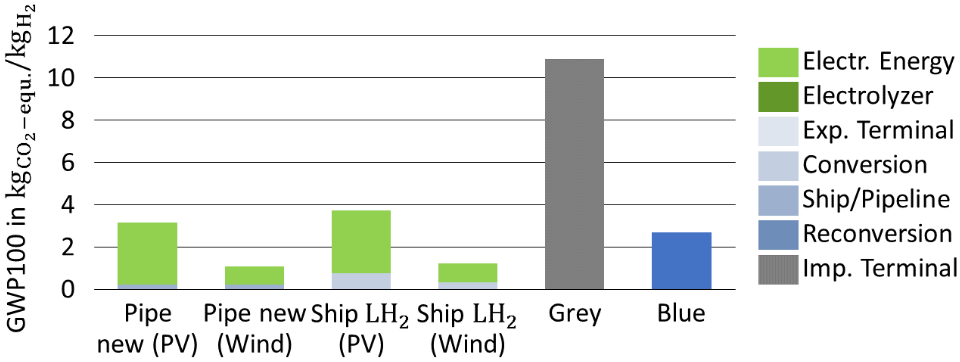


Figure 5-13: *Contribution analysis of GWP100 for green hydrogen from Morocco in* $kg_{CO_2-e.}/kg_{H2}$*; comparison between new, retrofitted pipeline and ship transport*

After the economic and ecological analysis, the next subchapter describes the energy partnership between Morocco and Germany.

5.3.3 Energy Partnership

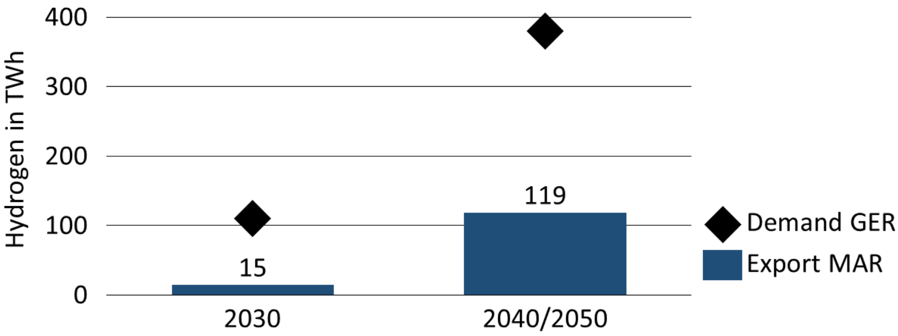


Figure 5-14: *Comparison of Morocco's export and Germany's import efforts in* TWh */BMWI-05 20/, /LBS-01 20/*

The EP was already established in 2012 /GIZ-01 21/ and renewed on a ministerial level in 2016 /PAREMA-01 19/. The partnership is meant to provide institutional framework for political dialogue. Focus were set on topics like renewable energy production, power grid interconnection and electricity markets. In December 2019, hydrogen appeared as an additional topic /BMWI-33 19/.

As described in the German NHS (see subsection 2.3.3), the topic of hydrogen was included in the Moroccan Energy Partnership in order to promote it further. However, the interest is not one-sided. Morocco has already expressed strong interest in deepening the topic of power-to-x in the Berlin Energy Transition Dialogue in

April 2018 /BMWI-33 19/. A study was commissioned by the Moroccan research institute Moroccan Research Institute for Solar Energy and New Energies (IRESEN) in cooperation with the Fraunhofer Institute ISI, IMWS and IGB. This study was published in February 2019 and will serve as the basis for Morocco's hydrogen road map /BMWI-32 19/. The strategy was expected to be published in 2020, but is not yet released /LBS-01 20/. Nevertheless, Morocco is expected to aim to become a global exporter by 2050, covering 2 to 4 % of the global market (see Figure 5-14) /LBS-01 20/.

The German-Moroccan partnership is also already celebrating successes. As already mentioned, electricity was exported from Morocco to Spain for the first time in 2019. Furthermore, Germany has agreed to provide about 90 million euros for the development of a hydrogen industry /RIED-01 20/. But concerns are risen as well. A green hydrogen export could slow domestic energy transition /WI-01 20/.

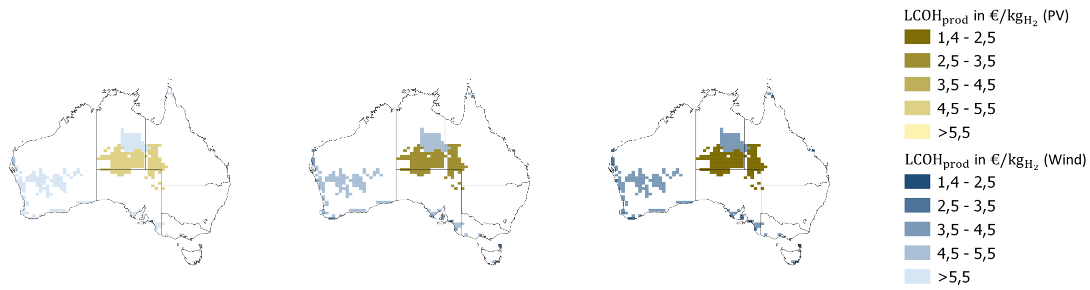
In conclusion, German-Moroccan Energy Partnership (PAREMA) explicitly offers platform for exchange on national energy strategies and contribution to the development of a power-to-x road map /PAREMA-01 19/. German accompaniment is also evident in the research and preparation of the Moroccan Hydrogen Strategy. Lastly, concrete financial funding is offered to support German-Moroccan projects. In terms of smart power, the interaction of the financial and institutional dimensions can be seen here (see subsection 2.3.3).

As a final case study, Australia is considered in the following section. Here, the long distance and the proximity to the other dedicated hydrogen importer Japan is interesting.

5.4 Australia

Australia, a continent in its self, has not only vast areas but also high renewable potential and is therefore rightly called the "giant" /FRO-01 18/. Figure 5-15 shows that the areas with the most favorable solar irradiation are located inland. In contrast, wind power is more spread across the country. In Australia, hydrogen has been on the political agenda for some time. Japan has been committed to hydrogen for a long time and, along with Germany and South Korea, is considered a major future hydrogen importer. Hence, both countries Australia and Japan are close allies with regard to hydrogen. /COAG-01 19/

For Germany, Australia is particularly interesting because of technological exchange and high potential of hydrogen production. This chapter also pays attention to the long distance between Germany. It turns out that ammonia is more favorable at long distances.



(a) *$LCOH_{prod}$ in 2020 at best 10 % of locations in Australia* **(b)** *$LCOH_{prod}$ in 2030 at best 10 % of locations in Australia* **(c)** *$LCOH_{prod}$ in 2050 at best 10 % of locations in Australia* **(d)** *Legend*

Figure 5-15: *Development of $LCOH_{prod}$ over time at best 10 % locations in Australia*

As in previous section, this section begins with the economic assessment, then moves on to the environmental analysis and ends with the description of the energy partnership.

5.4.1 Economic Overview

Australia has a large capacity of hydrogen production. $LCOH_{deliv}$ from Australia can also keep pace with hydrogen production costs from other countries.
Figure 5-16 first shows that Australia is above the average of the other green countries. But the values in the graph all refer to LH_2 as a hydrogen carrier. However, unlike NH_3, LH_2 has high boil-off losses. These become more and more important with increasing distance. Comparing the relationship between pipelines and ship transport, there is a break even point for LH_2 and NH_3, where the high conversion costs of NH_3 are lower than the boil off losses of LH_2. Figure 5-17 shows that over the long distance between Australia and Germany (see Table A-6), NH_3 is the cheaper choice even with reconversion in Germany. Nevertheless, the costs are higher than the costs of hydrogen from Norway.
In this subsection following can be summarized:

- As a hydrogen carrier, NH_3 becomes more economical than LH_2 for long distances.

The next subsection briefly discusses the ecological footprint.

5.4.2 Carbon Footprint

The overall picture of the GWP100 for Australia in Figure 5-8 is similar to the results for Chile in subsection 5.2.2 and Morocco in subsection 5.3.2. Hydrogen produced from solar energy has a higher GWP100 than hydrogen produced from wind

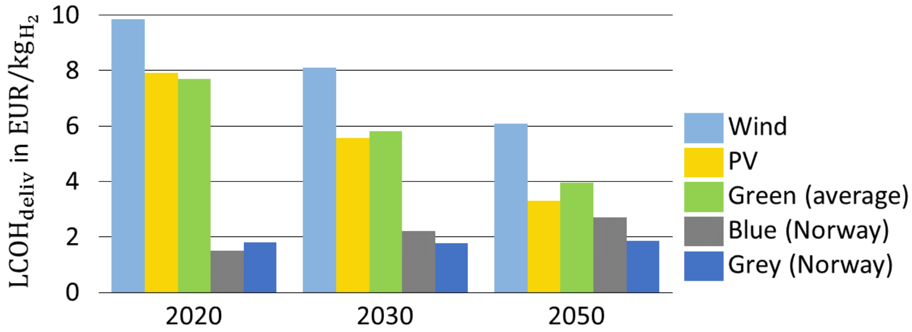


Figure 5-16: *Cost competitiveness with focus on Australia, levelized costs of delivered hydrogen in* EUR/kg$_{H2}$ *('Green' corresponds to average costs of green hydrogen produced via PEM, transported as* LH_2*), 'Grey' and 'Blue' is taken from Figure 5-1 and corresponds to grey and blue (ATR) hydrogen transported via pipeline*

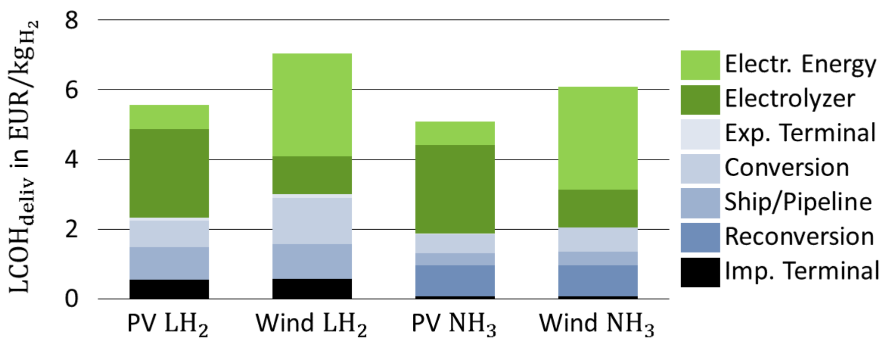


Figure 5-17: *Cost structure of green hydrogen from Australia in 2030; levelized costs of delivered hydrogen in* EUR/kg$_{H2}$*; comparison ship transmission using as* LH_2 *and* NH_3 *hydrogen carrier*

energy and using NH_3, the reconversion process is responsible for the most emissions.

Furthermore, comparing the results from Figure 5-18 with the results from Chile in Figure 5-8, it can be seen that the GWP100 for the supply pathway with LH_2 is $1\,kg_{CO_2-e.}/kg_{H2}$ higher. This is attributable to the higher boil-off losses. The difference between the pathways from Chile and Australia is smaller for NH_3, because NH_3 has fewer losses during transport. Thus, it can be noted that also in terms of GWP100, NH_3 becomes more attractive with increasing distance compared to LH_2. Therefore, the following can also be stated in the ecological sense:

- As a hydrogen carrier NH_3 becomes ecologically more reasonable than LH_2 for long distances

In the following the energy partnership with Australia is reviewed.

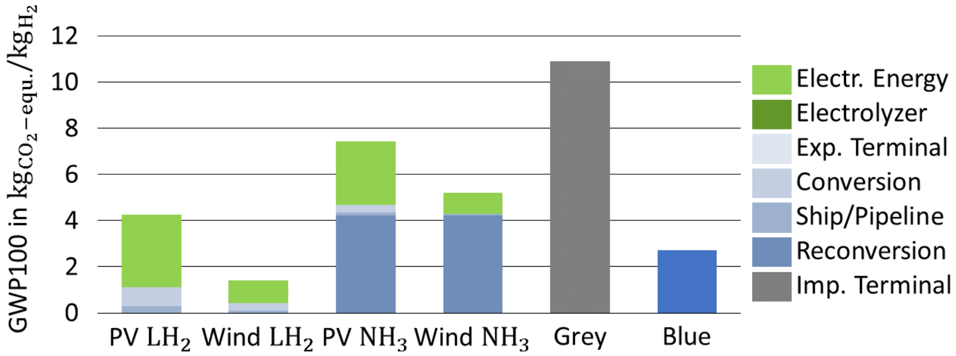


Figure 5-18: *Contribution analysis of GWP100 for green hydrogen from Australia in* $kg_{CO_2-e.}/kg_{H2}$; *comparison ship transmission using as LH_2 and NH_3 hydrogen carrier*

5.4.3 Energy Partnership

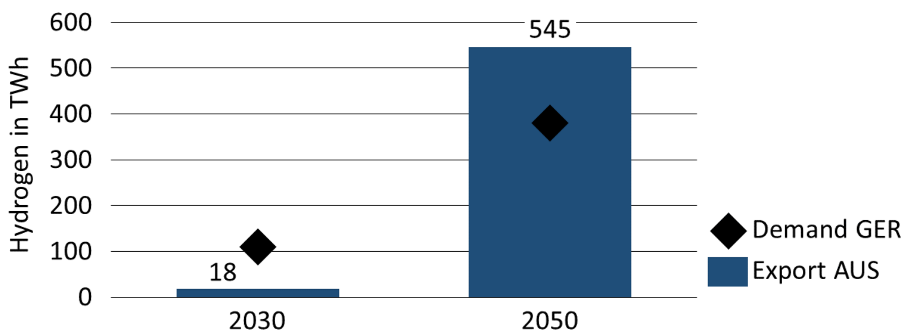


Figure 5-19: *Comparison of Australia's export and Germany's import efforts in* TWh */BMWI-05 20/, /COAG-01 19/*

Australia sees hydrogen as an opportunity to participate in economical value creation as a global exporter. The National Hydrogen Strategy does mention hydrogen quantities that may be exported in 2050 (see Figure 5-19). However, these are not explicitly stated as targets. Like Germany, it counts on energy partnerships, financial support and emphasis acceptance issues. The partnership with Germany was already established in 2017 and focuses heavily on research /IASS-01 20/. But Germany is not mentioned in the Australian NHS. The focus is much more on South Asia. China, Japan and the Republic of Korea have already agreed to become hydrogen customers. Nevertheless, Australia wants to become a global exporter and wants to get more involved in bilateral partnerships. /COAG-01 19/

Based on the GIZ reports, it can be seen that the partner countries Australia and Germany only started to actively focus on hydrogen in 2018 and 2019. As already mentioned, the partnership between Australia and Germany was established in 2017. In the first reports no Power-to-X or hydrogen related topics were on the agenda /BMWI-18 18/. Instead, focus was set on energy efficiency in industry and economic cooperation. It was not until 2018 that the hydrogen talks began /BMWI-33 19/. In the most recent report, hydrogen was the first topic mentioned /BMWI-32 19/.

Japan, which paved the way for a hydrogen society in the fourth strategic Energy Plan in 2014 /LBS-01 20/, is already further along in its relationship with Australia. For example, a cooperation agreement for market creation was signed by both countries. Furthermore, successful project between both countries were executed. The Hydrogen Energy Supply Chain (HESC)-Project installed an entire supply chain from Australia to Japan. The hydrogen carrier was liquid hydrogen. For this purpose, the first and only purposely built LH_2-tanker was used.

Another point is that Australia is committed to technology openness in its NHS /BMWI-32 19/. For example, the hydrogen in the HESC-project is based on coal-fired electricity. Germany, on the other hand, clearly focuses on green hydrogen in its NHS /BMWI-05 20/.

In summary, Germany is late in positioning German companies as partners in Australia's very first projects. Also, no participation of the GIZ in the hydrogen strategy preparation process was detectable. Nevertheless, Australia stands out as a committed partner in the hydrogen economy and is a technological frontrunner, especially in cooperation with Japan.

After examining the four cases, the next chapter 6 recapitulates and discusses the insights. The findings are collected and structured within the Smart Power framework.

6 Implications for Power Resources and Measures

Chapter 5 presents the results of the economic assessment, the ecological analysis and the review of the energy partnerships. The discussion in this chapter combines the insights from the quantitative and qualitive analysis with the power resources identified in subsection 2.3.3. Regarding this, section 6.1 first considers which outcomes support Germany's power resources in the energy sector. This is followed by a discussion in section 6.2 of power measures that Germany is already using and of those measures which could be used in the future. It is important to note that all statements are subject to the scope and assumptions of the quantitative analysis.

6.1 Review and Impact on Germany's Power Resources

This work identified three power resources held by Germany in the energy sector: first, the narrative *Energiewende*, which developed over time and promises that a climate neutral society is economic and technological feasible; second, a institutional network that brings players and parties together and that allows you to put issues on the agenda; third, the financial resources that Germany is willing to provide. This section refers back to the power resources introduced in subsection 2.3.3 and draws first developments of those resource using the findings of chapter 5. It thereby goes into more detail on the second part of the following research question:

- What does Smart Power mean in the context of hydrogen supply and how do hydrogen dynamics affect Germany's Smart Power?

The narrative can be broadened by enabling hydrogen to boost the energy transition outside the electricity sector. However, it can also be deepened by strengthening credibility. The narrative *Energiewende* portrays Germany as a reliable partner that is committed to the energy transition. From this resource of credibility, Germany emphasizes economic cooperation. In energy partnerships, for example, mutual economic cooperation is one of the top priorities. Thus the notion of a lucrative green hydrogen economy that is becoming a reality is supported, even though green hydrogen is still far behind grey hydrogen according to the results of the cost analysis. In contrast to Norway and Australia, Germany directly commits to green hydrogen in its national hydrogen strategy. Germany thus remains consistent with the ecological aspect of the narrative and proves its credibility. Furthermore, Germany underlies its commitment to green hydrogen with a clear financial pledge.

Another aspect of the narrative is the economic feasibility. The analysis clearly shows that green hydrogen is more expensive than fossil hydrogen. It is necessary to take measures to make climate-neutral hydrogen competitive, in order to support the narrative. Hence, if the measures described in the next chapter are successful in making hydrogen competitive, they will thus strengthen the narrative.

In the dimension of the network, Chapter 5 primarily looks at energy partnerships, using four examples. But beyond the four partnerships, it should be noted that Germany explicitly highlights the importance of strengthening the existing energy partnerships and the creation of new ones. This effort supports the creation of the hydrogen economy, but it also supports Germany's enduring power resource, even in the long term. Especially the young partnership with Chile shows that promising results can be achieved through successful diplomacy, both on the political level, where the GIZ has accompanied the NHS, and on the economic level, where the Haru Oni project was launched. This resource will also have a positive impact on Germany's international cooperation in other future issues.

Also in the financial resource, the results show that companies of the partner countries and German companies benefit from Germany's funding. The Chilean, Italian and German consortium carrying out the Haru Oni project will receive 8.3 million euros from the budget established under the National Hydrogen Strategy. Moroccan projects will also receive 70 million euro in loans. This shows that Germany is able and willing to financially support its interests.

This section has described the impact of hydrogen on Germany's power resources in the energy sector. The next chapter describes the measures that Germany is using and which measures could still be used in order to strengthen the power resources further or in order to prepare for a favorable hydrogen supply.

6.2 Measures Already in Place and Further Proposals

Similar to section 6.1, this section goes through each of the three identified power resources and describes the power measures that Germany already uses and gives an outlook which measures could further be used in the future. Hence, in this section especially the last research question is tackled:

- What measures are and can be used to secure hydrogen supply by Germany?

A transparent communication and a clear certification could strengthen the narrative *Energiewende* further. The analysis shows that there are clear differences between the paths in an ecological sense. With the right choice of technologies, it is possible to import low-emission hydrogen to Germany. In particular, the analysis shows that the supply pathway based on wind has a GWP100 of less than $1.5\,\mathrm{kg_{CO_2-e.}}/\mathrm{kg_{H2}}$, which is about 6 times less than the GWP100 for grey hydrogen. Furthermore, it cannot be assumed that green hydrogen has a GWP100 of $0\,\mathrm{kg_{CO_2-e.}}/\mathrm{kg_{H2}}$. Under the given assumptions and in the scope of the thesis, hydrogen produced with solar energy always has a higher GWP100 than blue hydrogen via ATR. Of course, risks and side effects of carbon dioxide storage are not included and the high GWP100 is largely due to the fact that the electricity for the energy-intensive production process of solar panels is mainly based on fossil fuels. Also, in the debate about blue hydrogen, it is important to distinguish whether the hydrogen is produced via SMR or ATR. In addition, it is also important to consider the end use and the distance between export and import country when choosing hydrogen carriers. But the right choice of technologies enables favorable and climate-friendly hydrogen supply path. Those would strengthen the narrative. However, these are dependent on various factors such as distance, renewable energy potential, or end-use. A policy maker does not have make this choice. Instead, he could enable transparency as basis for public discussion and technology openness.

In addition, an open discussion about carbon storage and the GWP100 of green hydrogen would help to retain credibility by not ignoring the negative aspects of hydrogen. Even though Germany is clearly committed to green hydrogen, it indicates blue hydrogen as a transition technology. However, blue hydrogen has a lower GWP100 than green hydrogen produced with solar energy, but requires long-term carbon storage. Moreover, it has shown that the environmental footprint of green hydrogen, especially solar based hydrogen, is not zero. The German government could engage in a domestic debate not to lose trust.

Furthermore, Germany could argue via the narrative *Energiewende* in order to advocate for a strong EU ETS. The EU ETS is an essential link between carbon dioxide emissions and the economy, as also shown by the cost trend of grey hydrogen in subsection 5.1.1.

At the network level, the Germany's NHS itself states that existing energy partnerships shall be strengthened and new ones established. Both measures strengthen the resource of the network itself, but also aim directly at building the hydrogen economy. The new focus on hydrogen in existing partnerships is particularly evident in the GIZ reports. Within two years, the topic of hydrogen was set as a focus topic in 9 partnerships /BMWI-18 18/, /BMWI-32 19/. The case studies also show that

GIZ itself as a coordinator of the energy partnerships played a central role in the formation of the hydrogen strategy, especially in Chile and Morocco. In Chile, GIZ participated in the first stakeholder roundtable and continued to support the ministry in the process, so that GIZ was explicitly thanked in the Chilean NHS. In Morocco, a similar approach was not evident. However, the study carried out in the framework of the partnership between Moroccan and German research institutes is considered as basis for the upcoming hydrogen strategy. In this case, the partnership supports the realization of the Moroccan NHS also on the scientific level. The first signs of success are visible with regard to hydrogen in the energy partnerships. Hence, Germany could develop further partnerships. Canada or Iceland would be suitable in the short term. /BMWI-21 20/. In addition, the formation of consortia has been a promising approach so far. Both the Haru Oni project in Chile and the Hydrogen Energy Supply Chain (HESC)-project in between Japan and Australia were initiated in this way. At the European level, such an institution is already being created with the Hydrogen Alliance, which is intended to bring stakeholders together. At the German level, the H2 Global Foundation is to be established. On the one hand, it will mediate between stakeholders. On the other hand, it will manage the money for international co-operations that were announced in the NHS /GRÜGE-01 20/.

In the financial dimension, Germany also has significant measures in place. The results of the economic analysis show that a significant difference gapes between $LCOH_{deliv}$ of green and conventional hydrogen. This difference can be bridged by three approaches. First, one makes the grey hydrogen more expensive. A policy called EU ETS for this purpose has been implemented across Europe. Second, the cost of green hydrogen decreases. This can be realized by scaling effects and market maturity. For this purpose, specific technologies or entire projects can be funded. In Germany, for example, living laboratories are being deployed to promote technical maturity in practice. This would also be conceivable for the international context. In order to promote specific technologies, e.g. the electrolyzer, which has a high share especially in hydrogen costs produced by solar energy, is a good choice. But also support for the development of infrastructure has a high leverage. However, the high conversion costs are difficult to achieve with financial measures. Support for OPEX could be useful here. Thirdly, the difference is bridged by public funding. This is how renewable electricity was introduced into the electricity market. Also in the case of hydrogen, the H2 Global Foundation is supposed cover the difference between the market price and the price for the supply of green hydrogen, including a margin, by means of CCfDs /GRÜGE-01 20/.

Lastly, Germany can be expected to become a major hydrogen consumer. Estimates for the hydrogen market in 2050 are between 3000 TWh and 10 000 TWh /COAG-01 19/. As Germany has announced to consume 380 TWh, Germany declared itself an important customer covering about 4 to 13 % of the global market. This makes Germany an attractive partner for countries aiming to establish themselves as global exporters.

This chapter reviews the findings by linking the results of the data-based analysis from chapter 5 to the concepts from chapter 2. The following chapter looks back again at the work as a whole and gives further suggestions.

7 Conclusion and Suggestions

This thesis provided on the one hand concrete insights and on the other hand an in-depth as well as a holistic understanding of hydrogen supply by tackling the overarching research question:

- How can Germany prepare for an advantageous hydrogen supply applying the Smart Power concept by Jospeh S. Nye?

Hydrogen supply is a multi-dimensional and multi-layered subject. To encompass the complexity of hydrogen supply, this thesis approached the issue from a geostrategic perspective by identifying power resources to derive power measures. The derivation of measures was enriched by insights from an economic, ecological and institutional analysis of hydrogen supply costs, global warming potential of imported hydrogen and energy partnerships. In the course of this work, multiple insights were gained in addition to the measures.

In the following, key messages of this thesis are summarized (see section 7.1). The suggestions in section 7.2 reviews aspects to refine the analysis and identifies exciting fields for further research.

7.1 Conclusion

This section concludes on the key findings of the analysis of this thesis. Before presenting them, it is noted that the quantitative analysis holds many insights into the costs and environmental impacts of each technology. The following list is focusing on key aspects and is not claiming to be exhaustive. Therefore, one can refer back to chapter 5 for more specific insights:

- **Through its role in the energy transition to this point, Germany has built up Smart Power resources that are useful in hydrogen economy.** These power resources are the narrative *Energiewende* that has developed over decades, the diplomatic structures that Germany has created in recent years, and the promise of being an attractive financial donor.

- **These power resources are strengthened by the dynamics created by the hydrogen subject.** Especially, the narrative *Energiewende* is broadened (hydrogen expands the narrative from the electricity sector to the entire energy sector) and deepened (hydrogen pushes forward the energy transition and creates a new opportunity for business) as well as the diplomatic network is intensified and expanded.

- **It makes sense to strengthen or establish new energy partnerships.** Diplomatic structures can actively participate in the process of interest formation. The role of GIZ in the creation of the Chilean NHS can be seen as an example.

- **The choice of supply paths and technologies has a strong impact on GWP100.** Therefore, transparency of GWP100 and a clear certification of hydrogen carbon footprint could increase credibility.

- **The choice of technologies for optimal supply costs depends on multiple parameters. Policy makers should not exclude specific technologies.** The optimal choice of technologies depends on parameters such as distance or end-use. An universal best supply path does not exist.

- **Policymakers can actively seek to close the cost gap between grey and green hydrogen, as it otherwise will remain for the foreseeable future.** This can be done by subsidizing technologies or projects so that green hydrogen becomes cheaper, by making grey hydrogen more expensive, for example with the help of the EU ETS, and by covering the differential costs through CCfDs.

- **Consortia formation involving consumer and producer, as well as living labs are a feasible and promising way to start the market.** Haru Oni project in Chile and the Hydrogen Energy Supply Chain (HESC) between Australia and Japan are promising examples.

7.2 Suggestions

This section looks at the approach taken in the analysis and makes suggestions for further research. Following aspects provide potential for more specification and further research:

- The Smart Power concept was used in this analysis to link intitutional, economic and environmental aspects. Three power resources were identified. However, these power resources are not exhaustive. A broader analysis of these power resources would further deepen the understanding of Germany's influence in the international energy economy. The EU, for example, significantly influences geostrategic politics, but was not considered in this thesis.

- A key message of the study is that Germany's Smart Power resources can be expanded. It was not considered that they can also be endangered. For example, the narrative *Energiewende* could be weakened by a loss of trust in the event of a large-scale blackout of the electrical grid. A change in political leadership can also affect the direction of energy partnerships. In Germany, Angela Merkel's term in office will end in 2021. The consequences of a change at the head of government are unknown. Furthermore, institutional stability in partner countries is not necessarily permanent.
- Energy partnerships play an essential role. The scope was narrowly focused on four already existing energy partnerships. An analysis of further countries could validate the statements of this thesis.
- Water supply was not considered in the economic analysis or in the ecological analysis. However, this process step can, under certain circumstances, make a significant contribution to the total account, especially if the use of desalination plants is necessary.
- In the LCA, the production and construction of the PV and wind plants were based on an energy mix from the past. Since it is expected that this will change in the future. This could also be adjusted.
- The EU ETS was considered as the only regulatory instrument. Of course, there are other instruments such as taxes or levies. The inclusion of these elements could bring the cost analysis closer to the market economy.
- It was assumed that no intermediate storage is installed between the renewable energy plant and the electrolyzer. An optimization of such a storage facility as well as the dimensioning of the electrolyser would refine the cost analysis
- The export of green hydrogen could slow down the local energy transition. A holistic analysis of the energy mix of both countries would be useful for future considerations.

References

AGORA-07 20 Prognos et al.: Klimaneutrales Deutschland - In drei Schritten zu null Treibhausgasen bis 2050 über ein Zwischenziel von -65

AGORA-11 19 Deutsch, Matthias et al.: EU-wide innovation support is key to the success of electrolysis manufacturing in Europe - Background. Berlin: Agora Energiewende, 2019.

AUS-02 19 Energiepartnerschaften. In: https://www.auswaertiges-amt.de/de/aussenpolitik/themen/energie/energiepartnerschaften/238784. (Abruf am 2021-02-22); Berlin: Auswärtiges Amt, 2019.

BBU-01 20 Cormos, Calin-Cristian et al.: Environmental evaluation of european ammonia production considering various hydrogen supply chains. In: Renewable and Sustainable Energy Reviews 130/2020. Cluj-Napoca, Romania: Faculty of Chemistry and Chemical Engineering, Babes-Bolyai University, 2020.

BDI-01 20 Thesen, Jill: Wasserstoff - Energieträger der Zukunft. In: https://bdi.eu/artikel/news/wasserstoff-energietraeger-der-zukunft/. (Abruf am 2021-02-15); Berlin: Bundesverband der Deutschen Industrie e. V. BDI, 2020.

BMU-01 20 Klimaschutz in Zahlen 2020 - Fakten, Trends und Impulse deutscher Klimapolitik. Berlin: Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU), 2020.

BMWI-05 20 Die nationale Wasserstoffstrategie. Ausgefertigt am 2020-06-10; Berlin: Bundesministerium für Wirtschaft und Energie (BMWi), 2020.

BMWI-18 18 BMWi: Jahresbericht 2017 - Energiepartnerschaften. Berlin: Bundesministerium für Wirtschaft und Energie, 2018.

BMWI-21 20 Jensterle, Miha et al.: Grüner Wasserstoff: Internationale Kooperationspotenziale für Deutschland - Kurzanalyse zu ausgewählten Aspekten potenzieller Nicht-EU-Partnerländer. Berlin: Bundesministerium für Wirtschaft und Energie, 2020.

BMWI-32 19 BMWi: Energy Partnerships and Energy Dialogues. Berlin: Federal Ministry for Economic Affairs and Energy, 2019.

BMWI-33 19 BMWi: Jahresbericht 2018 - Energiepartnerschaften und Energiedialoge. Berlin: Bundesministerium für Wirtschaft und Energie, 2019.

BUTT-01 17 Buttler, Alexander et al.: Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. Amsterdam: Renewable and Sustainable Energy Reviews, 2017.

CGS-01 13 Bohnenberger, Fabian: Modell "Handelsmacht". Bonn: Center for Global Studies, 2013.

COAG-01 19 Australia's national hydrogen strategy. Canberra: COAG Energy Council Hydrogen Working Group, 2019.

COFR-01 09 Nye Jr, Joseph S.: Get smart: Combining hard and soft power. New York: Council on Foreign Relations, 2009.

CYUT-01 17 Nikolaidis, Pavlos et al.: A comparative overview of hydrogen production processes. Cyprus: Department of Electrical Engineering, Cyprus University of Technology, 2017.

DIN-02 06 DIN 14040 – Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen (ISO 14040:2006) - Deutsche und Englische Fassung EN ISO 14040:2006. Berlin: DIN Deutsches Institut für Normung e. V. (DIN), 2006

DIN-03 06 Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen (ISO 14044:2006); Deutsche und Englische Fassung EN ISO 14044:2006. Berlin: DIN Deutsches Institut für Normung e.V., 2006.

EC-05 20 European Commission: Declaration of the European Clean Hydrogen Alliance. 2020.

ECOFYS-01 19 Steinbacher, Karoline et al.: An outlook on Germany's international energy transition policy in the years to come: Solid foundations and new challenges. In: Energy Research & Social Science 49/2019. Berlin: Ecofys, a Navigant Company, 2019.

ECOINV-01 19 The ecoinvent Database, Version 3.6: www.ecoinvent.org; Zürich: ecoinvent, 2019.

ENERG-01 21 Seelos, Christian: Energate blickt zurück: das war das Energiejahr 2020. In: https://www.energate-messenger.de/jahresrueckblick. (Abruf am 2021-01-21); Essen, Germany: energate messenger, 2021.

ESWG-01 20 Debatte: Wasserstoff - Zukunftsenergie oder Sackgasse?. In: https://www.erdgas-suedwest.de/natuerlichzukunft/veranstaltung-wasserstoff-zukunftsenergie-sackgasse/. (Abruf am 2021-02-02); Ettlingen: Erdgas Südwest GmbH, 2020.

ETH-03 20 Antonini, Christina et al.: Hydrogen production from natural gas and biomethane with carbon capture and storage - A techno-environmental analysis. Zürich: ETH Zürich, 2020.

EUROSTAT-03 20 A hydrogen strategy for a climate-neutral Europe. Brüssel, Belgien: Europäische Kommission, 2020.

EWI-01 20 Brändle, Gregor et al.: Estimating Long-Term Global Supply Costs for Low-Carbon Hydrogen. Köln: Institute of Energy Economics at the University of Cologne (EWI), 2020.

FFE-113 20 Pichlmaier, Simon et al.: Integration of Renewable Energies through the Production of Hydrogen under Investigation of Disruptive Developments in Investment Costs: A Techno-economic Evaluation. München: Forschungsgesellschaft für Energiewirtschaft mbh, 2020.

FFE-12 17 Regett, A.; Conrad, J.; Fattler, S.: Das Verbundprojekt Dynamis - Dynamische und intersektorale Maßnahmenbewertung zur kosteneffizienten Dekarbonisierung des Energiesystems in: BWK Ausgabe 1/2 2017, S. 58. Düsseldorf: Verein Deutscher Ingenieure (VDI), 2017

FFE-144 19 Fattler, Steffen; Conrad, Jochen; Regett, Anika et al.: Dynamis Hauptbericht - Dynamis - Dynamische und intersektorale Maßnahmenbewertung zur kosteneffizienten Dekarbonisierung des Energiesystems - Online: https://www.ffe.de/dynamis. München: Forschungsstelle für Energiewirtschaft e.V., 2019. DOI: 10.34805/ffe-144-19

FFE-55 18 Laufendes Projekt: BEniVer - Begleitforschung Energiewende im Verkehr. In: https://www.ffe.de/beniver. (Abruf am 2019-01-21); (Archived by WebCite® at http://www.webcitation.org/75aqGM5Uf); München: Forschungsstelle für Energiewirtschaft e. V., 2018.

FRO-01 18 International Aspects of a Power-to-X Roadmap - A report prepared for the World Energy Council Germany. Köln: Frontier Economics Ltd., 2018.

GER-02 16 Li, Lina: Soft Power for Solar Power: Germany's New Climate Foreign Policy. Berlin: Germanwatch e.V., 2016.

GIZ-01 21 Raisch, Veit-Clemens: Deutsch-Marokkanische Energiepartnerschaft. In: https://www.giz.de/de/weltweit/57157.html. (Abruf am 2021-03-01); Bonn: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, 2021.

GMAO-01 18 MERRA-2 - Modern-Era Retrospective analysis for Research and Applications, Version 2: https://gmao.gsfc.nasa.gov/reanalysis/; Greenbelt (MD, USA): Global Modeling and Assimilation Office (GMAO), 2018.

GOC-03 20 Ministry of Energy: National Green Hydrogen Strategy. Santiago, Chile: Government of Chile, 2020.

GOC-04 20 Ministry of Energy: Plan of Phase-out and/or Reconversion of Coal Units. Santiago, Chile: Government of Chile, 2020.

GRÜGE-01 20 Junker, Carmen: Welche Wasserstoff Förderung gibt es?. In: https://www.gruenesgeld24.de/welche-wasserstoff-foerderung-gibt-es/. (Abruf am 2021-03-01); Aschaffenburg: Grünes Geld, 2020.

GSEA-01 06 Hoffmann, W.: PV on the way from a few lead markets to a world market. Alzenau: German Solar Economy Association, 2006.

HEID-01 20 Pawelec, Grzegorz et al.: Clean Hydrogen - Monitor 2020. Brussels, Belgium: Hydrogen Europe Intelligence Department, 2020.

HU-01 15 Goldthau, Andreas et al.: Soft power with a hard edge: EU policy tools and energy security. In: Review of International Political Economy 22/2015. Cambridge, MA, USA: Belfer Center for Science and International Affairs, Harvard Kennedy School of Government, Harvard University, 2015.

IASS-01 20 Quitzow, Rainer et al.: The German energy transition as soft power. In: Review of International Political Economy 27/2020. Potsdam, Germany: Institute for Advanced Sustainability Studies e.V., 2020.

IASS-04 16 Quitzow, Rainer et al.: The German Energy Transition in International Perspective. Potsdam, Germany: Institute for Advanced Sustainability Studies (IASS), 2016.

IEA-05 19 The Future of Hydrogen - Seizing today's opportunities. Paris: IEA, 2019.

IEA-06 19 IEA G20 Hydrogen report: Assumptions. Paris: IEA, 2019.

IEA-102 17 Energy Policies of IEA Countries Norway - 2017 Review. Paris, Frankreich: International Energy Agency (IEA), 2017.

IPCC-02 13 Stocker, Thomas F. et al.: Climate Change 2013 - The Physical Science Basis - Part of the Working Group I Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Genf, Schweiz: Intergovernmental Panel on Climate Change ipcc, 2013.

ITUL-01 13 Lucas, Alexandre et al.: Energy supply infrastructure LCA model for electric and hydrogentransportation systems. In: Energy 56/2013. Porto Salvo, Portugal: MIT Portugal Program, IST-Technical University of Lisbon, 2013.

LBS-01 20 Albrecht, Uwe et al.: International Hydrogen Strategies - A Study Commissioned by and in Cooperation with the World Energy Council Germany. Ottobrunn: Ludwig-Bölkow-Systemtechnik GmbH, 2020.

MFRL-01 20 The Norwegian Government's hydrogen strategy. Oslo: Norwegian Ministry of Petroleum and Energy Norwegian Ministry of Climate and Environment, 2020.

NASA-01 19 Modern-Era Retrospective analysis for Research and Applications, Version 2 - Project Overview. In: https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/. (Abruf am 2019-10-25); Houston, TX: NASA - National Aeronautics and Space Administration, 2019.

NYE-01 04 Nye, Joseph S.: Soft Power - The Means to Success in World Politics. New York: Public Affairs, 2004.

NYE-01 11 Nye, Joseph S.: The Future of Power. New York, 2011.

PAREMA-01 19 Wahabzada, Farhanja: German-Moroccan Energy Partnership - About the Bilateral Partnership. Rabat, Morocco: German-Moroccan Energy Partnership (PAREMA), 2019.

PEAR-01 73 Nye, Joseph S. et al.: Power and Interdependence. Glenview: Pearson Education, Inc., 1973.

PFWA-01 18 Wilde, Joerg: Generalization of the Annuity Factor. In: Accounting and Finance Research Vol. 7, No. 2/2018. Essen, Germany: Pension Fund of Water Associations (Ruhrverband), 2018.

PRO-02 20 Kreidelmeyer, Sven et al.: Kosten und Transformationspfade für strombasierte Energieträger - Endbericht zum Projekt "Transformationspfade und regulatorischer Rahmen für synthetische Brennstoffe". Basel: Prognos AG, 2020.

PSI-01 17 Mutel, Chris: Brightway: An open source framework for Life Cycle Assessment. In: Journal of Open Source Software 02/2017. Villigen, Schweiz: Paul Scherrer Institut, 2017.

PU-01 06 Meunier, Sophie et al.: The European Union as a conflicted trade power. In: Journal of European Public Policy 13/2006. Princeton, USA: Princeton University, 2006.

RIED-01 20 Riedel, Donata: Wasserstoff-Industrie startet in Marokko mit deutscher Aufbauhilfe. In: https://www.handelsblatt.com/politik/international/klimakrise-wasserstoff-industrie-startet-in-marokko-mit-deutscher-aufbauhilfe/26689224.html?ticket=ST-6829270-GQZRd1PnJBhk1Ls70zqd-ap1. (Abruf am 2021-03-01); Düsseldorf: Handelsblatt, 2020.

SIE-01 20 Benzinger, Alfons: Siemens Energy and Porsche, with partners, advance climate-neutral e-fuel development - Joint Press Release. München: Siemens Energy, 2020.

SMU-01 18 Wijayanta, Agung Tri et al.: Liquid hydrogen, methylcyclohexane, and ammonia as potential hydrogen storage: Comparison review. In: International Journal of Hydrogen Energy 44/2019. Surakarta, 57126, Indonesia: Mechanical Engineering, Faculty of Engineering, Sebelas Maret University, 2018.

STE-02 14 Sterner, Michael et al.: Energiespeicher – Bedarf, Technologien, Integration. Heidelberg: Sterner, 2014.

STEF-01 20 Steffen, Bjarne: Estimating the cost of capital for renewable energy projects. In: Energy Economics 88/2020. 8092 Zurich, Switzerland, 8092 Zurich, Switzerland: Department of Humanities, Social and Political Sciences, Energy Politics Group, ETH Zurich, 8092 Zurich, Switzerland, 2020.

UC-01 79 Waltz, Kenneth N.: Theory of International Politics. Berkely: University of California, 1979.

UNEP-01 14 World Database on Protected Areas. Cambridge, UK: UNEP-World Conservation Monitoring Centre, 2014

UO-01 21 Cesaro, Sac et al.: Ammonia to power: Forecasting the levelized cost of electricity from green ammonia in large-scale power plants. In: Applied Energy 282/2021. Oxford, United Kingdom: University of Oxford, Department of Engineering Science, 2021.

UO-01 57 Kaplan, Morton A.: System and Process in International Politics. Oxford: University of Oxford, 1957.

UOC-01 07 Yang, Christopher et al.: Determining the lowest-cost hydrogen delivery mode. In: International Journal of Hydrogen Energy 32 (2). Davis, CA, USA: University of California, Institute of Transportation Studies, 2007.

UOC-01 79 Baldwin, David A.: Power Analysis and World Politics. Cambridge: University of Cambridge, 1979.

UOH-01 18 Aakko-Saksa, Päivi T. et al.: Liquid organic hydrogen carriers for transportation and storing of renewable energy – Review and discussion. In: Journal of Power Sources 396/2018. Helsinki, Finland: University of Helsinki, 2018.

UOSUS-01 18 Newell, Peter: Trasformismo or Transformation? The global political economy of energy transitions. In: Review of International Political Economy 26/2019. Brighton, UK: School of Global Studies, University of Sussex, 2018.

UOTOK-01 20 Aziz, Muhammad et al.: Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilization. In: energies 13/20. Tokyo, Japan: Institute of Industrial Science, The University of Tokyo, 2020.

WEB-01 02 Weber, Max: Wirtschaft und Gesellschaft - Grundriss der verstehenden Soziologie. Tübingen: Zweitausendeins-Verlag, 2002.

WI-01 20 Merten, Frank et al.: Bewertung der Vor- und Nachteile von Wasserstoffimporten im Vergleich zur heimischen Erzeugung. Wuppertal: Wuppertal Institut, 2020.

WUL-01 17 Wulf, Christina: Wasserstoff im motorisierten Individualverkehr – Möglichkeiten und deren Bewertung . Dissertation. Herausgegeben durch Technischen Universität Hamburg-Harburg, geprüft von Kaltschmitt, Martin und Klassen, Thomas: Hamburg, 2017.

YU-01 57 Dahl, Robert Alan: The Concept of Power. Yale: Department of Political Science, Yale University, 1957.

ZAPF-01 16 Zapf, Martin: Stromspeicher und Power-to-Gas im deutschen Energiesystem - Rahmenbedingungen, Bedarf und Einsatzmöglichkeiten. Wiesbaden: Springer Fachmedien, 2017

ÖKO-04 20 Öko-Institut e.V.: Energiewende in Deutschland: Definition, Ziele und Geschichte. In: https://www.energiewende.de/start. (Abruf am 2020-11-03); Freiburg: Öko-Institut e.V., 2020.

A Appendix

The appendix contains data tables for the economic and environmental analysis and country fact sheets with key graphics.

A.1 Data Tables

Table A-1: *WACC and corresponding Annuity Factors (see. equation 4-5) /STEF-01 20/*

State	WACC	AnF (20 a)	AnF (25 a)	AnF (30 a)	AnF (40 a)
Australia	7.3 %	10.4	11.3	12.0	12.9
Chile	7.3 %	10.4	11.3	12.0	12.9
Germany	3.0 %	14.9	17.4	19.6	23.1
Morocco	10.4 %	8.3	8.8	9.1	9.4
Norway	7.3 %	10.4	11.3	12.0	12.9

Table A-2: *Assumptions for Electrolysis /PRO-02 20/, /BUTT-01 17/, /IEA-06 19/, /AGORA-11 19/*

Technology		2020	2030	2050
AEL	Lifetime in a	40	40	40
	Stack lifetime in h	75 000	95 000	125 000
	CAPEX in EUR/kW	878	717	512
	OPEX in % of CAPEX/a	1.5	1.5	1.5
	Efficiency η in %	68	69	71
PEM	Lifetime in a	20	20	20
	Stack lifetime in h	60 000	75 000	125 000
	CAPEX in EUR/kW	1233	914	468
	min. CAPEX in EUR/kW	259	168	119
	OPEX in % of CAPEX/a	1.5	1.5	1.5
	Efficiency η in %	71	72	75

Table A-3: *Data and assumptions for Natural Gas Reforming (ATR) /EWI-01 20/*

Parameter	2020	2030	2050
Lifetime in a	25	25	25
CAPEX in USD/kW_{H_2}	1627	1360	1280
OPEX in % of CAPEX/a	3	3	3
Efficiency in %	69	69	69
CO_2 Capture Rate in %	90	90	90
Total emissions in kg_{CO_2}/kg_{H_2}	9.7	9.7	9.7
Captured emissions in kg_{CO_2}/kg_{H_2}	8.7	8.7	8.7
Captured emissions in kg_{CO_2}/kg_{H_2}	1	1	1
Availability in %	95	95	95

Table A-4: *Assumptions for transport infrastructure with LH_2 as energy carrier /EWI-01 20/, /BBU-01 20/, /IEA-06 19/, /SMU-01 18/*

Technology		2020	2030	2050
Pipeline	Lifetime in a	40	40	40
	CAPEX-new in EUR/(tpa km)	4.03	4.03	4.03
	CAPEX-retrofit in EUR/(tpa km)	0.83	0.83	0.83
	OPEX and Fuel in % of CAPEX/a	5	5	5
	Utilization in %	75	75	75
	Design throughput in ktpa	340	340	340
Ship	Lifetime in a	30	30	30
	CAPEX in EUR/t_{H_2}	31 818	28 636	12 886
	OPEX in % of CAPEX/a	4	4	4
	Capacity in t_{H_2}	11 000	11 000	11 000
	Speed in km/h	30	30	30
	Berthing time in h	48	48	48
	Fuel use in MJ_{H_2}/km	1487	1487	1487
	Boil off in %/d	0.2	0.2	0.2
Liquefaction	Lifetime in a	30	30	30
	CAPEX in EUR/tpa	5385	4847	3876
	OPEX in % of CAPEX	4	4	4
	Electrical Use in kWh/kg_{H_2}	6.1	6.1	6.1
	Availability in %	90	90	90
Export Terminal	Lifetime in a	30	30	30
	CAPEX in EUR/tpa	635.1	571.6	285.8
	OPEX in % of CAPEX	4	4	4
	Electrical Use in kWh/kg_{H_2}	0.61	0.61	0.61
	Boil-off rate in kg/kg_{H_2}	0.003	0.003	0.003
Import Terminal	Lifetime in a	30	30	30
	CAPEX in EUR/tpa	4198	3778	1889
	OPEX in % of CAPEX	4	4	4
	Electrical Use in kWh/kg_{H_2}	0.2	0.2	0.2
	Boil-off rate in kg/kg_{H_2}	0.02	0.02	0.02

Table A-5: *Assumptions for transport infrastructure with ammonia as energy carrier /EWI-01 20/, /IEA-06 19/, /SMU-01 18/*

Technology		**2020**	**2030**	**2050**
Pipeline	Lifetime in a	40	40	40
	CAPEX in EUR/(tpa km)	2.6	2.6	2.6
	OPEX and Fuel in % of CAPEX/a	5	5	5
	Utilization in %	75	75	75
	Design throughput in ktpa	240	240	240
Ship	Lifetime in a	30	30	30
	CAPEX in EUR/t_{H_2}	8780	7902	3.951
	OPEX in % of CAPEX/a	4	4	4
	Capacity in t_{NH_3}	53 000	53 000	53 000
	Speed in km/h	30	30	30
	Berthing time in h	48	48	48
	Fuel use in MJ_{H_2}/km	2500	2500	2500
	Boil off in %/d	0	0	0
Ammonia Conv. (incl. ASU)	Lifetime in a	20	20	20
	CAPEX in EUR/t_{NH_3}/h	3000	3000	3000
	OPEX in % of CAPEX	2	2	2
	Electrical Use in kWh/kg_{NH_3}	0.64	0.64	0.64
	Availability in %	100	100	100
Ammonia Reconv.	Lifetime in a	30	30	30
	CAPEX in USD/t_{NH_3}/h	10.2	10.2	10.2
	OPEX in % of CAPEX	4	4	4
	Electrical Use in kWh/kg_{NH_3}	0.64	0.64	0.64
	H_2 recovery rate in %	99	99	99
Export Terminal	Lifetime in a	30	30	30
	CAPEX in EUR/tpa	106	95	48
	OPEX in % of CAPEX	4	4	4
	Electrical Use in kWh/kg_{H_2}	0.005	0.005	0.05
	Boil-off rate in kg/kg_{H_2}	0	0	0
Import Terminal	Lifetime in a	30	30	30
	CAPEX in EUR/tpa	604	543	272
	OPEX in % of CAPEX	4	4	4
	Electrical Use in kWh/kg_{H_2}	0.02	0.02	0.02
	Boil-off rate in kg/kg_{H_2}	0	0	0

Table A-6: *LCA-variables for tanker activity (t without subscript corresponds to t_{LH_2/NH_3})*

Carrier	State	Distance in km	Fuel in $t_{H2}/t/km$	Losses in $\frac{t}{t\,km}$	fraction for LCA in 1/t/km
LH_2	Australia	21 212.1	1.127×10^{-6}	2.78×10^{-6}	0.2314×10^{-11}
	Chile	12 510.5	1.127×10^{-6}	2.78×10^{-6}	0.1435×10^{-11}
	Morocco	2668.91	1.127×10^{-6}	2.78×10^{-6}	0.0561×10^{-11}
	Norway	602.4	1.127×10^{-6}	2.78×10^{-6}	0.0609×10^{-11}
NH_3	Australia	21 212.1	3.932×10^{-7}	0	0.4723×10^{-12}
	Chile	12 510.5	3.932×10^{-7}	0	0.2950×10^{-12}
	Morocco	2668.91	3.932×10^{-7}	0	0.1162×10^{-12}
	Norway	602.4	3.932×10^{-7}	0	0.1264×10^{-12}

Table A-7: *LCA-variables for pipeline activity*

State	Distance in km	Q_{H_2} in kt/a	Q_{NH_3} in in kt/a	Utilization rate r_u	fraction for H_2	fraction for NH_3
Australia	21 212.1	340	240	0.75	6.4×10^{-9}	6.5×10^{-9}
Chile	12 510.5	340	240	0.75	7.8×10^{-9}	11.1×10^{-9}
Morocco	2100	340	240	0.75	4.7×10^{-8}	6.6×10^{-8}
Norway	902.4	340	240	0.75	10.9×10^{-8}	15.3×10^{-8}

Table A-8: *General data and assumptions /EWI-01 20/*

Parameter	**Value**
LHV	33.33 kWh/kg
HHV	39.4 kWh/kg
LHVa	5.17 kWh/kg
Exchange rate	0.85 EUR/USD

Table A-9: *Molecular Masses*

Molecule	Chemical notation	Molecular mass in g/mol
Hydrogen	H_2	2.016
Nitrogen	N_2	28.0134
Water	H_2O	18.02
Ammonia	NH_3	17.031

A.2 Fact Sheets

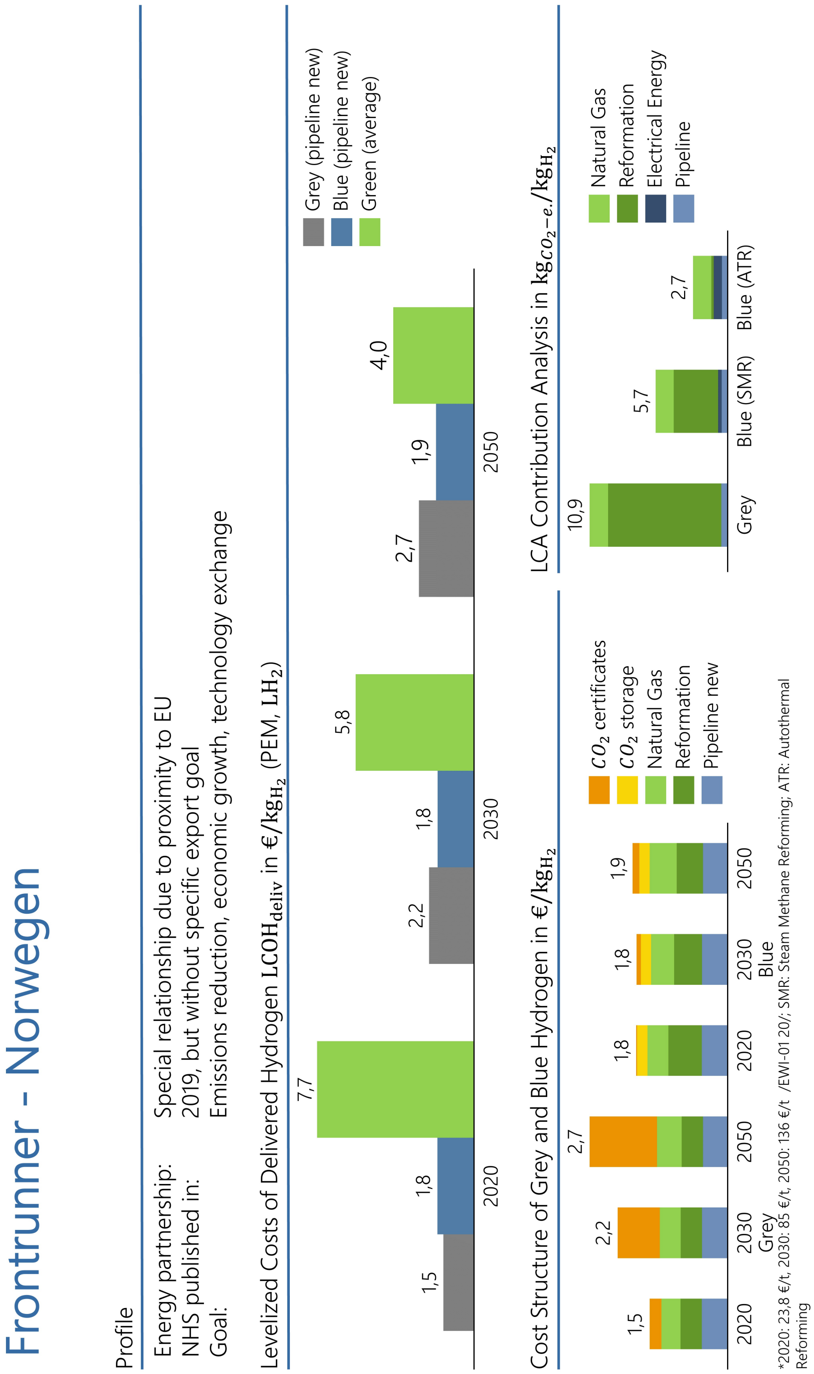


Figure A-1: *Fact sheet - Norway*

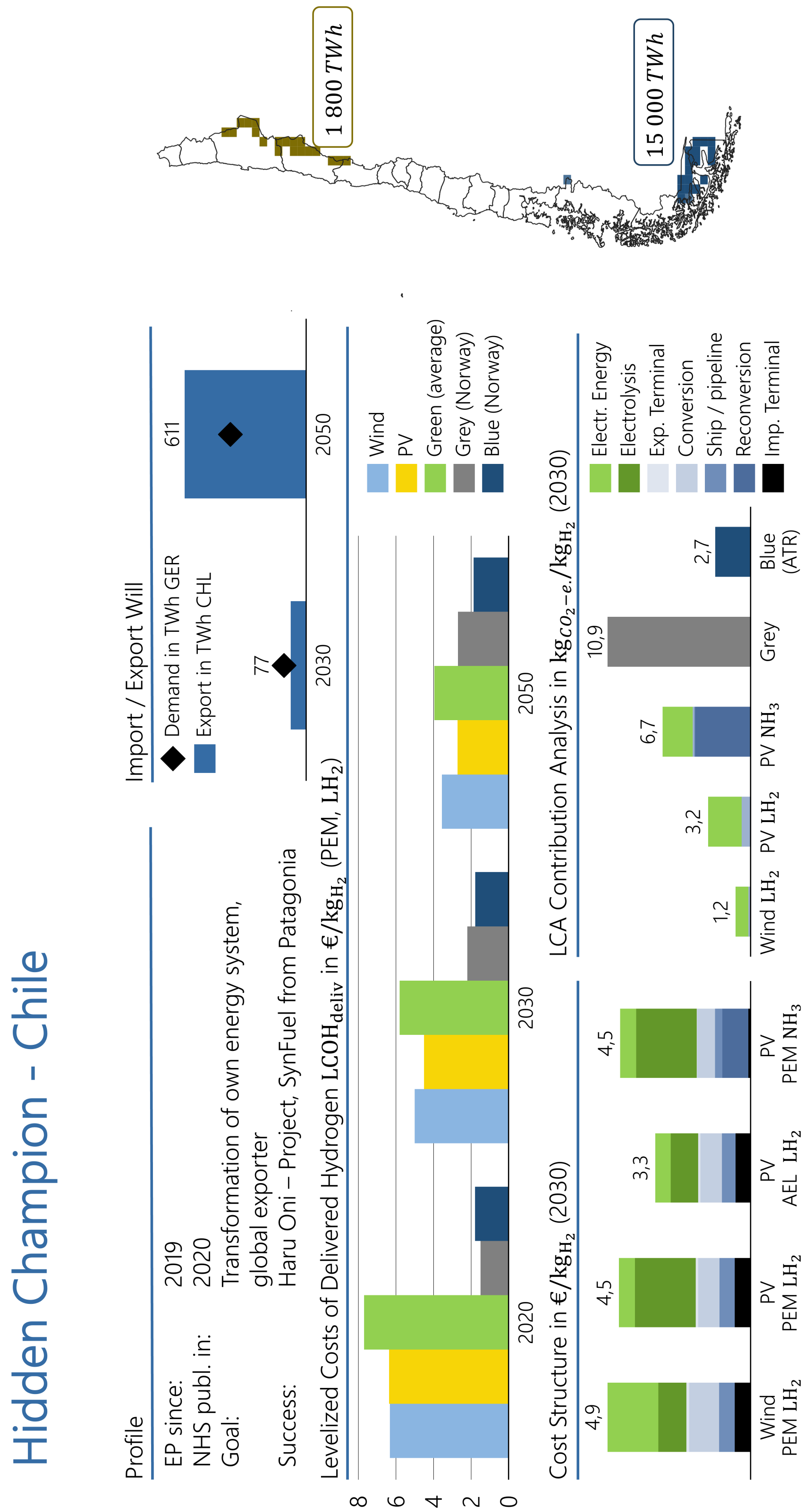


Figure A-2: *Fact sheet - Chile*

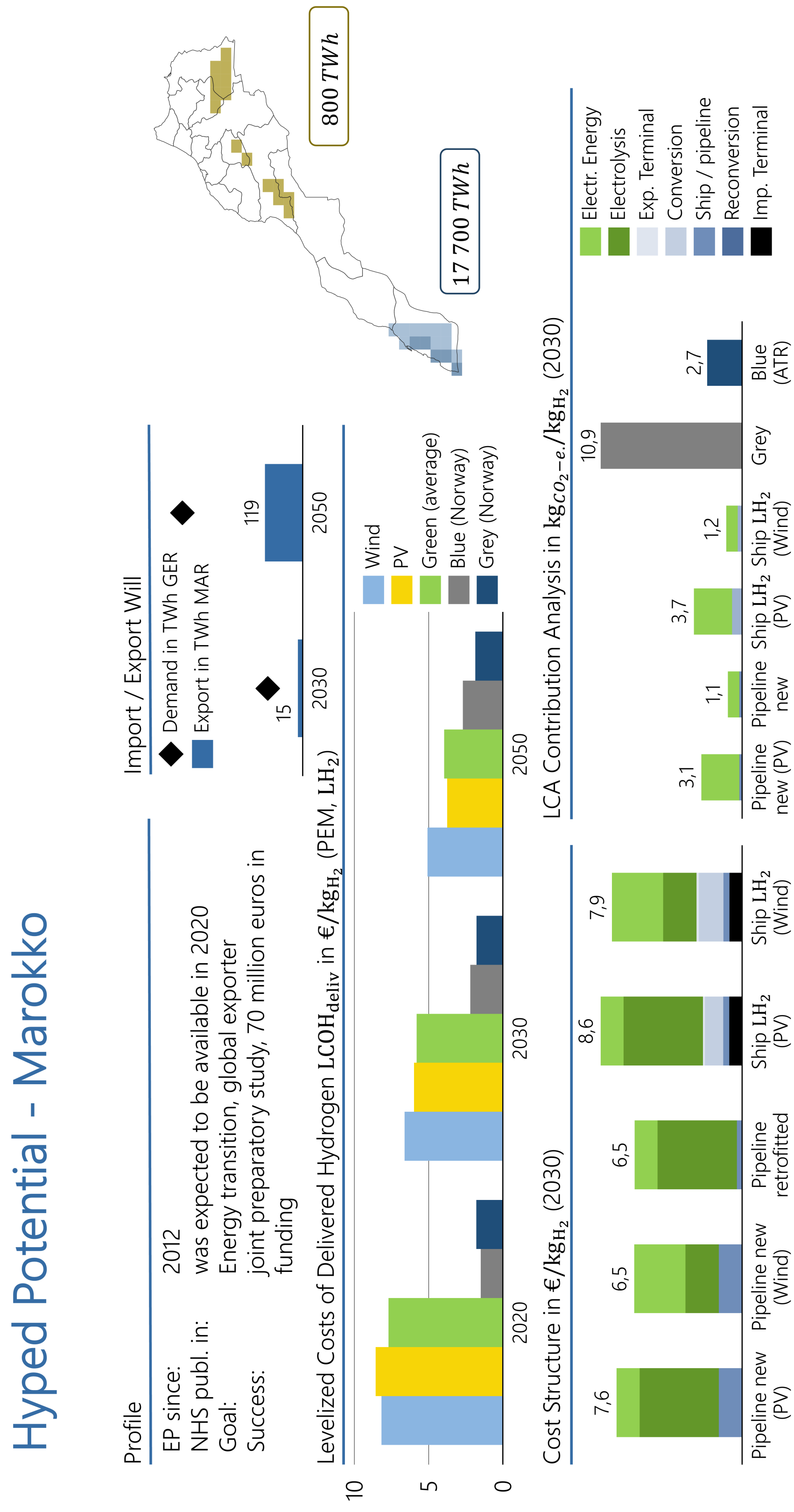


Figure A-3: *Fact sheet - Morocco*

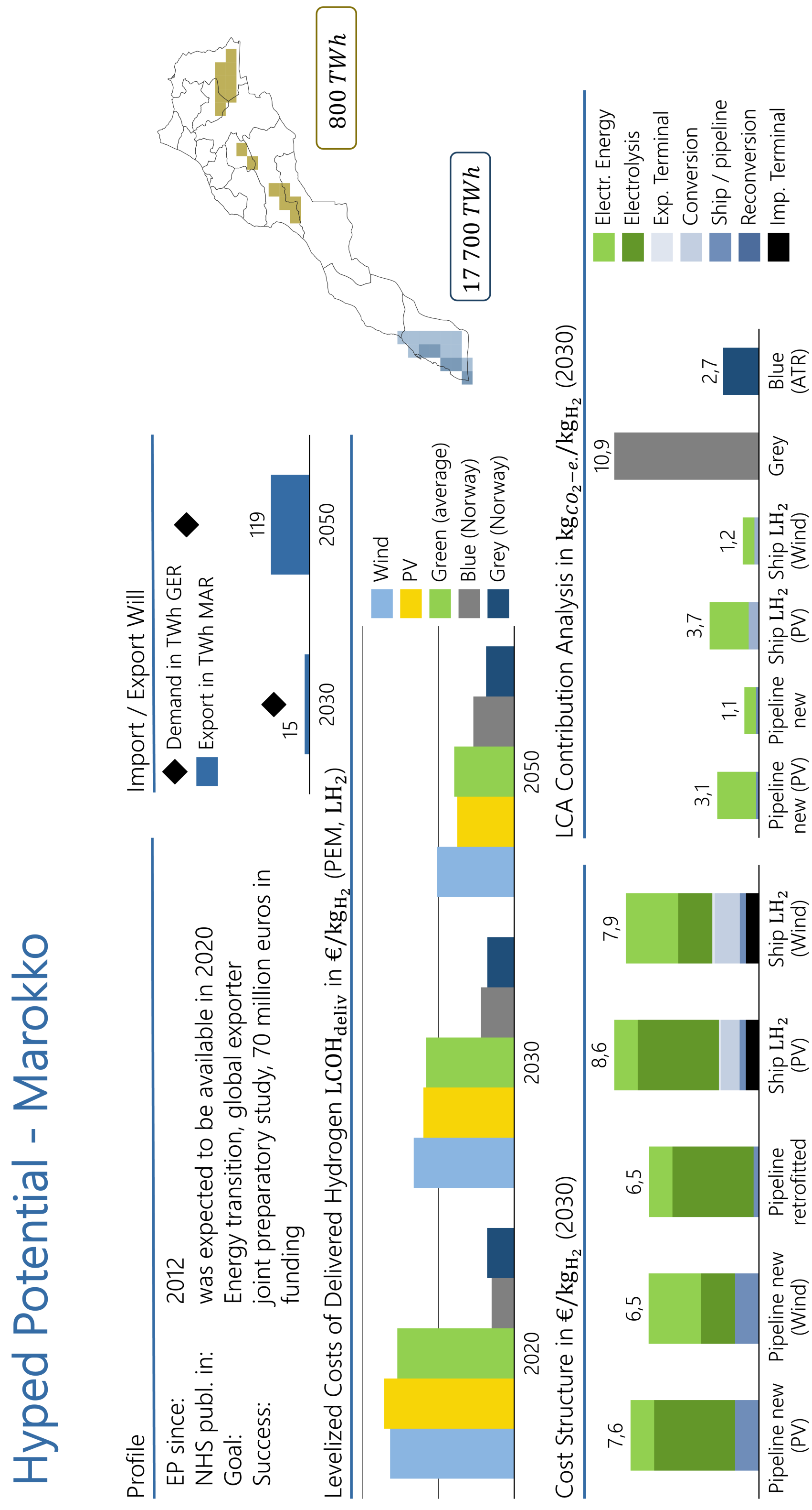


Figure A-4: *Fact sheet - Australia*