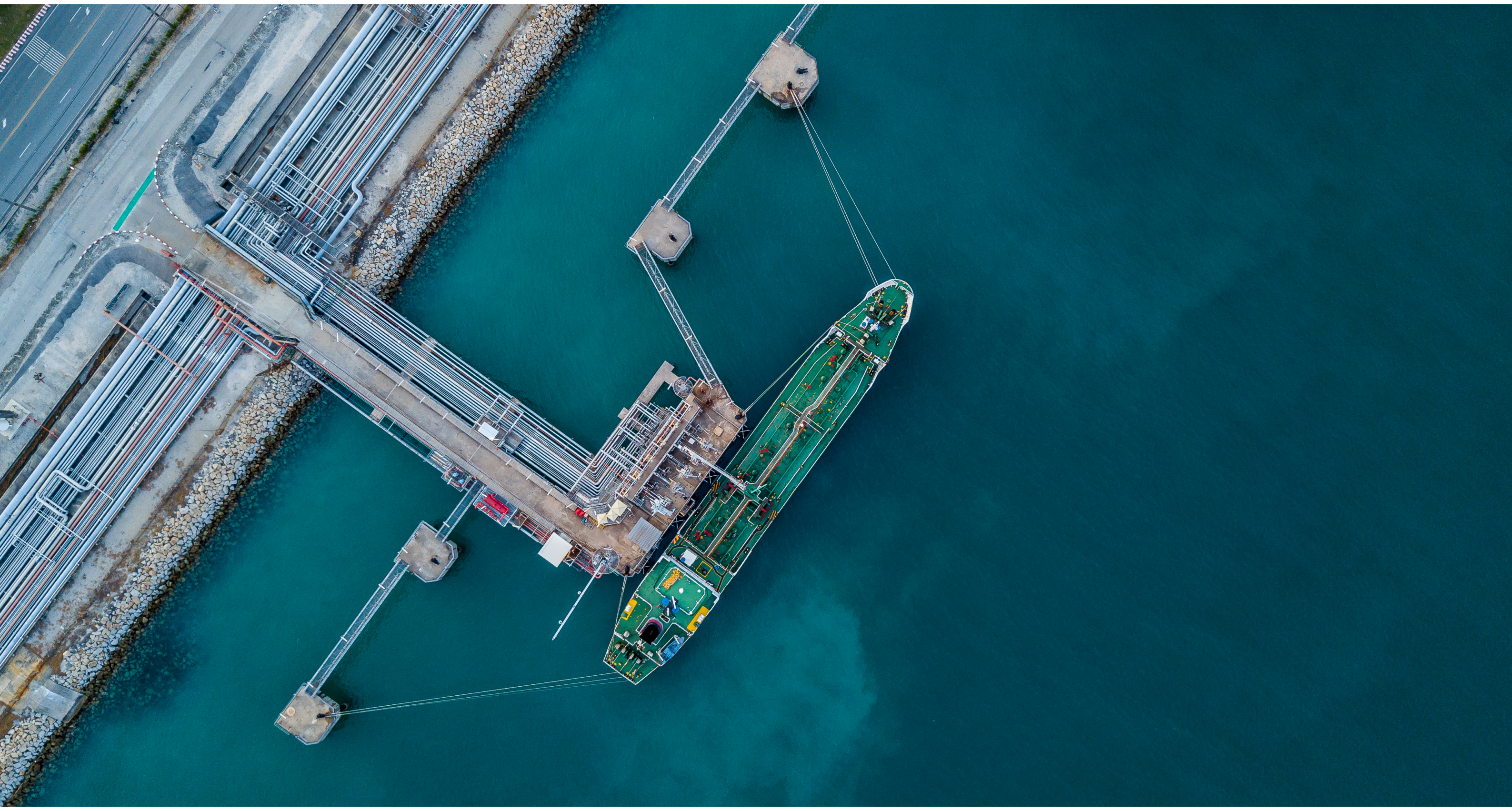
Roadmapping the development of a green hydrogen industrial port complex

A case study in an Icelandic setting



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Roadmapping the development of a green hydrogen industrial port complex

A case study in an Icelandic setting

by

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Preface

I have always been intrigued by technical and societal problems and, importantly, their possible solutions. Climate change, in particular, is near and dear to my heart and deserves all my energy and dedication. This has motivated me to pursue an engineering degree and find durable and sustainable measures to tackle the challenges at hand. Throughout my studies, I have developed a particular interest in ports because of their scale and ambition to serve a social goal. In this thesis, I was fortunate to combine port development with the increasing importance of driving the energy transition by creating a green hydrogen economy. Whilst writing this thesis, it was motivating to read the many (international) hydrogen investment announcements, even though the tragic situation in Ukraine had to play a role in that. My thoughts go out to the many victims of the war.

Although sceptics might argue about the feasibility of hydrogen, this graduation research has genuinely confirmed my belief that a hydrogen economy is a critical element of the solution to the current energy crisis and that it is feasible once every stakeholder puts their shoulders to the wheel. I hope this thesis can play a role in that regard and it can be of value to future port developers. Developing a hydrogen port does not happen overnight, but if efforts continue, it will be there sooner than later. Oliver Wendell Holmes once described this poetically and accurately:

> *"To reach a port we must sail, sometimes with the wind, and sometimes against it. But we must not drift or lie at anchor."*

During this thesis period, I figuratively experienced winds from all directions. Without a multitude of extra sails, I would not have been able to reach the final thesis version that lies before you. Therefore, I would very much like to express my profound appreciation to my graduation committee. I would like to thank Daan Schraven for setting up this research and for his critical questions during committee meetings; Martijn Leijten for his continuous advice and support; Hans Bakker for his empathetic mentoring ability to keep me motivated and on the right track; and Martijn Coopman, my company supervisor, for this opportunity and his trust in me. Besides my graduation committee, I am thankful to my respondents for helping me to gain a broad understanding of the case study. In particular, thank you to Valgeir Ægir Ingólfsson and Birgitta Rúnarsdóttir, both representing Fjarðabyggð. Also, my sincere gratitude to John and Elisabeth for the stimulating and enlightening discussions. I wish every next student the same support. Hopefully, (s)he can sail on hydrogen instead of wind.

With the completion of this graduation thesis, my Master's degree in Construction Management Engineering at the TU Delft has come to an end. I am grateful to everyone who has supported me during my study journey. I would like to express my heartfelt gratitude to my parents and siblings, who have been by my side at any cost. Likewise, thank you to my friends for offering adequate social and sportive distraction at the right moments. Finally, mama and Lilly, thank you for your inexhaustible amount of optimism and support.

J. Andriopoulos
Delft, July 20, 2022

Executive Summary

Introduction

The Paris Agreement was created in an effort to enhance the global response to the issue of climate change. In order to reach this goal, greenhouse gas emissions must be at least 40% below 1990 levels by 2030 and the temperature rise must be kept below 2 degrees Celsius this century. Moreover, the recent fossil fuel price increases, due to the situation in Ukraine, are pressing eye-openers to the geopolitical dependency on a small number of nations and mark the urgency of the energy transition.

Renewable energy projects are rapidly being constructed to replace fossil fuels. However, the main disadvantage of renewable energy generation is its intermittent character, resulting in a mismatch between energy supply and demand. Hydrogen generation as a means of energy distribution and storage is argued to be a viable solution to this challenge because this flexible energy carrier can be produced by any energy source and can be converted into various energy forms. The energy carrier is believed to be critical for decarbonising heavy industries, heating, and transportation.

Although hydrogen can be produced from a variety of energy sources, the only long-term key to facilitating the energy transition and establishing a new green economy would be through the electrolysis of water, fueled by renewable energy. To be economically viable, the energy would have to be provided at a large scale and at a competitive price. This makes it a global endeavour, requiring cross-border collaboration to create international supply chains.

With its potential to generate an abundance of wind energy, geothermal energy, and hydropower, Iceland is exploring its opportunity to produce hydrogen for its domestic markets and export markets. Therefore, this research is taking the Icelandic situation as a case study.

Problem statement

A lack of infrastructure to create, store, and transport hydrogen in significant amounts is one of the obstacles to developing the hydrogen economy. Infrastructure development needs effective coordination and substantial expenditures. In this sense, port authorities play a crucial role in bringing together all the relevant parties in the supply chain. However, creating a long-term plan to convince investors and other decision-makers presents a hurdle. The creation of a port master plan is constrained by numerous uncertainties, limited technological knowledge, and unknown social needs. There is a need for strategically roadmapping the port development process and thus structuring the decision-making process. So far, no hydrogen industrial port complex has been built and no studies have been performed about systematic thinking for the purpose of generating the possible pathways to develop such a port. The primary purpose of this thesis is to address this information gap. Hence, the following research question was established:

> *"What does the development process of a greenfield integrated green hydrogen industrial port complex look like for the port of Fjarðabyggð?"*

Research approach

The approach is set up using single-case, practice-oriented, design research methods. As such, it is meant to provide knowledge that can contribute to successful intervention in order to change the existing situation, based on insights from real-life scenarios. The study is separated into the practical problem definition phase and the problem-solution phase following the Double Diamond paradigm. Going through a process of two times exploring an issue more widely followed by taking targeted action, allows for understanding the case context before creating a targeted design solution. Semi-structured stakeholder interviews are performed to define the issue. Finally, desk research is done to offer a solution.

Results

Green hydrogen supply chain

Hydrogen is the world's most abundant element but does not occur in its pure form in vast quantities and thus has to be released from its compounds using energy in the process. In the case of green hydrogen, pure water is split into oxygen and hydrogen using electrolysers. Although hydrogen has a high energy content per mass unit (making it beneficial for many purposes), it is the lightest element and thus has a low energy density per unit of volume. For that reason, it is inefficient to store and transport hydrogen in its natural gaseous form. Hydrogen should therefore be compressed, liquefied, or converted into higher-energy-density hydrogen-based fuels (hydrogen carriers). The main options studied in this research are Liquid Hydrogen (LH2), Ammonia (NH3), and Liquid Organic Hydrogen Carriers (LOHCs). All options have advantages and disadvantages and the global hydrogen market has not yet determined the preferred one. Therefore, a port complex should consider accommodating all future scenarios and thus take into account the specific carrier design requirements.

Influencing factors in developing a hydrogen industrial port complex in Iceland

The port industry operates in a dynamic global market, resulting in logistical, technological and economic uncertainty. Accordingly, developing a greenfield hydrogen industrial port complex is a non-linear project that allows for many interactions between various components. Special attention must be paid to the uncertainties in the greater system in order to assure capacity, functionality and service quality throughout the foreseen life cycle. For that reason, a SWOT analysis is performed.

Six strength factors are identified. These include the availability of a suitable area for a port complex of large scale, the energy pioneering nature of the people, the existing collaboration with the Port of Rotterdam (offering large export opportunities and knowledge sharing), the aspiration to increase self-sufficiency by replacing fossil fuel and fertilizer imports, and further growing subsidy opportunities.

However, five weaknesses are the lack of long-term governmental vision, little social acceptance towards the construction of new power generation facilities for export purposes, an absence of clarity in the future hydrogen markets in Iceland, limited in-depth knowledge as a result of the novelty of hydrogen technologies, and a vigorous opposition of the tourism industry towards increased industrial activity in Iceland.

Yet, five opportunities can be exploited by building a hydrogen port complex. Constructing a hydrogen industrial port complex for domestic purposes will allow for an accelerated energy transition in Iceland. Also, building in the identified eastern fjord will result in increased economic development of the Eastern Region. What is more Iceland might increase its geopolitical position by exporting energy instead of importing. Additionally, with the global development of certification schemes that prove the guarantee of origin of hydrogen produced with renewable energy, the demand for green Icelandic hydrogen will undoubtedly increase in comparison to blue or grey hydrogen. Finally, setting up an Icelandic-Dutch hydrogen treaty will foster a hydrogen economy.

On the contrary, the research identifies five threats that include the potential transformation of markets once the hydrogen economy grows out of its infancy, a changing regulatory framework that could lead to surprises in the permitting and off-take of hydrogen, emerging (international) competitors who could reduce the advantageous position of being amongst the first large-scale hydrogen developers, potential negative media coverage that has a significant influence on the social acceptance, and the blocking power of the general public.

Integrated Hydrogen Port Development framework

This research shows that the development of such a system is not so much a technical challenge but rather depends on strategic decision-making. At this stage, without an overarching Icelandic strategy for developing a hydrogen economy (internal use and export), it has proven impossible to produce a detailed port master plan. Therefore, this research has created an eight-phase roadmap that should be worked through in chronological order to successfully come to a port master plan that tackles threats, opportunities, and uncertainties.

The framework begins with the development of a national hydrogen strategy and the formulation of a shared vision among the port authority, hydrogen developers, and energy providers.

Consequently, it is necessary to select the optimal markets and carriers. Here, it is necessary to strike a balance between production for the domestic market and production for export. Ideally, the two should be combined, since the export market allows for economies of scale, while the local market should be supplied to achieve domestic goals. Identifying export markets requires collaborating with other ports, such as Rotterdam, to locate existing industries. To build the domestic market it is necessary to have in-depth discussions with the following industries: heavy trucks, public transport, private transport, fertiliser manufacturing, shipping sector, fish factories, and fish farms. The selection of carriers will depend primarily on customer preferences but special attention must be paid to each carrier's individual safety needs.

In the third phase, a comprehensive stakeholder analysis and engagement plan must be conducted. To develop key values as design- and assessment criteria later in the process, the selected key stakeholders must be interviewed.

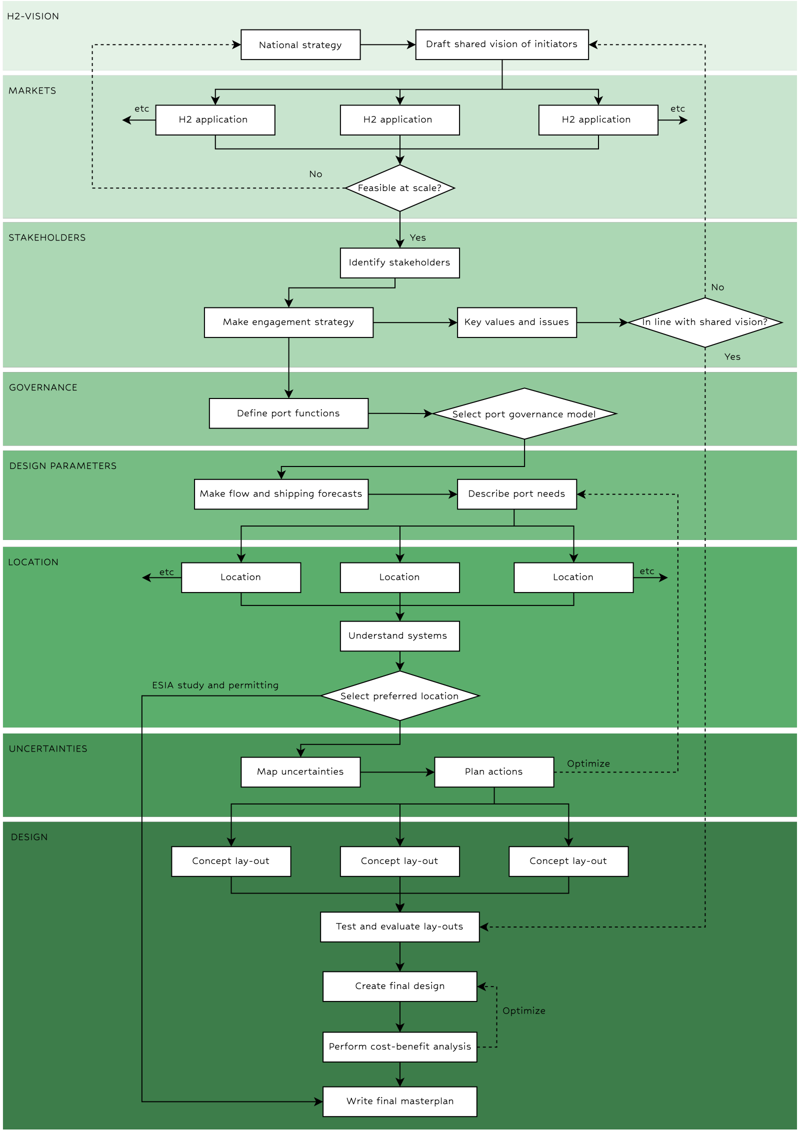
In the fourth phase, the port organisation should be established in terms of port functions and governance model. For the port of Fjarðabyggð, the landlord model is determined to be the most viable choice. In this manner, the port authority would optimise investments by establishing an enticing environment for numerous private enterprises to invest in superstructure, while a neutral port development company would focus on common infrastructure to reduce infrastructure investment duplication.

The fifth phase collects design criteria. Here, flow- and shipping-related projections, and port user- and location requirements should be compiled. Using design formulas, it is possible to compute the primary dimensions of the port's wet and dry zones.

The focus of the sixth, is therefore on selecting the optimal site given the design criteria. This is accomplished by picking various locations in advance and assessing their physical-, environmental-, governance-, and socioeconomic systems. After choosing the location with the fewest adverse effects from functional needs and the most considerable opportunities for the port, location-specific threats should be defined during subsequent investigations. This is also the starting point for the ESIA process to obtain the right permits, licenses, and planning consents.

The seventh phase tries to maximise flexibility by addressing uncertainty upfront. Describing uncertainty with precision assists in identifying the most appropriate solutions for vulnerabilities and objectives for opportunities. To select appropriate measures, seizing-, shaping-, mitigating-, or hedging-related activities must be planned.

In phase eight, the port itself can be developed. Multiple lay outs should be developed in response to location-specific threats and in accordance with port requirements. Thereafter, a Multi-Criteria-Analysis should be used to select the preferred option (or a combination of options). Evaluation criteria should be based on the previously specified key values. Then, (social) cost-benefit assessments should be conducted to assess the port's added value. Eventually, the finalised common vision, the port architecture with numerous phases, and the strategy to service distinct markets should be unified into a final long-term master plan that serves as a comprehensive and adaptable basis for the port's future expansion and development. The final master plan serves as basis for the final investment decision. The ESIA must also be completed and the permits, licences and planning consents must be received.



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1

Introduction

This chapter addresses the fundamental reasoning for this research and the way the research is set up. The chapter starts with drafting the research context in section 1.1. This leads to the problem statement that this research attempts to address and to the research setting to describe the purpose of the research. This is described in sections 1.2 and 1.3, respectively. Consequently, section 1.4 describes a set of research questions. Then, section 1.5 covers the research outline. Ultimately, the chapter is summarised in section 1.6.

1.1. Research context

1.1.1. Energy transition required

The sixth assessment report of the IPCC recently made humanity face the facts once again. This neutral body for assessing the science of climate change demonstrated the urgent need for a complete system change and refuted the last arguments of climate change sceptics (IPCC Secretariat, 2020). Five new emission scenarios have been developed. In all scenarios, the temperature will continue to rise until approximately 2050. This century, the temperature will increase by more than 1,5 to 2 degrees Celcius unless greenhouse gas emissions are significantly reduced (Samset et al., 2020). If one wants to limit climate change, one needs at least to emit zero net CO_2 by shifting from fossil fuels to more sustainable sources of energy.

In that light, 174 states have set their targets by means of the 2015 Paris agreement. This legally binding international treaty on climate change aims to keep the temperature rise below 2°C this century by cutting greenhouse gas emissions by 40% by 2030 compared to pre-industrial levels (UNFCCC, 2015). With only 89 months left, there is still much work to be done, and policymakers attempt to switch from words to actions while maintaining economic development (Li et al., 2019).

Renewable energy projects are being constructed rapidly to replace fossil fuels. However, the main disadvantage of renewable energy generation is its intermittent character, resulting in a mismatch between energy supply and demand (Li et al., 2019). Hydrogen generation as a means of energy distribution and storage is argued to be a viable solution to this challenge. It can be produced using renewable energy sources, including hydro, wind, wave, solar, biomass, geothermal energy, and non-renewable energy sources like coal, natural gas, and nuclear power. It may be stored as fuel and utilised in vehicles, power production systems employing fuel cells, internal combustion engines, and turbines (Abe et al., 2019). Therefore, hydrogen is considered a flexible energy carrier because it can be produced by any energy source and converted into various energy forms (IEA, 2015).

Hydrogen as an energy carrier is believed to be critical for decarbonising heavy industries, heating, and transportation (Chatzimarkakis et al., 2021). If strategic supply chains are in place, they could one day distribute energy stocks on a global scale at a competitive price (Rivera-Tinoco et al., 2010). The main implementation challenges are currently connected to the production, storage, and distribution network (Abdalla et al., 2018).

1.1.2. The future of hydrogen as an energy carrier

The idea of using hydrogen as an energy carrier dates back over two centuries, gaining traction in the 1980s after the global energy crisis of the 1970s (Niaz et al., 2015). Unlike fossil fuels, its future potential has not decreased as hydrogen is abundant and the most available renewable energy source. Hydrogen is known for its cleanliness as a) water vapour is the only product after combustion and b) it has zero emissions if produced using renewable energy (Ivancic et al., 2010). Hydrogen is a suitable energy carrier because of its high energy density (Ouyang et al., 2013). It could serve as an optimal solution to overcome seasonal energy supply and demand mismatches from renewable energy sources. The hydrogen could be supplied via national gas networks and boats, and stored in salt caverns and depleted gas fields (European Commission, 2014). The Hydrogen Council stated, in its new roadmap released in February 2021, that by 2050 hydrogen could provide 18% of the world's total energy consumption while reducing CO_2 emissions by 40%–60% in diverse sectors such as residential, transportation, and industry (McKinsey & Company, 2021).

By contrast, financially speaking, the concept is not yet able to compete with fossil resources. The economic argument for clean hydrogen is challenging. The industry has the potential volumes, but transportation has the likely profit margins. The most significant users of hydrogen today are energy-intensive businesses. With Europe striving for climate neutrality by 2050, clean hydrogen is gaining traction in industries such as steel and chemicals. However, these are very price-sensitive businesses that are subject to global competition. Companies are reluctant to spend far above the regular price for a more environmentally friendly option. As a result, the green hydrogen economy requires tailored assistance. EU policy is trying to repeat the success story of renewables, but there is a substantial difference. Unlike solar and wind, green hydrogen production is driven by operational, instead of capital expenditure. The cost of a green energy supply is responsible for 80% of the total hydrogen cost. Furthermore, subsidies to encourage large-scale deployment may lower the cost of electrolysers, but this does not guarantee that green hydrogen generation will be less expensive. The price for the energy must be high enough to make renewable energy projects feasible and cheap enough to ensure green hydrogen is competitive with gas (Ren et al., 2017).

However, even if renewables became cheaper and hydrogen would be cost-competitive with fossil fuels, it would not be possible to meet the ultimate demand of many (industrial) countries by local production only. For example, the Netherlands faces limited surface area and limited resources. A solar panel in the Sahara produces 2–3 times the energy that it does in the Netherlands. If that Sahara energy were converted into hydrogen, transferred to the Netherlands, and then used in a fuel cell to transform hydrogen back into power, one would have more energy than installing the solar panel on a Dutch roof. One should calculate system costs rather than efficiency in a sustainable energy system (Ren et al., 2017). In this example, it is expected that in the long run, importing green hydrogen will always be more cost-effective than creating it in the Netherlands.

1.1.3. Iceland's intention for international collaboration

In essence, the hydrogen economy is a global endeavour (van Renssen, 2020). Therefore, authorities in Iceland are beginning to seek cross-border collaboration to mutually tackle the challenges ahead and, simultaneously, seek competitive export partners. Iceland has the opportunity to accelerate the development of a hydrogen supply chain by exporting to the Port of Rotterdam. With similar climate action ambitions and a long history of collaboration, this new partnership in the field of hydrogen export has the potential for a happy marriage. The supply chain can produce one of the most competitive hydrogen supplies through a combination of hydro, geothermal and new onshore wind power. This will lead to the supply of cost-competitive hydrogen for the users in the Rotterdam port and hinterland, allowing them to decarbonise and sustain their business and throughput via the Rotterdam port. With that in mind, the Port of Rotterdam has signed a memorandum of understanding with the Icelandic national power company "Landsvirkjun" to jointly explore the potential for green hydrogen production in Iceland and export to NW Europe via Rotterdam. As a result, a joint-pre-feasibility was undertaken with experts from both sides, which concluded that the best export port location would be in the Reyðarfjörður on the island's East coast. The site offers a wide range of advantages, including:

- an existing port complex;
- a safe harbour with sufficient depth;
- existing expansion plans;
- ample space for industries;
- the required distance from urban areas;
- current- and planned wind parks, hydropower- and geothermal plants nearby;
- and it is not located near environmentally sensitive areas.

Subsequently, a memorandum of understanding was signed between the Port of Rotterdam and the municipality of Fjarðabyggð where the Reyðarfjörður lies. The collaboration intends to work together to develop a hydrogen industrial complex with local use as well as export functionalities.

1.2. Problem statement

One of the challenges in boosting the hydrogen economy is the current infrastructure's inadequacy (Li et al., 2019). Building hydrogen supply chain infrastructure (production plants, storage facilities and delivery modes) needs to be coordinated in parallel and requires significant investment with substantial risks (Dagdougui, 2012). A supply chain's intrinsic qualities imply that each component is interrelated rather than separated. The creation of a competitive market in all sorts of renewable and sustainable energy necessitates a complicated design, planning, and optimisation approach (Baños et al., 2011; De Meyer et al., 2014).

Port authorities and decision-makers in Iceland face the same difficulties. Although the country has a great potential to develop low-cost green hydrogen, it is challenged with defining a long-term strategy to attract potential developers and convince future stakeholders. The lack of knowledge, certainty, (inter)national strategy, and targets for the hydrogen port development in a greater supply chain poses insecurity and risks. The intricacy of making balanced energy system decisions is depicted in figure 1.1. It demonstrates that the best solution route is not always obvious.

Clearly, the one taking early initiative benefits from a first-mover advantage, leading to a competitive position in the market and supply chain. Therefore, the decision maker's task is to plot the optimal path through a maze of possible futures with inadequate maps. Prior to investing, a port master plan must be made that incorporates system requirements, uncertainties, and future scenarios. In order to successfully develop the supply chain as a whole, this master plan should consider the interests of all stakeholders.

Currently, (international) port authorities are unaware of what is required to realise the construction of a hydrogen industrial port complex and seek a roadmap to help them navigate this process. Because no future port environment is the same, this roadmap should be suited to the local context.

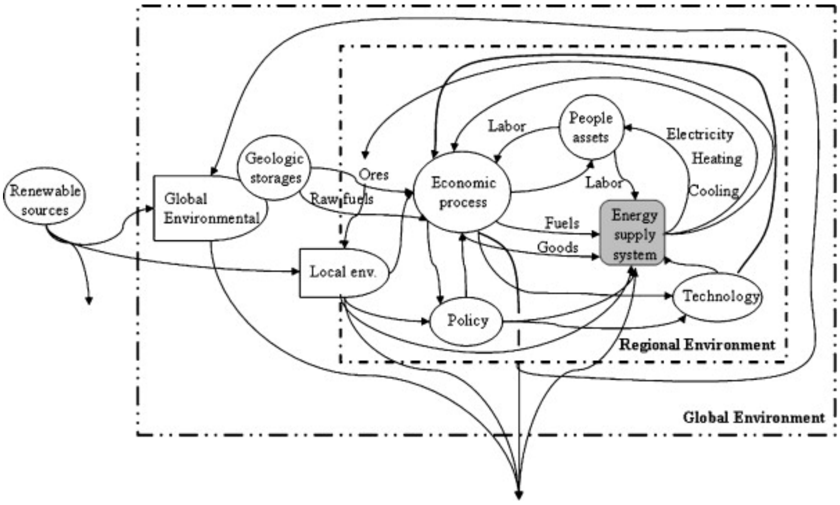


Figure 1.1: The intricate linkages between energy systems by Wang et al. (2009)

1.3. Research setting

1.3.1. Research gap

The step towards project contextualisation is not difficult once the problem and the need for a broader perspective have been established. To summarise the preceding sections:

To align stakeholders and concurrently develop the whole supply chain of a hydrogen industrial port complex, there is a need for strategically road mapping the development process and thus structuring the decision-making process. The roadmap must include decision moments, actions and phases, and serve as a guide to making a hydrogen port reality.

So far, no concrete studies have been performed about systematic thinking for the purpose of generating the possible pathways to develop a hydrogen port complex in general, and for the Icelandic situation in particular. This poses a knowledge gap, ranging from design to implementation, that this research aims to close. As a result, the research leads to improved feasibility judgements in hydrogen industrial port complex projects, as well as more optimum use of hydrogen generation in future port projects, while balancing the interests of all stakeholders. In Chapter 2, the research approach is discussed in greater depth.

1.3.2. Research goal

Having discussed the academic problem statement, it is now necessary to clarify the objective of this research. Whilst carrying out this research project, the research objective is to estimate the current feasibility of developing a hydrogen industrial port complex (further referred to as HIPC) in Iceland by performing a SWOT analysis and to advise the municipality of Fjarðabyggð on how to create it by producing a roadmap (external aim). The roadmap takes local circumstances and the results of the SWOT analysis into account. This applied method for roadmapping, at the same time, contributes to science by striving to narrow the described knowledge gap (internal aim).

1.3.3. Scope

The scope of this research can be demarcated by focussing on what it will focus on and what is not in scope.

The scope includes:
- offering insights on the development process of a hydrogen industrial port complex;
- focussing on the generation of green hydrogen: this can be understood as hydrogen production from sustainable energy sources using electrolysers (Dincer, 2012);
- exploring both export opportunities as well as local usage;
- narrowing to four hydrogen carriers only, namely, Liquid Hydrogen (LH2), Ammonia (NH3), and LOHCs such as Methylcyclohexane (MCH) and Dibentyltoluene (DBT);

The scope does not include:
- focussing on other applications of the Icelandic energy surplus;
- generating, storing and exporting other forms of hydrogen than green hydrogen;
- master planning, designing, operationalising and maintaining the eventual hydrogen industrial port complex;
- importing hydrogen;
- transporting of hydrogen by pipeline between export and import location.

Figure 1.2 illustrates the general green hydrogen supply chain. The chronological steps are renewable energy production, hydrogen production, carrier conversion, storage, port handling, transport, distribution, converting back to hydrogen gas, and usage. This research only concentrates on the first five steps. Thus, no emphasis will be put on the steps contoured in red.

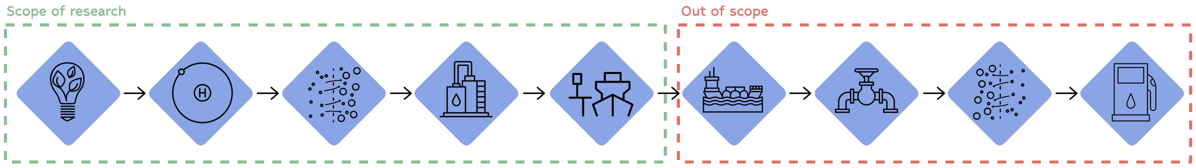


Figure 1.2: The green hydrogen supply chain research scoping

1.4. Research questions

A research question can be used to express the above-mentioned goal:

> *"What does the development process of a greenfield integrated green hydrogen industrial port complex look like for the port of Fjarðabyggð?"*

In order to answer the main research question and meet the objective of the research, the following subquestions should be answered in this report:

1. *What is green hydrogen and what does its supply chain look like?*
2. *How are ports generally designed and in what forms can they be organised?*
3. *What factors influence the development of a hydrogen industrial port complex in an Icelandic setting?*

1.5. Research outline

This study's research design closely follows the succession of the research questions. Figure 1.3 provides an overview of the report outline. In broad lines, the report comprises four parts that all consist of a couple of chapters; Research initiation, Theoretical background, Design-based research, and Research evaluation.

The research initiation can be found in the first two chapters. First and current chapter 1 addresses the research context and fundamental reason for research. Then, chapter 2 aims to explain the research methodologies of this research. It explains the type of research and introduces the Double-diamond design process model.

The theoretical background is required to explain the two fundamental aspects of developing a hydrogen port. Therefore, it consists of two chapters. Chapter 3 aims to answer sub-question 1 by explaining the different forms of hydrogen and the supply chain of hydrogen in an all-encompassing context. The second sub-question is answered in chapter 4, which describes the influencing factors in port development, the regular master planning process, and the different port governance models.

The added value of this research to the existing body of knowledge can be found in the design-based research part. It naturally follows Double-diamond design process model and thus consists of two chapters. Chapter 5 aims to define the practical problem and draft an accompanying design brief. This is done through a SWOT-analysis and answers sub-question 3. Chapter 6 then aims to formulate a solution to the design brief by creating the IHPD-framework.

The last part of this report covers the research evaluation and consists of three chapters. Chapter 7 reflects on the results of the design-based research part and discusses the limitations of the research. Subsequently, chapter 8 provides an answer to the main research question and recommends topics for further research. Ultimately, chapter 9 aims to self-reflect on the overall thesis process.

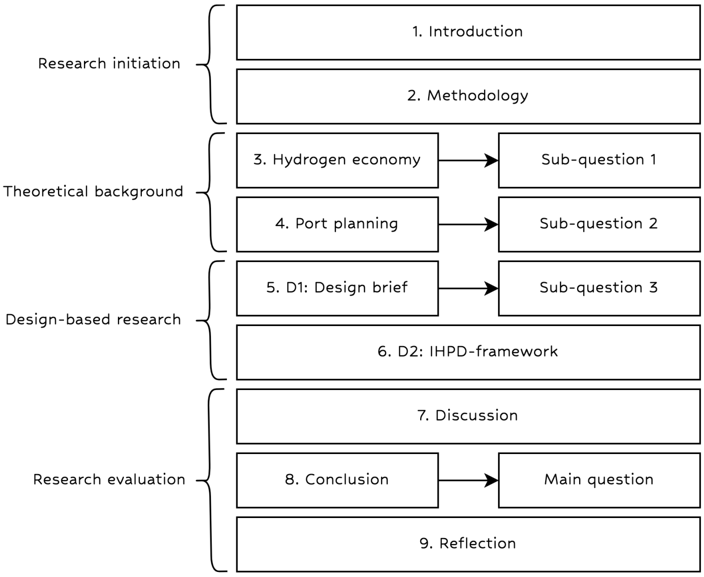


Figure 1.3: Research outline

1.6. Chapter summary

This chapter has addressed the fundamental reasoning for this research and has presented the way the research is set up. The chapter identified the need for a global energy transition from fossil fuels to renewable energy and the role of hydrogen in that regard. Icelandic parties have expressed their intention for large-scale hydrogen production and potentially for its export. However, port authorities and decision-makers are faced with creating a competitive hydrogen market and developing the accompanying infrastructure. To align stakeholders and concurrently develop the whole supply chain of a hydrogen industrial port complex, there is a need for strategically roadmapping the development process and thus structuring the decision-making process. The roadmap must include decision moments, actions and phases, and serve as a guide to making a hydrogen port reality.

2

Methodology

In order to comprehensively answer the main research question as described before, it is imperative to construct a fitting research design with corresponding suitable methodologies. This chapter describes the choices made and substantiates the implementation in accordance with the project's objective. Section 2.1 defines the general research design whereafter a specific design model is presented in Section 2.2. Al last, section 2.3 summarised the chapter.

2.1. Research design

Research typification

The research objective could be classified as practice oriented research because, according to Verschuren and Doorewaard (2010), it is meant to provide knowledge and information that can contribute to successful intervention in order to change the existing situation. Interventions attempt to solve a practical problem and occur when policies are implemented that are created by local-, regional-, (inter)national governments, as well as management of (non-)profit organisations (Verschuren & Doorewaard, 2010). In its entirety, practice-oriented research is composed of a five-part intervention cycle consisting of; problem analysis, diagnosis, design, change, and evaluation. This is the predetermined process for finding a solution to current operational problems and implementing a successful intervention (Verschuren & Doorewaard, 2010). This research is a design because the problem analysis and diagnosis can be drafted and an intervention plan, in the form of a design, should be developed to find a solution for the problem (Verschuren & Doorewaard, 2010).

Single-case study

For a successful conceptualisation of the port development process and application to the Icelandic context, the researcher requires insight from real-life scenarios. For that matter, the researcher opts for a single-case study methodology. A case study technique allows one to delve into a complex matter in its natural environment (Crowe et al., 2011). Consequently, it can assist in explaining the complexity of a specific circumstance (Kemanusiaan, 2007). Not only does it fit the practice-oriented research objective, but choosing single-case study results in a holistic, in-depth investigation rather than breadth which tends to remain more on the surface (Feagin et al., 1991). Also, the empirical character requires the researcher to observe and gather or generate relevant materials (Verschuren & Doorewaard, 2010).

Although the proposed research will draw conclusions on the unique conditions of Iceland, more generic statements about hydrogen port development could be relevant to future projects. Potentially this research could lead to a readily applicable format for countless hydrogen projects to come. However, considering the small and idiosyncratic sample of a case study, it is impossible to determine the probability of the study's representativeness; therefore, 'merely' provisional truths will be provided (Hodkinson & Hodkinson, 2007).

2.2. Double-diamond design process model

For the purpose of this research, fitting in the orientation described above, a design thinking approach is chosen. This approach is sound because it emphasises two important characteristics; the collaboration of researchers and practitioners, and iteration to optimise the solution. The design thinking methodology has been developed over the years (Dorst, 2011) and the amount of models has also increased. In this research, the Double Diamond method (Design Council, 2007b), founded by the British Design Council, is adopted to conduct this practice-oriented design study in order to allow a deeper insight into the practical problem definition and the eventual solution. Of all models, the double diamond model is the more complete one because it was initially created for designers' use whilst the other models were mainly developed for business and management purposes (Tschimmel, 2012).

The Double Diamond model, also known as 4D's, can be described as an overview of two figurative diamonds representing a process of two times exploring an issue more widely or deeply (divergent thinking) and then taking focused action (convergent thinking). The first diamond strives to define the practical problem, after which the second diamond seeks to find the solution to the problem. By going through the two diamonds, four steps can be distinguished:

1. Discover (diverge): focusing on thoroughly understanding the problem without making assumptions;
2. Define (converge): defining the challenge in a different way after understanding the problem in the first step;
3. Develop (diverge): finding different answers to the clearly defined problem, based on the input of multiple sources;
4. Deliver (converge): testing out different solutions at a small scale to then desert the ones that will not work and improve the ones that will (Design Council, 2022).

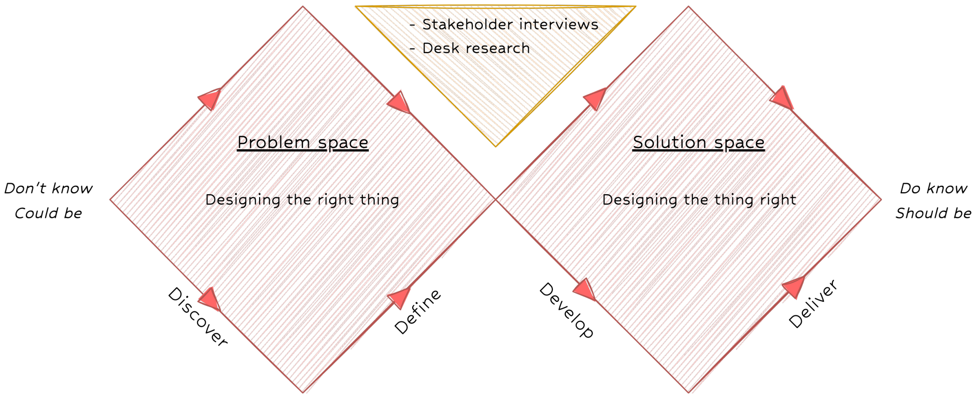


Figure 2.1: Graphical depiction of the Double Diamond process model (adopted from Design Council (2007a))

The double-diamond method is a framework at the highest system level and is not defined by a set sequence of research methods. Considering the research objective described in 1.3.2, the proposed research will have both a theoretical as well as a practical nature. In order to comprehensively answer the research question, it is imperative to select a suitable methodology. The next two subsections describe the chosen research methods and their purpose per diamond. The sequence of the chosen methods is important for the trustworthiness of the research.

Diamond I: designing the right thing

The first diamond is a figurative representation that depicts the problem analysis as the reason for the solution. The aim is to define the practical problems worth solving in a substantiated manner. This implies that the researcher looks further than the symptoms and encaptures the needs before looking at a solution. By first going through a diverging phase, anointed 'Discover', the researcher is supposed to keep an open-minded view to absorb and observe what is going on by thinking broadly and analysing stakeholders involved with the topic. The successive converging phase, dubbed 'Define', stimulates critical and analytical thinking to get to the point and conclude with a design brief.

This is done by conducting *semi-structured stakeholder interviews*. The interview is a qualitative research approach that allows for the acquisition of a practical viewpoint on the issue, which can give crucial information on the topic (Baarda, Bakker, Fischer, Julsing, & van Vianen, 2021). When conducting interviews, a number of decisions must be taken. First, the decision is taken to conduct the interviews verbally rather than in writing. Because this set of interviews was conducted during the preliminary stage of the research (the first diamond) and spoken interviews permit more open-ended inquiries and explanations of responses, they were conducted orally (Baarda, Bakker, Fischer, Julsing, & van Vianen, 2021). Using the same logic, it has been concluded that the interviews must be semi-structured (Baarda, Bakker, Fischer, Julsing, Kostelijk, et al., 2021). A restricted structure is used to reveal the viewpoints of the individuals under study in any order. To guarantee that the relevant material is presented, however, a prepared subject list is developed (Bryman, 2012). This type of interview is great for asking open, non-preset questions, as contrasted to the fully structured interview, which consists of a series of predetermined, frequently closed questions. The introductory information and the prepared list of questions can be found in Appendix A. Because of the exploratory nature of this diamond, only key stakeholders were interviewed. The key stakeholders are selected in consultation with the local port authority. They are selected on the assumption they dispose of hydrogen-related knowledge and could have an influence on the future hydrogen port project. Their attitude towards the hydrogen port development is of no importance here. The goal is to do identify and interview as many key stakeholders as possible in order to get a broad list of viewpoints. Therefore, during every interview, the interviewee is asked about the involvement of other important actors in accordance with the snowball sampling technique.

Diamond II: designing the thing right

The second diamond is a figurative representation that depicts the problem solution as an answer to the design brief. For this research, this implies that the researcher finds ways to roadmap the development process in such a way that the experienced problems are solved. By first going through a diverging phase, anointed ‘Develop’, the researcher is supposed to collect information, concepts, and theories that can be useful. The successive converging phase, dubbed ‘Deliver’, requires the formation of a sequence that can be run through to develop the port. To test the various components of the roadmap, they are applied to the Icelandic circumstances where possible based on information assembled during the stakeholder interviews.

This is done by *doing desk research*. The desk research method aims to obtain a deeper grasp of the relevant concepts and expound on discoveries that might help to solve problems. According to Verschuren and Doorewaard (2010) desk research “is a research strategy in which the researcher does not gather empirical data himself or herself, but uses material produced by others.” Furthermore, the method can be characterised by 3 factors;

- a mix of existing material and reflection;
- direct contact with the research object is not possible;
- and the content is used in a different way than it was intended at the time of its creation (Verschuren & Doorewaard, 2010).

Desk research is more than just a list of references. It is intended that the written literature evaluation would be critical. When writing a literature review, one must judge the relevance of the work as well as how each piece fits into the larger narrative about the solution that one develops (Bryman, 2012; Verschuren & Doorewaard, 2010). Desk research enables the researcher to use a large amount of data quickly but one should not forget that the materials utilised in principle were obtained for purposes different than those intended by the researcher and there always is a biased perspective on the research material as a result of no direct contact with the research units (Verschuren & Doorewaard, 2010).

2.3. Chapter summary

This chapter presented the research type and outlined the methodological research model. This research can be classified as a practice oriented design research because it aims to solve a problem of an existing situation by doing a problem analysis and designing an intervention plan. In this study, the practical problem is analysed through the use of a single-case study. This allows for a holistic deep dive into a complex matter by taking into account specific circumstances. To make this happen, the double-diamond design process model is applied. It is a process of two times exploring an issue more widely and then taking focused action. The first diamond strives to result in a design brief, after which the second diamond seeks to find the solution to the problem.

3

Hydrogen economy

To answer the main research question described in section 1.4, one must understand the production of hydrogen in an all-encompassing context. For that reason, this chapter aims to evaluate hydrogen as an energy carrier and its supply chain. Section 3.1 will manifest the need for hydrogen as a replacement of fossil fuels, whereafter the various (current) production categories are elaborated upon in section 3.2. After that, the chemical characteristics are described in section 3.3. Subsequently, the diverse value chains concerning production, handling and demand are portrayed in section 3.4. Then, section 3.5 covers the specific green hydrogen production techniques. Later, the multiple forms of hydrogen storage and distribution are explained in section 3.6. Finally, section 3.7 answers the first sub-question by summarising the chapter.

3.1. Hydrogen as an energy storage

Energy is an essential component of our daily lives since it is necessary for almost all human activity. However, we continue to take energy for granted in certain ways, even as the energy situation worsens (Chamoun et al., 2015; Rusman & Dahari, 2016). Fossil fuels, such as petroleum, natural gas, and coal, account for more than 80% of global energy consumption (Sun et al., 2018). Since 1950, the world's growing population and people's constant desire to enhance their living standards have resulted in rising energy consumption. The world's energy consumption is expected to peak in 2035, while the global economy would enter a lengthy slump after 2040 (Abe et al., 2019). The world's main economies rely on fossil fuels to a large extent today. However, because fossil fuels are rapidly depleting, an overreliance on them has become a major worldwide concern in today's economy (Sun et al., 2018). According to estimates, current fossil fuel reserves are expected to last a maximum of 40 years for petroleum, 60 years for natural gas, and 156 years for coal (Midilli et al., 2005)). Therefore, numerous scientists and engineers have determined that replacing the present fossil fuel system with an ecologically clean, inexpensive, and more sustainable energy on demand might address the world's energy concerns. Following extensive research, hydrogen emerged as a promising outstanding sustainable future energy carrier due to its exceptional features (Chowdhury & Qubbaj, 2022; Ren et al., 2017). Hydrogen can contribute to a more sustainable energy future in two ways. Firstly, already existing applications of hydrogen could be produced from cleaner energy sources. Secondly, the use of clean hydrogen in new applications as a fuel and input substitute. Hydrogen can thus be seen as an indirect pathway for decarbonizing other economic sectors (Botero, 2021).

3.2. Hydrogen categorised

Hydrogen is the universe's oldest, lightest, and most abundant element. It may be found in a variety of substances, including water and fossil fuels. Hydrogen gas is largely employed in the (petro)chemical sector as a feedstock for crude oil refining, ammonia synthesis (particularly for fertiliser manufacture), and methanol production for a range of products (including plastics). Hydrogen may be utilised as a fuel as well. It can create heat above 1000°C without generating CO_2 when burned. Furthermore, hydrogen may be utilised in fuel cells, where it combines chemically with oxygen to generate energy without generating any pollutants or greenhouse gases. Water vapour is the only by-product of this chemical process (IRENA, 2022).

Regardless of the abundance of the element in a range of substances, hydrogen does not occur in vast quantities in its pure form. There are no large reserves of hydrogen that can be extracted from the earth. For that reason, hydrogen has to be released from its compounds, using energy in the process. Steam Methane Reforming, Coal Gasification, and Water electrolysis are the three most widely used and technologically mature production processes among a wide range of options. These three predominant manufacturing technologies account for nearly the entire global production of hydrogen (Acar & Dincer, 2019). Typically, different hydrogen production methods are used by referring to a colour-code system. The creation of hydrogen from coal, natural gas, and lignite is described as black, grey, or brown. Hydrogen derived from fossil fuels is generally referred to as 'grey' hydrogen. The colour blue denotes the creation of hydrogen from fossil fuels in conjunction with Carbon Capture, Utilisation and Storage (CCUS). The term "green" refers to hydrogen produced using renewable energy. In general, there is no unique colour for hydrogen created from biomass, nuclear power, or a variation of hydrogen produced from grid energy because emissions vary widely based on the sources, geographical region, and CCUS methods used.

Today, around 120 million tonnes (Mt) of hydrogen are generated worldwide, with two-thirds of that being pure hydrogen, used for oil refining and ammonia production, and one-third being a combination of gases, used for methanol- and steel production (IEA, 2019). Around 60% of global production occurs in "dedicated" hydrogen production plants, which create hydrogen as their principal output. The rest of the world's hydrogen supply is 'by-product' hydrogen, meaning it originates from facilities and processes that were originally planned to generate something else. Dehydrating or cleaning this by-product hydrogen is common, and it may then be transferred to a number of hydrogen-using processes and facilities. The majority of hydrogen is presently generated close to its final destination, with materials sourced from the same country. It must be noted that the majority of hydrogen generated today is grey hydrogen, most notably produced by natural gas steam methane reforming or coal gasification. These techniques account for 95% of today's hydrogen supply and produce a significant amount of CO2 and thus are incompatible with achieving net-zero emissions (IRENA, 2022). Today's total CO2 emissions from hydrogen generation are 830 megatonnes CO2 per year (IEA, 2015). Figure 3.1 depicts a global picture of hydrogen production and consumption for the year 2019. It stands out that the overwhelming majority of hydrogen is produced by fossil fuels today and hydrogen is mainly used for refining and ammonia production.

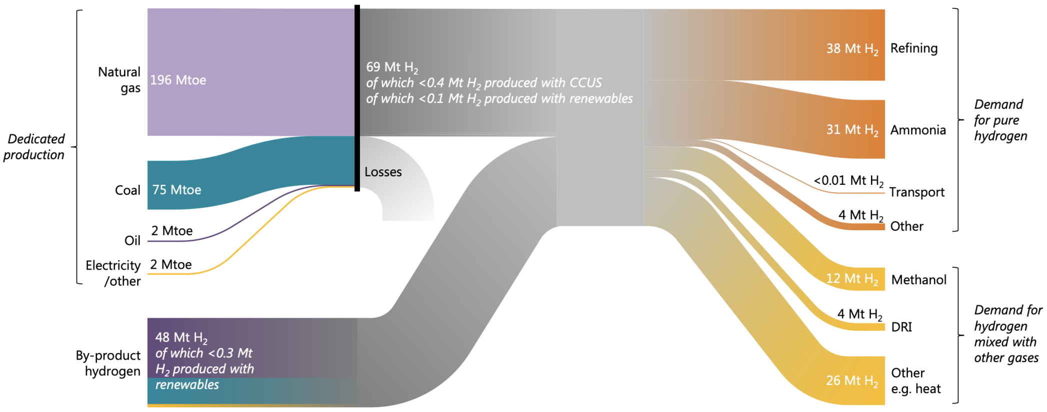


Figure 3.1: Hydrogen value chains in 2019 (IEA, 2019)

3.3. Hydrogen characterised

In terms of characteristics, hydrogen is in many aspects favourable over other energy carriers. Generally, it is light, storable, reactive, has a high energy content per mass unit, can be used without air pollutants, can be made from low-carbon energy sources, and can be produced at large scales (Botero, 2021). Hydrogen has more energy per unit of mass than natural gas or gasoline, which makes it a viable transportation fuel. However, because hydrogen is the lightest element, its energy density per unit of volume is low. Compared to other fuels, higher amounts of hydrogen must be transferred to supply the same energy demands. This can be accomplished by using larger or faster-flowing pipes and larger storage tanks for example. Hydrogen may be compressed, liquefied, or converted into higher-energy-density hydrogen-based fuels, although this (and any future re-conversion) consumes energy. Table 3.1 displays the chemical properties of hydrogen compared to other energy carriers.

Chemical characteristics comparison		
Property	Hydrogen	Comparison
Density (gaseous)	0,089 kg/m^3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70,79 kg/m^3 (-253°C, 1 bar)	1/6 of natural gas
Boiling point	-253°C (1 bar)	90°C below LNG
Energy unit of mass	120,1 MJ/kg	3x that of gasoline
Energy density (ambient conditions)	0,01 MJ/L	1/3 of natural gas
Flame velocity	346 cm/s	8x methane
Ignition range	4-77%	6x wider than methane
Autoignition temperature	585°C	220°C for gasoline
Ignition energy	0,02 MJ	1/10 of methane

Table 3.1: Chemical characteristics of hydrogen compared to other energy carriers

3.4. Value chain complexity

Value chains of the hydrogen economy can take a variety of routes. Demand may originate from a range of industries and markets, and there are several different ways to provide and handle it. Figure 3.2 displays the full value chain, from supply to end-use. The exact pathway choice is dependent on many factors, making the development process complex and challenging. Both for already existing use purposes and yet-to-be developed markets, investments and regulations must be coordinated in size and time for each feasible value chain. Considering no single company or organisation can control production, demand and infrastructure single-handedly, governments are tasked with a coordinating role that ensures market organisation, good infrastructure and regulations (van Wijk et al., 2019). Yet, building trust throughout the value chain in order to coordinate investments takes time and innovation to enable cross-sectoral collaboration (IEA, 2015).

For a novel energy carrier like hydrogen, infrastructure such as pipelines and transport networks are critical (Abdalla et al., 2018; Li et al., 2019; Ogden, 2003). While hydrogen may be generated locally, it benefits from economies of scale in storage and transport. Setting up an international supply chain also contributes to an overall cost reduction, considering it is highly dependent on the cost of the initial energy source (van Wijk et al., 2019). This, in turn, stimulates demand and technological innovation (Abe et al., 2019). In many nations and areas, governments' capacity to commit to major (and required) infrastructure expenditures is restricted. Public-private investment models can assist, but they can also add to the complexity. These expenditures will need to be coordinated across national boundaries in certain situations, which necessitates international collaboration at a level not yet seen before for hydrogen (IEA, 2015).

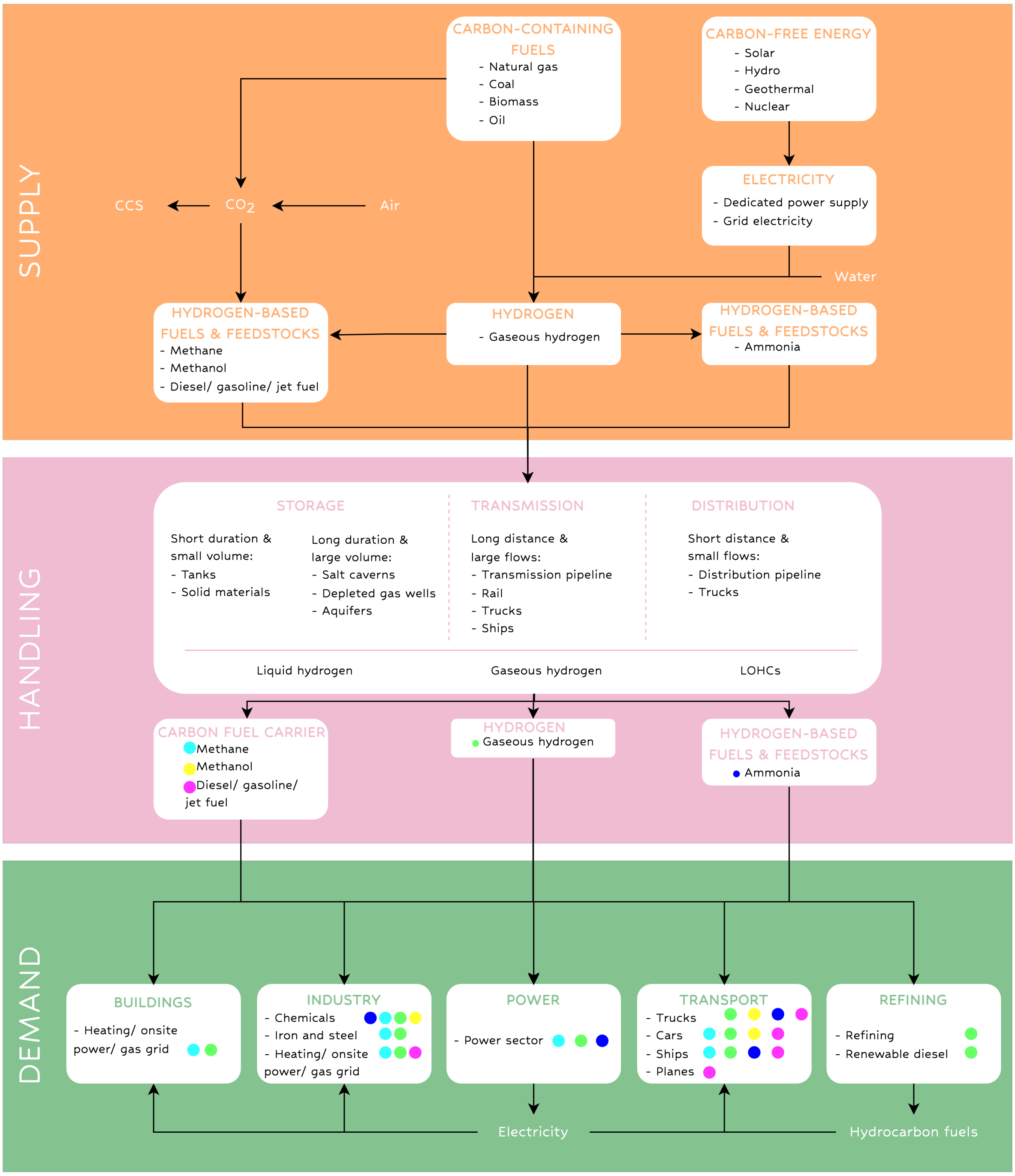


Figure 3.2: Mutiple hydrogen value chains containing combinations of supply, handling and demand technologies (adopted from IEA (2019))

3.5. Green hydrogen production

Electrolysis of water requires electricity, pure water, and an electrolyzer. Michael Faraday discovered in 1832 the general principle of electrolysis, which is based on the notion of splitting water using two electrodes and a direct current. (Santos et al., 2013). Today, alkaline electrolyzers (Alk) and proton exchange membrane electrolyzers (PEM) are the most prevalent forms of electrolyzers utilized on a commercial basis, with alkaline electrolysis being the more established technology. The solid oxide electrolytic cell (SOEC) is the third prominent electrolysis technique. However, this technology is in its infancy and is not yet commercially viable (Bloomberg NEF, 2019).

Alkaline electrolyzers take around 9 litres of water and 50 to 78 kWh of electrical energy for every kilogram of hydrogen generated (Acar & Dincer, 2019). The electrolyzer is composed of a cathode and an anode immersed in an alkaline liquid electrolyte. Between the electrodes is a membrane that permits the charged molecules and passage of water while preventing the passage of hydrogen and oxygen. When a direct current is delivered, negative electrodes at the cathode divide water molecules into hydrogen (H2) and hydroxide (OH). After hydroxide passes through the membrane, the negatively charged molecule combines with the positively charged anode to form water and oxygen (Acar & Dincer, 2019). The reactions occurring in the alkaline cathode, anode, and overall reaction are as follows:

$$
\begin{gathered}
4\,e^- + 4\,H_2O \longrightarrow 2\,H_2 + 4\,OH^- \\
4\,OH^- + O_2 \longrightarrow 2\,H_2O + 4\,e^- \\
2\,H_2O \longrightarrow 2\,H_2 + O_2
\end{gathered}
$$

PEM electrolysis, an alternative traditional electrolysis method, uses a comparable concept of water separation across a membrane. Yet, a solid conductor rather than a liquid electrolyte is utilized. Literature frequently compares the two prominent electrolysis processes, stating that alkaline electrolysis is economically favourable whereas PEM electrolysis offers a couple of technological advantages. The technological benefits of PEM include the electrolyzer's quick start-up and reaction time and its high-pressure discharge (15-80 bar) (Bloomberg NEF, 2019; Saba et al., 2018). In contrast, PEM requires costly elements for the membrane, like iridium or platinum, that might restrict the scalability of this method and raise uncertainties over its future (Kleijn & Van Der Voet, 2010).

3.6. Storage and distribution of hydrogen: carrier comparison

The low energy density of hydrogen gas causes challenges in efficiently storing and transporting it. The most frequent approach to storing the gas involves compressing it in high-pressure tanks (at least 200 bar). Despite the fact that the technology is well understood, it still has drawbacks, such as high energy consumption and safety, considering H2 has a broad range of flammability in the air (from 4%to 75%) (Rivarolo et al., 2018). Therefore, converting hydrogen gas into hydrogen-based fuels and feedstock is essential to reduce costs and use existing infrastructure for storage, transport and distribution (Rivarolo et al., 2018). This is done by liquefaction or attachment to a carrier to convert it into fuel (such as ammonia, synthetic liquid fuels, and methane). After converting, the goods can be reconverted into hydrogen, directly used in industry, or used as a fuel in the shipping sector (IEA, 2015). Despite the fact that the procedure requires more steps, binding hydrogen to another material may be advantageous for feedstock transport and storage due to reduced storage space and transportation costs (Gasunie, 2018).

This research explores the export possibilities of hydrogen by ship. The three main ways to transport hydrogen by ship are by converting it into Liquid Hydrogen (LH2), Liquid Organic Hydrogen Carriers (LOHCs), or Ammonia (NH3). In terms of characteristics, economic performance, and application viability, these modes of transportation are seen to be the most promising hydrogen carriers (Wijayanta et al., 2019). For that matter, this report will look at these forms of hydrogen transport and storage. Table 3.2 compares the significant properties per form of transport. The values are based on the work of Abrahamse (2021) and Aziz et al. (2019).

Parameter	**Unit**	**H2**	**LH2**	**MCH**	**DBT**	**NH3**
Chemical formula	-	H_2	H_2	C_7H_{14}	$C_{21}H_{32}$	NH_3
State of matter	-	Gaseous	Liquid	Liquid	Liquid	Liquid
Density	[kg/m3]	0,0838	71	770	1057	683
Melting/freezing temperature	[°C]	-259	-259	-127	-34	-78
Required temperature	[°C]	>-253	-253	No req.	No req.	-33
Boiling/condensation temperature	[°C]	-253	-253	101	395	-33
Hydrogen content	[%]	100	100	6,2	6	17,65
Energy density	[MJ/L]	0,0108	9,1	5,7	7,4	15,6

Table 3.2: Carrier properties

Besides the (dis)advantages that will be discussed in the following subsections, the main motive for choosing a particular form of transport is the final price of the hydrogen. The lower the price of hydrogen at the end of the supply chain, the larger the demand and as a result, the wiser the choice for that form of transport. Research has proven that LH2 currently is more expensive than NH3 and LOHCs (Abrahamse, 2021; IEA, 2015). The recent pre-feasibility study for exporting hydrogen from Iceland to the Port of Rotterdam shows similar results. Figure 3.3 displays a calculation of the total hydrogen cost price per carrier in two scenarios. The left graph being a 4TWh green hydrogen supply chain in 2025 whilst the right graph shows a comparison for a 20 TWh green hydrogen supply chain in 2030.

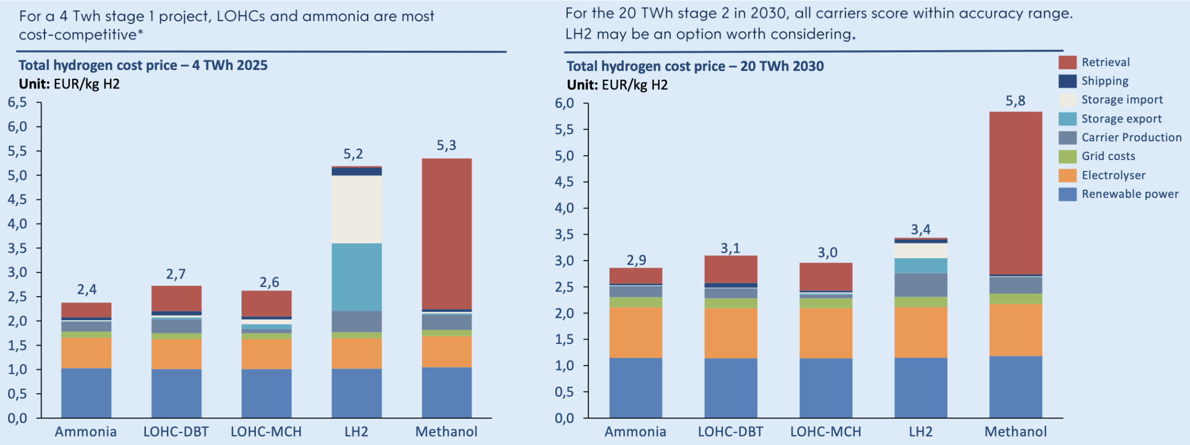


Figure 3.3: Estimated final hydrogen cost price pet kilogram (Coopman & Halgrimsson, 2021)

Liquid Hydrogen

By liquefying hydrogen gas the volumetric energy density is increased from 0,0108 MJ/L (under atmospheric conditions) to 9,1 MJ/L (Aziz et al., 2019), enabling more energy to be stored and transported per volumetric entity. Liquefaction is done by cooling down the hydrogen gas to a temperature of -253°C. Despite the fact that liquid hydrogen is regarded as a well-established commodity in the market, technological advancements such as up-scaling production and the construction of transportation vessels are still required (Meadows, 2008). Storing and transporting LH2 can be compared to LNG where the gas has to be cooled down to -162°C (van Wijk et al., 2019). In the industry, a distinction can be made between two existing processes to liquefy hydrogen: the Reversed Helium Brayton Cycle and the Claude Cycle (Roobeek, 2020). The general process of the conversion and reconversion of LH2 can be seen in figure 3.4. The process requires a lot of electricity to cool at synthesis and heat at decomposition, increasing the overall production cost (Aziz et al., 2019). In practice, between 21,6 and 24,0 GJ is needed to liquefy a ton of H2. Consequently, the procedure uses an additional 25-35% of the energy used for the production of the hydrogen itself (IRENA, 2022).

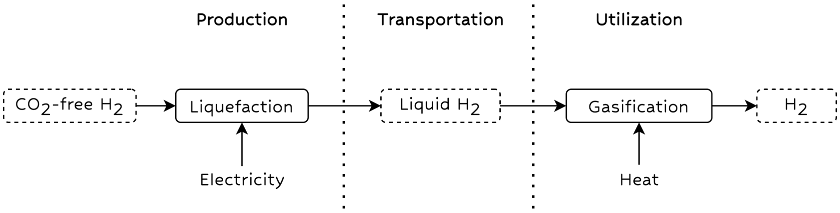


Figure 3.4: Hydrogen route for storage and transportation in the form of Liquid Hydrogen (adopted from (Aziz et al., 2019))

Once converted, liquid hydrogen is stored in cryogenic tanks (IEA, 2015). These storage tanks are supplied with optimal insulation to keep the temperature stable and thus minimise energy losses (Wijayanta et al., 2019). This is due to the double walls with a vacuum space, filled with insulation material (perlite), in the middle (Tijdgat, 2020). Nonetheless, storing and transporting LH2 is always accompanied by losses due to evaporation (boil-off), shortening the dwell-time of the good (Reuß et al., 2017). When it evaporates, in open-air LH2 will become a heavy gas when the surrounding air freezes, and since it is a heavy gas, it will collect on the ground (Wijayanta et al., 2019).

LH2 will be transported aboard a new Liquefied Natural Gas (LNG) tanker-style vessel (Tijdgat, 2020). Although the development of such vessels is still in its early stages (IEA, 2015), the first liquified hydrogen carrier (The Suiso Frontier, manufactured by Kawasaki Heavy Industries) has recently set sail between Japan and Australia (Watson et al., 2022). Compared to other forms of hydrogen carriers, the complex storage and low volumetric density of LH2 do not make it the most suitable form for shipping (Tijdgat, 2020).

In general, the choice for production, storage and transport in the form of liquid hydrogen has advantages and disadvantages. The most important ones have been listed in table 3.3. Information was gathered from Coopman and Halgrimsson (2021), Abrahamse (2021), and Tijdgat (2020).

Advantage	Disadvantage
Fewer steps in the conversion process	Design of LH2-vessel in early stages
Versatile product	Expensive and complex storage
Comparable supply chain to LNG	Low volumetric density
A possible use for cold energy at unloading port	Requires a lot of energy to cool and keep cool
High potential future price reduction	All new infrastructure needed
	Inevitable losses during storage due to evaporation (boil-off)

Table 3.3: Advantages and disadvantages to choosing for Liquid Hydrogen as a carrier

Ammonia

Compared to LH2, ammonia contains 1,7 times more hydrogen per cubic metre and already liquefies at -33C. The good, used to produce fertiliser for agriculture for over 100 years now, is produced by binding hydrogen (H_2) to nitrogen (N_2). The process is known as the Haber-Bosch process. Because nitrogen can be gotten from the air using electricity, the method is easily accessible (van Wijk et al., 2017). The reaction of the two takes place in the presence of a catalyst, under a temperature of 400-500 C, and under a pressure of 100 to 250 bar (Giddey et al., 2017; Morgan, 2013). The general process of synthesis and decomposition can be seen in figure 3.5. To produce 1 ton of ammonia, 178 kg of hydrogen is needed and 822 kg of nitrogen is needed (Giddey et al., 2017; IRENA, 2022). To produce nitrogen an air separation unit is required that uses 0,11 kWh per kilo N_2 (Tijdgat, 2020). Furthermore, the Haber-Bosch process requires 0,64 kWh per kilo of NH_3 produced (Morgan, 2013). Added together, this means that the whole production process costs 34 GJ per tonne of ammonia (Tijdgat, 2020). In addition, the dehydrogenation (synonym for cracking) of ammonia requires a substantial amount of energy in the form of heat. This could be provided in the form of waste heat (IEA, 2015). The current efficiency of the cracking process is about 85% (Thomas & Parks, 2006).

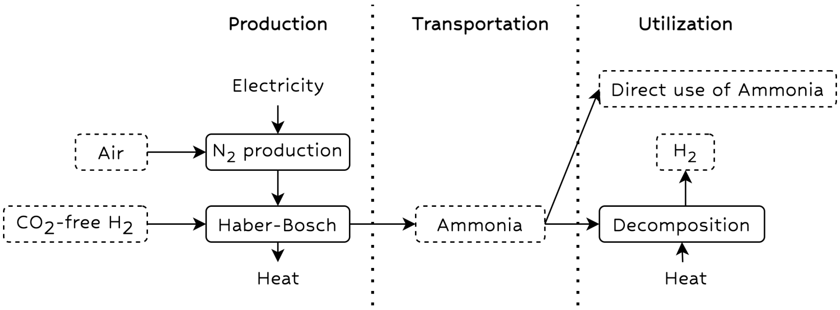


Figure 3.5: Hydrogen route for storage and transportation in the form of Ammonia (adopted from (Aziz et al., 2019))

Under atmospheric conditions, NH3 is a gas. Once it is cooled down to a temperature of -33°C, it becomes liquid. With that in mind, Ammonia can be stored and transported in various tanks with a capacity ranging from 15,000 to 60,000 tons (Institute for Sustainable Process Technology Power, 2017). The following summation gives an overview:

- pressurised thermos tanks: maintain the temperature with efficient insulation but once the temperature rises, and as a result, the pressure rises, the tanks are able to withhold.
- semi-pressurized/ semi-refrigerated (SP/ SR) tanks: are similar to pressurised tanks but once the temperature rises the gas can be re-liquefied by refrigeration.
- fully refrigerated tanks: hold ammonia at atmospheric pressure and allow little pressure to be built up by direct re-liquefaction of the boil-off.

Because of its similar storage conditions and boiling points, an example can be taken from Liquefied Petroleum Gas (LPG) for the storage of ammonia (Tijdgat, 2020).

In general, the choice for production, storage and transport in the form of ammonia has advantages and disadvantages. The most important ones have been listed in table 3.4. Information was gathered from IEA (2019), Coopman and Halgrimsson (2021), and Abrahamse (2021).

Advantage	**Disadvantage**
Already existing technology and transport network	Highly toxic good with restrictions in supply chain
High energy density results in a high volumetric storage efficiency	Risk of fine dust formation and acidification if escaped
Low-risk profile if refrigerated	Large scale cracking is still in development
Expected to become a global (shipping) fuel	Requires a lot of energy for synthesis and decomposition
Low liquefaction temperature required	

Table 3.4: Advantages and disadvantages to choosing for Ammonia as a carrier

Liquid Organic Hydrogen Carriers

As a means of storage and transportation, hydrogen can also be attached to a Liquid Organic Hydrogen Carrier (LOHC). It refers to a group of organic compounds that can absorb and release hydrogen through a chemical reaction. A LOHC may be hydrogenated before storage and dehydrogenated at the location of hydrogen consumption. The basic structure of the LOHC stays unchanged after the release of rechargeable hydrogen, requiring no additional carrier manufacturing. Also, the hydrogen purity stays equal after reconversion (Markiewicz et al., 2015). Because LOHCs are very comparable to crude oil and oil products, existing oil infrastructure can be used and the good does not have to be refrigerated or compressed (Niermann et al., 2019). By contrast, the carrier always has to be transported back because the LOHC can not be produced at the point of hydrogenation and be directly used at the point of dehydrogenation. Another disadvantage is the high-temperature requirements for the conversion and reconversion process as it demands much energy and results in high costs.

Currently, a few LOHCs have been commercially released and are in advanced stages of development. The following are two of the most promising ones on the market: Methylcyclohexane (MCH) and Dibenzyltoluene (DBT). For hydrogenation and dehydrogenation, the H2 concentration and energy needs are roughly the same (Wijayanta et al., 2019). Also, the fact that the LOHC chemicals last for 1000 cycles of hydrogenation and dehydrogenation, applies to both (Wulf & Zapp, 2018). Although the two have much in common, they do have minor differences in production, advantages, and risks. The following two paragraphs review both LOHCs separately. In general, however, MCH is the cheaper option DBT is the safer option (IEA, 2015).

MCH is a toluene-hydrogen reaction product. Toluene is a common industrial feedstock and solvent, however, it has the drawback of being poisonous (IEA, 2015). The process can be seen in figure 3.6 and is characterised as cyclic because Toluene is recycled after dehydrogenation. The hydrogenation process takes place at temperatures between 180 and 300 C and at a pressure of 2 bars. Because the reaction is exothermic, byproduct heat generation could be used for other processes. The dehydrogenation occurs at higher temperatures ranging from 230 to 400 $°C$ and low pressure. This endothermic reaction requires a lot of energy in the form of heat. The dehydrogenation process of MCH uses less heat than ammonia but more than DBT (Irfan Hatim et al., 2013). About 4.7 GJ per ton H2 is required for hydrogenation, and 36 GJ per ton H2 is required for dehydrogenation (Tijdgat, 2020). Because both substances are poisonous and have comparable densities, toluene or MCH storage is analogous to methanol storage and should be kept in stainless steel tanks.

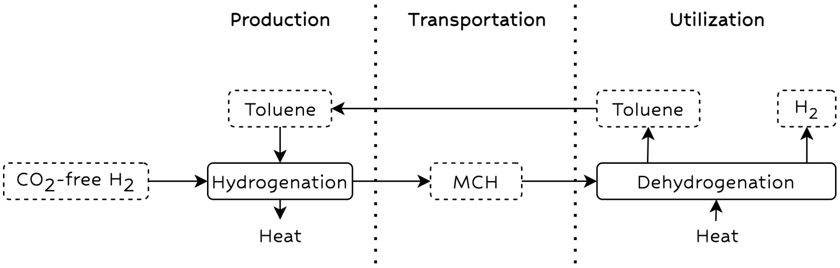


Figure 3.6: Hydrogen route for storage and transportation in the form of MCH (adopted from (Aziz et al., 2019))

Advantage	Disadvantage
Use of existing infrastructure	Toluene is often expensive
Toluene is an easily available existing carrier	A lot of energy is required for dehydrogenation
Extra functionality of byproduct heat during hydrogenation	Toluene is toxic and flammable
	Requires transporting back recycled toluene
	Requires extra purification step for the purpose of PEM fuel cells

Table 3.5: Advantages and disadvantages to choosing for MCH as a carrier

The second LOHC considered in this research is DBT. When not attached to hydrogen, the carrier is called dibenzyl toluene (H0-DBT) but after hydrogenation, the good becomes perhydro-dibenzyl toluene (H18-DBT). DBT is already utilised in the industry as a heat transfer medium, although, unlike toluene, it is not yet mass-manufactured in significant amounts. Compared to other LOHCs, the (de)hydrogenation process is more complex because multiple different catalysts are required. An overview of the process can be seen in figure 3.7. The exothermic hydrogenation requires a pressure of 50 bar and a temperature of 150C, whilst the endothermic dehydrogenation already occurs in atmospheric pressure but requires a temperature of about 300C. About 4.7 GJ per ton H2 is required for hydrogenation, while approximately 34.2 GJ per ton H2 is required for dehydrogenation (Tijdgat, 2020). DBT can be stored similarly to oil products because both can be kept fluid at ambient temperatures. Because DBT is non-toxic, it is easier to meet storage tank standards than methanol or toluene.

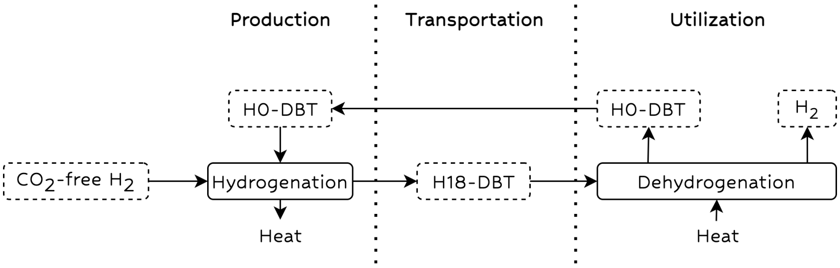


Figure 3.7: Hydrogen route for storage and transportation in the form of DBT (adopted from (Aziz et al., 2019))

Advantage	**Disadvantage**
Not toxic and flammable so safe and easy to handle	Small scale production of DBT
No purification process is needed for the purpose of PEM fuel cells	Complicated (de)hydrogenation process using multiple catalysts
Use of existing infrastructure	Large energy requirement for dehydrogenation
	DBT is still expensive
	Requires transporting back recycled DBT

Table 3.6: Advantages and disadvantages to choosing for DBT as a carrier

3.7. Chapter summary

This chapter has provided an insight into the hydrogen economy, its value chain, and its supply chain, and therefore answers the first sub-question.

In essence, hydrogen is a chemical element that be obtained by breaking hydrogen-containing compounds. This process requires energy but when aggregating the hydrogen with oxygen as a later stage, the energy is released again and H_2O is the sole emission. As such, hydrogen is considered to be an energy carrier and is ideally suited for energy storage and transportation.

When the hydrogen is produced using renewable energy and H_2O (in a process called electrolysis), it is labelled as green hydrogen. The consumption of hydrogen is diverse and can be found within the power sector, refining, the transport sector, the industry, and (building) heating. However, due to its low energy density at ambient conditions, the hydrogen gas needs to be converted into hydrogen-based fuels and feedstock to make it effective for transport and storage.

This chapter described the most cost-competitive solutions. The so-called carriers considered are liquid hydrogen (LH2), ammonia (NH3), and liquid organic hydrogen carriers (LOHCs) such as dibenzyl toluene (DBT) and methylcyclohexane (MCH). Currently, all options have both advantages and disadvantages, and the market is not yet determined for a particular option. The creation of liquid hydrogen necessitates a substantial amount of energy, specialised transport vessels, and infrastructure. This is offset by the fact that it no longer requires "loading and unloading." Ammonia, on the other hand, is a very toxic chemical, needing substantial safety precautions for the transport and storage of hydrogen in ammonia. This is offset by the fact that ammonia is a substance with which the industry has great experience and, like hydrogen, is immediately used in a range of production processes and as a marine fuel. The disadvantage of LOHCs (such as DBT and MCH) is that the hydrogen carrier must be returned before a new load of hydrogen may be loaded. In addition, unloading demands a tremendous quantity of energy, and large carriers generate expense and safety difficulties. This is mitigated by the fact that existing infrastructure may be employed and the carriers are very straightforward to handle.

In these forms, the hydrogen can be transported using pipelines, ships, trains, or trucks. The goods can be stored in tanks for a short duration, and in salt caverns, depleted gas wells, or aquifers for a long duration. At the end of the supply chain, the carriers can either be reconverted into hydrogen gas or directly used, depending on the application.

4

Port planning

The port industry operates in a dynamic global market and is impacted by political events, international commerce, and global economic conditions as a whole, resulting in logistical, technological, and economic uncertainty. This complicates the design and planning of these complex socio-technical systems (Taneja, 2013). This chapter covers existing literature regarding the planning of ports. First, the concepts of uncertainty and flexibility are covered in section 4.1. Next, traditional port planning approaches are discussed in section 4.2. Then, port governance models are discussed in section 4.3. Eventually, sub-question 2 is answered by summarising the chapter in section 4.4.

4.1. Influencing factors in port development

4.1.1. Ports as engineering systems

Complex socio-technical systems

Ports can be considered engineering systems as they are man-made and are designed to accomplish functional goals or objectives in response to stated requirements of one or more stakeholders (Blanchard & Fabrycky, 2011). They are made up of a symbiotic relationship between physical infrastructure, facilities, equipment, materials, people, information, software, and money. These elements correspond to subsystems that interact to provide the desired system response.

Developing a greenfield hydrogen industrial port complex is a nonlinear project that allows for many interactions between various components (Bettis & Hitt, 1995). Several of the port system's components are complex systems in their own right (Taneja, 2013). The development process, therefore, is very unpredictable, involves a large number of stakeholders, and requires many interactions of subsystems. Therefore, a greenfield hydrogen industrial port complex can be categorised as a complex socio-technical system. The system is complex because it displays behaviour that is unexpected, emerging and/or unpredictable (Bakker & de Kleijn, 2018) and it necessitates an integrated approach to design, engineering, and governance that welcomes emergence and adaptability. Furthermore, the HIPC is a socio-technical system because the fulfilment of societal functions has a central role (Geels, 2004). After all, the infrastructure's worth is determined only by the services it offers to society and the economy (Weijnen & Correljé, 2021). A socio-technical system is a social structure built on a technical foundation, characterised by its interaction of requirements (Whitworth, 2009). Socio-functional requirements imposed by stakeholders influence the design of the technical system, whilst techno-functional requirements impose technical restrictions on the port on which the stakeholders base their position.

Engineered system context

The engineered port system is part of a larger system hierarchy. In this case, the HIPC is the System-of-Interest (SoI). In the discipline of systems engineering, this can be understood as the system of direct concern to the observer. The focus of this system is driven by the scope of authority or control with implicit recognition that this scope may not capture all related elements (SEBoK Editorial Board, 2021). When planning the SoI, the System Context is of equal importance. It describes the context for a SoI so that the necessary understanding can be reached about diverse external influences and the right systems engineering decisions can be made across the life of that SoI (SEBoK Editorial Board, 2021). Like with all system contexts, system boundaries are inherent. The synergistic interactions between a group of elements form a system boundary and determine what it means to be a member of the system.

Figure 4.1 shows the system context by attributing system boundaries around the SoI, being the HIPC. The outer layer, the port environment, is comprised of a variety of economic, technological, political, and social aspects. It considers factors such as social and cultural changes, inflation, currency exchange rates, political uncertainty, demographic consequences, and natural calamities (Taneja et al., 2012). The external environment influences the port-related industry. This can be understood as the port and shipping industry, and in this research also includes the hydrogen industry. It includes elements such as sustainability, safety, technology, stakeholders (and their collaboration), and financial considerations in the industry. The port market is shaped by a variety of variables, including the scale of its hinterlands, contests from other ports, port guidelines, and the port's strategic vision. The SoI can be found in the midst of the aforementioned layers. A thorough grasp of the (uncertain) factors included within these layers of impact and the linkages between them is required to comprehend the port system's dynamics. It is critical to consider the uncertainties inherent in the environment, industry, and market while designing a port development project (Taneja, 2013).

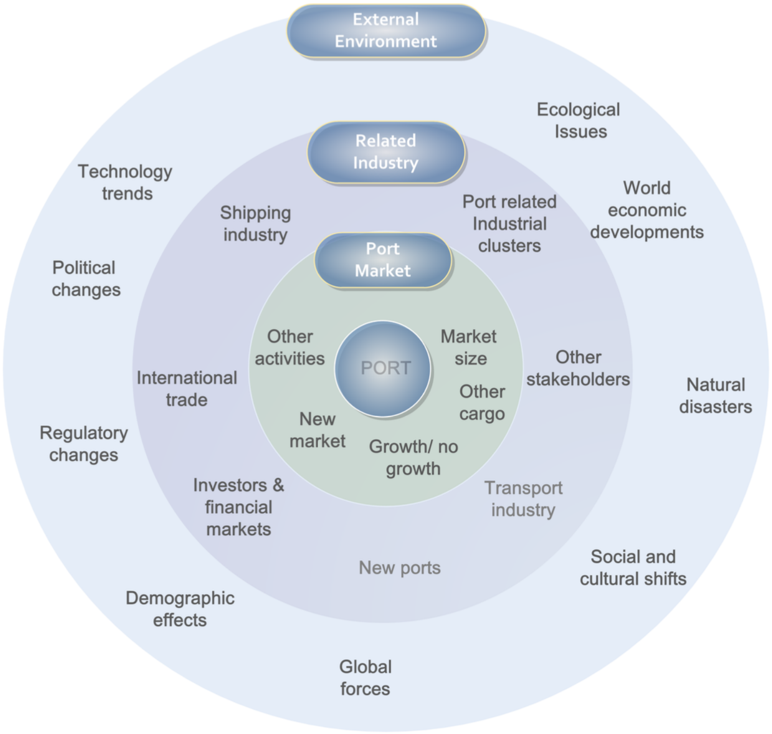


Figure 4.1: Port system and external forces (Taneja, 2013)

4.1.2. Uncertainty

Ports' prospects are fraught with uncertainty. They are associated with new functional and scale requirements, new external restrictions, and altered expectations. They must, however, assure capacity, functionality, and service quality throughout the foreseen lifecycle (Taneja, 2013). According to Taneja et al. (2012), the primary cause for failed port development projects is insufficient consideration of uncertainty throughout the planning phase. In fact, dealing with uncertainties throughout the planning phase improves the success of long-term initiatives in dynamic environments (García-Morales et al., 2015). Dealing with uncertainties can be understood as minimizing and managing in order to use the uncertainty to the planner's advantage.

Uncertainty defined

Before addressing and dealing with uncertainties, the term must be adequately defined. According to Walker et al. (2010), uncertainty is defined as "any departure from the unachievable ideal of complete determinism". In the hydrogen port development context, uncertainty can be practically explained by an unknown amount of knowledge about the source and impact of a specific, or series of, developments toward a port's desired performance.

Uncertainty could have both a negative connotation, considered a vulnerability, or a positive connotation considered an opportunity. Taneja (2013) describes vulnerabilities as "possible developments that can degrade the performance of a plan so that it is no longer successful" and opportunities as "developments that can increase the success of the plan". Traditionally designed infrastructure projects typically face the full significance and expense of vulnerabilities, while ignoring the opportunities variant of uncertainty. One must remember that the capacity for future resolution of some uncertainties is a trait that enables it to produce value.

Sources of uncertainty

Generally, a distinction is made between two types of uncertain phenomena: uncertainty due to lack of knowledge about the phenomena (e.g. inaccurate data, subjective judgements, ongoing scientific research), or uncertainty due to variability in the phenomena (economic changes, political turmoil, natural disasters). The former is reducible through more investigation and research, whilst the latter is insoluble (Taneja, 2013).

Another distinction is made between endogenous and exogenous uncertainty in port planning. Exogenous uncertainty refers to external driving forces that are outside the planner's or decisionmaker's control, whereas endogenous uncertainty occurs within the system's boundary. Examples of endogenous uncertainty factors can be found within the project context and corporate context. Project uncertainty, such as costs, timetables, expected material and quantities, are to a certain extent within own control and can be estimated using a reasonable assessment of the level of uncertainty. The same applies to corporate visions and strategies such as marketing, pricing, service enhancement, and other traffic-generating methods (such as volume contracts, secured vessel turnaround times, and berthing windows). Exogenous factors, on the other hand, are harder to estimate. The biggest uncertainties are associated with market factors such as global trade patterns, shipping service changes, and new energy markets. Practical port planning examples include land and energy pricing, the constant danger of new market entrants, changing safety- and environmental standards, privatisation trends, and the dependence on powerful consumers and suppliers that both contribute to port competition (Selkou & Roe, 2004). More examples as described by Taneja (2013) can be found in table 4.1.

Project context	Costs, construction delays, estimated quantities of material, material prices, revenues, labour issues, changing functional requirements
Corporate context	Pricing decisions, marketing, service improvement, volume discounts, guaranteed vessel turnaround times, berthing windows, land- and energy prices, currency and interest rates, competition between ports, the continuing threat of a new entrant, potential for global substitutes, presence of powerful customers and suppliers
Market context	Developments of global trade, trends in the shipping market, structural change in shipping services, globalisation of consumption and production, the emergence of global transport and logistics networks, international sourcing, growth of hinterlands, change in port hinterland relations, new technologies, future scales
Reporting	The primary functional goals are reported more quantitatively, whereas both secondary goals are defined qualitatively.
Political context	Deregulation, privatisation, physical and capital mobility, international security policies, safety and environmental regulations

Table 4.1: Examples of uncertainties per category (Taneja, 2013)

Actions to counter uncertainty

Once constructed, port infrastructure facilities are often irreversible. They necessitate massive, irreversible, high-risk investments with a very long economic payback time. However, as established facilities, they may face economic rivalry as a result of rising space demand or additional functional requirements. As a result, it is critical to include flexibility in the planning and design of port infrastructure. Flexibility has long been regarded as a critical objective when it comes to coping with uncertainty in the planning and design of complex engineering systems (Ahmed et al., 1996; Floricel & Miller, 2001).

Flexibility is recognized as the capacity to adapt or perform to changing requirements in order to remain functional. The degree of flexibility represents the ease with which a port can respond to uncertainty in a timely and cost-effective manner (van Koningsveld & Taneja, 2019). In relation to port infrastructures, three distinct forms of flexibility exist; flexibility in use, flexibility in timing, and flexibility in size. A port is flexible in use if it is capable of accommodating a variety of activities (Taneja, 2013). Flexibility in timing is achieved if the port planner has the right (without obligation) to carry out a strategic action now or in the future. This is called a 'real option'. It goes without saying that flexibility in size means that there is a possibility to expand or shrink in size.

4.2. Port master planning

A port's construction process begins with the creation of a master plan. A port's master plan contains a layout that allocates land to the different purposes necessary, a description of the stages required to implement the plan, and an indicative implementation schedule for each development phase. It includes preliminary plans for significant infrastructure projects such as dredging and reclamation, approach channels and basins, breakwaters, quays, terminal areas, and highways. These structures are dimensioned in the early design process. Port master planning is critical in identifying a port's position in the maritime hierarchy, not only because it identifies and specifies the port areas that require development, but also because it serves as the vehicle for the port's market expansion strategy (Frankel, 1989). In a nutshell, a Master Plan serves as a road map for future growth, detailing the port's objectives and how they will be realised within the constraints of market, legal, social, and environmental considerations.

Port planning is concerned with the creation of new (green-field) ports, the expansion of existing ports, and the transformation of existing (brown-field) ports. In each of these instances, the designs have a direct effect on the surrounding environment, whether man-made or natural. Port development therefore needs approval of national, regional, and/or local authorities. As a result, permitting requires the completion of an Environmental and Social Impact Assessment (ESIA), which involves considerable stakeholder participation. Additionally, a social cost-benefit analysis or economic study is frequently required in order to obtain government permission and/or financing from a development bank. Therefore, the planning process consists of a) technical studies and financial analyses and b) the environmental and social impact assessments and economic studies that are required as part of the legal permits and regulatory approval processes. In reality, they are intertwined and much depend on each other.

Although the development process never looks the same and can not be labelled as linear, the following six general steps can be distinguished.

Step 1: strategy and objectives

The first step of port master planning generally involves the definition of the function of the port. The defined function is a result of the port strategy. The port strategy defines the objectives and strategy of the port development. What is the purpose of this port? Which types of freight flow is it designed to handle? Who will the clients be? Which hinterland is it to serve? Which industries will it serve? The function of the port can be inspired by regional development plans or national strategies. Therefore, it must be noted that although most ports operate on a commercial basis and are judged to be profitable, they also have to preserve their standing in a competitive environment. These factors, together with stakeholder interaction, are key to formulating a fitting strategy.

Step 2: market study

Subsequently, a market study has to be performed. These studies are scoped within the demarcated port strategy and consist of a) cargo forecasts and b) shipping forecasts. Aspects to consider are expected cargo volumes to and from the port, shipping traffic (sea and inland), and hinterland traffic (road, rail, pipeline, barge). Both studies should be performed by maritime transport economists and in their turn, lead to requirements for the to be build facilities. Market studies are extremely vulnerable to uncertainties and thus require many different forecasting methods.

Step 3: facility planning

Based on the projected cargo- and shipping numbers, the requirements for large-scale facilities can be estimated. Facility planning generally includes aspects such as waterfront length, terminal area, nautical access, and port basin area. In order to determine how much waterfront length is required, port planning must know which terminals have to be built, what the average and maximum ship sizes will be, and what the required berth length is. To determine the required size of the terminals, facility planners must know what handling equipment will be used, what storage area is required, and in the case of a HIPC, what plot sizes hydrogen producers require. Facility planners depend on local conditions and design rules when calculating the nautical access. To determine if breakwaters and dredging work is required, the orientation, the depth, and the width of the channel have to be determined. Also, to estimate the port basin area, the ship manoeuvring space, the waiting area and the berthing area must be thought of. All the aspects named above serve as input for land use planning.

Step 4: development of alternatives
Once the generically estimated dimensions are known, planners can start drafting multiple port layouts that display the location of facilities and potential phasing regimes to upgrade over time. In this context, several aspects are of importance. Amongst others are:

- soil conditions and topography;
- bathymetry and sediment transport;
- prevailing winds, waves, and currents;
- navigation requirements;
- the required distance from urban areas;
- location of terminals;
- traffic corridors;
- utility zones;
- administration and customs.

Per alternative, the interaction with the surrounding should be described. This includes hinterland connections, environmental and safety considerations, the location of workers and neighbouring towns, and the location of dangerous industrial zones. Eventually, the resulting different alternatives serve as input for cost estimation and the Environmental Impact Assessment.

Step 5: selection of alternatives
The next step is to select the preferred alternative to be worked out in more detail and create an initial business case. There are a couple of tools to select the preferred alternative. Firstly, a multi-criteria analysis could be performed. The criteria should be different in nature and in importance and should be both qualitative and quantitative. However, they should not go into too much depth as they should merely serve to make a choice between the existing alternatives. Secondly, financial and economic analyses could be performed that encapture the added benefit for the port authority, neighbouring region, and government. Future revenue streams, investment costs, operational costs, transport cost savings, job creation, and economic development of the region should be incorporated. Thirdly, the Environmental Impact Assessment should also result in a preferred alternative. Finally, consultation with stakeholders should not be forgotten when choosing the best alternative.

Step 6: detailed layout design
Consequently, the selected layout can be worked out in more detail. This step involves multiple different in-depth engineering studies such as dredging studies, terminal design studies, and navigation studies for the access channel. Morphological aspects, terminal safety aspects, and wind aspects are key in this regard. Also, the hinterland connections can now be developed further. Only after this step, an initial cost estimate can be made that serves as input for the subsequent decision process.

4.3. Port governance models

In general, a distinction is made between public ports, private ports, or a combination of the two. Numerous ports began as public facilities, but privatization of (public) facilities and private creation of totally new ports have grown popular. The efficacy of these strategies is highly dependent on the port's role and legal and institutional framework (van Koningsveld et al., 2021). Once the role of the port is defined, the profitability should be determined. Whilst determining the benefits of the high investment costs, private port projects only run financial analyses, whilst public projects also require economic analyses, including social costs and benefits (De Brucker et al., 1998). The following subsections cover the existing port models and table 4.2 summarizes the broad differences.

4.3.1. Public ports

Public ports are government-owned, be it the National Government, a municipality, or a separate status of Port Trust or Port Authority. In general, three different public port models can be distinguished:

- Public Service Ports: the port authority is responsible for all functions, including cargo handling and storage. This style was common in the past and is currently prevalent in some underdeveloped countries. Bureaucracy and red tape were frequently associated with it. This configuration can only exist in the absence of a natural hinterland and competing ports.
- Tool Ports: the port authority is responsible for providing the primary ship-to-shore handling equipment, while private enterprises handle goods under licenses granted by the port authority.
- Landlord Ports: the port authority owns the property and grants concessions to private sector enterprises to provide cargo handling and storage services. The port authority is also responsible for infrastructure, maritime safety, and access, as well as the upkeep of the approach channel and basins. Private companies own, operate and maintain their own equipment and employ their own labour.

4.3.2. Private ports

Fully private service ports are built and operated by private companies, including the responsibility for maintenance. In totally privatised ports, government agencies no longer play any significant role. However, statutory tasks such as navigational safety, environmental protection, and customs stay the responsibility of the government (Juhel, 1999). Captive Ports are a specific type of fully private ports that are constructed and operated exclusively for the benefit of one industry, such as tanker docks for a refinery or a bulk export terminal for a mining business. The primary benefit of the private model is that private enterprises may develop and operate ports with utmost flexibility. The greatest drawback of monopolistic behaviour is that it may impede the further creation of value to society (van Koningsveld et al., 2021).

4.3.3. Hybrid model

A hybrid version between public and private ports is also possible. So-called Built-Operate-Transfer (BOT) projects are seen by many politicians around the world as an attractive way to create infrastructure (Ligteringen, 2017). It is a project delivery method in which a government organization offers a private sector partner the right to construct and run a project in accordance with accepted design specifications. The project is not owned by the private sector parties. The private-sector party is compensated for taking on these tasks by the government entity or the project's end customers. In some instances, the private sector participant may finance a portion of the project (Public-Private Partnership). At the end of the contract time, the government body assumes operational control of the project. This model has two major advantages. First, it serves as a valuable test for the financial viability of the port project from a private perspective. Second, once in operation, the port's efficiency and profitability are determined by the private partner's financial interests, rather than by social and political factors.

Type	**Infrastructure**	**Superstructure**	**Stevedoring labor**	**Other functions**
Public service port	Public	Public	Public	Mainly public
Tool port	Public	Public	Private	Mainly public
Landlord port	Public	Private	Private	Mainly private
Private port	Private	Private	Private	Mainly private

Table 4.2: Characteristics of port different port governance models (adopted from (van Koningsveld & Taneja, 2019))

4.4. Chapter summary

The above chapter has offered insight into the complex process of port design by covering the typical general process phases and influencing factors. It has also addressed various port governance models. This chapter therefore provides an answer to sub-question 2.

Ports can be considered complex socio-technical engineering systems. For that matter, the engineering trajectory is a nonlinear, stage-gated, and iterative process that involves many interactions between various components. Port development is influenced by multiple layers of (uncertain) factors which have to be understood to comprehend the port system's dynamics. It is critical to consider the uncertainties inherent in the, among others, environment, industry, and market. Actions must be determined to incorporate flexibility as a means of countering the uncertainty.

A port's planning process consists of a) technical studies and financial analyses and b) the environmental and social impact assessments and economic studies that are required as part of the legal permits and regulatory approval processes. In reality, they are intertwined and much depend on each other. The following general steps have to be run through:

1. define strategy and objectives;
2. perform market study;
3. determine facility requirements;
4. draft multiple layouts;
5. select preferred alternative;
6. work out detailed layout design.

An important aspect of port development is the determination of the best governance model. A distinction is made between public ports, private ports, and a hybrid version. The choice depends on the purpose of the port, the wishes of the initiators, and the degree to which actors are capable of bearing responsibilities.

5

Diamond 1: design brief

This chapter aims to define the practical problem and draft an accompanying design brief. The conducted stakeholder interviews are utilised to arrive at these specific deliverables. By discussing the findings, this chapter aims to 'design the right thing'. The chapter is composed of four sections. First, Section 5.1 describes how the data was gathered. Subsequently, Section 5.2 portrays the results of the SWOT-analysis. Then, section 5.3 provides the objective setting for the second diamond. Finally, section 5.4 answers the third sub-question and summarises the chapter.

5.1. Stakeholder interview results

As was described in Section 4.1.1, a port development process is unpredictable, involves a large number of stakeholders, and requires many interactions of subsystems. A greenfield hydrogen industrial port complex is considered a complex socio-technical system. This indicates a need to understand the various perceptions of requirements that exist among stakeholders and key players.

In order to assemble the necessary information for the following sections, semi-structured stakeholder interviews were conducted. Initially, 14 different types of key stakeholders were selected. Unfortunately, six of these were unwilling to cooperate or did not respond. Arguably this causes a gap in the stakeholder representation and corresponding perspectives. The other eight were asked about their knowledge of hydrogen applications, their opinion on the creation of a HIPC, the requirements for such a port, and about markets that could benefit from hydrogen production. However, considering every stakeholder has its own set of knowledge, other follow-up questions and interjections were also asked to thoroughly understand the context. The general stakeholder protocol can be found in Appendix A.

The list of interviewed stakeholders can be found in table 5.1 and general conclusions of the interviews per overarching theme can be found in the following paragraphs.

Perspective	Organisation	Function
Port Authority	Fjarðabyggð Ports	Operations manager
Terminal Developer	Mitsubishi Corporation	Project manager business development
Innovation Center Iceland	Business Iceland	Head of energy and green solutions
Nearby industry	Alcoa aluminium Smelters	Procurement manager
Energy producers	Landsvirkjun	Director of business development
National Planning Agency	Skipulagsstofnun	Head of EIA division
Local government	Fjarðabyggð municipality	Director of employment and development
Icelandic road and coastal administration	Vegagerdin	Head of harbour division

Table 5.1: Stakeholder interview representation

As previously mentioned, four overarching themes can be identified. That said, all interviewees, having a distinctive background and stake in the project, shared differentiating views and approached questions differently. Therefore, arguably, it can be short-sighted to draw uniform and congruent conclusions from the interviews but does leave room for analysis and exploring patterns between the different perspectives which inform the SWOT analysis.

Knowledge of hydrogen applications

Although stakeholders indicated familiarity with the general concepts of hydrogen, they acknowledged missing in-depth knowledge about what the system should look like, what facilities are needed, and what the production process exactly withholds. For this matter, uncertainties about the project were hard to describe. Despite the limited in-depth knowledge of this subject area, stakeholders did show confidence that knowledge will be gained and pointed out that Iceland has a rich history of innovation, having been at the forefront of sustainability and working with renewable energy. While their dependence on international advisors such as the Port of Rotterdam was expressed, they noticeably still want to retain control of the decision-making and development process.

Opinion on the creation of a HIPC

The consensus is that all stakeholders favour the construction of a hydrogen port, including the stakeholders that would not have a direct benefit. These stakeholders can be considered 'passive advocates', not interested in being actively and directly involved in the development, nevertheless supporting the notion that the port would benefit the greater society and Icelandic economy. Among the initiators, the increase in the economic development in the East region of the island was stressed to be a key driver.

On the other hand, stakeholders denoted a certain degree of hesitation and restraint due to the absence of a national hydrogen strategy. Ultimately, companies base their strategy on the playing field created by politicians. Nonetheless, stakeholders have confidence in future policies, mentioning that the recent developments in Ukraine and the volatile global markets due to the Covid-19 pandemic would serve as an eye-opener and are convincing policymakers of the need for self-sufficient markets.

Furthermore, stakeholders were conscious of the critical outlook of the general public towards the increased energy production for industrial purposes. The Icelandic people highly value the landscape's environmental splendour, and many aspire to limit human intervention. This view is partially fuelled by the significance of the tourism industry, which is similarly an essential contributor to the local economy. Moreover, the safety aspects related to hydrogen production could be of concern to the neighbouring communities. Stakeholders expressed the importance of involving the general public and other opposing parties as these actors' voices can strongly influence the permitting process. On the other hand, the current public opinion might change over time as the recent seasonal energy shortfalls ask for a better solution for energy storage.

The requirements for a HIPC

The questions regarding the requirements for a HIPC were interpreted in various ways. Port users shared requirements which must be met in their own eyes. These include practical matters such as enough land and sufficient energy supplies, openness from the Icelandic authorities, an adequate depth access channel for large tankers, and a clear market to sell the hydrogen. The port authority indicated that the port would have to be cost-effective without cutting short on the offered services, as well as keeping an eye on safety and aesthetically integrating the port with the environment to minimise pushback.

Port initiators agreed on certain aspects imperative to the realisation of the port. These aspects included the political commitment from national and local government bodies, highlighting that these commitments should provide clarities on permitting, licensing, and subsidies. Currently, the uncertainty concerning the new power plant approval strains the progress of the project development. Moreover, international subsidy schemes would be required as national government funding would not be a viable option due to the financial independence of the port authority. Finally, stakeholders also touched upon the need for more clarity in the hydrogen markets as a basis for further port planning.

Possible hydrogen markets

Despite the will to develop a hydrogen port, stakeholders disclosed the absence of obvious hydrogen markets in Iceland. Notably, the international stakeholder was advocates of focusing on foreign markets due to the scale and the governmental support. In order to accomplish this, they stressed the need for long-term client commitment to hydrogen purchase. This would break the chicken and egg causality problem between demand and production. The Iceland-based stakeholders much more emphasised the domestic markets which may benefit from hydrogen. Although there are no concrete plans for developing the markets, stakeholders listed a few potentials such as; heavy trucking, public transport, private transport, fertiliser production, shipping industry, public energy storage, and fish plants. A common denominator was that many Icelandic markets are already renewable and thus would not benefit directly from hydrogen. For example, the aluminium factory and house heating network already run on the renewable energy and hot water from geothermal plants respectively.

Regarding the by-product, it was suggested that the hot water by-product could be used for house heating in regions without geothermal heating and that the oxygen by-product could be used for fish farms. The other way around, interest was expressed that the CO_2 by-product from the nearby aluminium factory could be used to produce methanol.

5.2. SWOT-analysis

Oftentimes, design is referred to as an issue solution. Before one begins fixing anything, one must ascertain to be tackling the correct problem. Identifying and describing the true nature of the problem is a critical first step toward resolution (van Boeijen et al., 2014). This can be done by means of a SWOT, or strength, weakness, opportunity, and threat, analysis. The purpose of SWOT analysis is to describe a system's internal strengths and external opportunities that it may use to achieve its goals, while simultaneously attempting to reduce its internal weaknesses and external threats (Leigh, 2010).

A SWOT analysis identifies the strengths and weaknesses (internal factors) of a system, in this case, the future hydrogen industrial port complex, and the opportunities and threats (external factors) in the environment. After the identification of these factors, strategies can be developed. These strategies may build on the strengths, eliminate the weaknesses, exploit the opportunities or counter the threats. For this reason, the SWOT analysis can be used to assist in the formulation of a strategy for the port authority of Fjarðabyggð (Dyson, 2004).

The problem the HIPC system wants to address is manifold due to its socio-technical complexity and its required scale to be viable. Therefore, the problem should be divided into several factors that are experienced by the involved stakeholders and became clear during the interviews. The insights are discussed in the following paragraphs consecutively without any preferred order.

5.2.1. Strengths

Existing feasible hydrogen port conditions

Although the hydrogen industrial port complex will be a greenfield complex in a yet unknown specific location, the fjord and municipality are set already. This means that a port authority already exists with the necessary network, and financial resources to make it a success. The existing port authority already serves an existing industrial port complex consisting of the biggest aluminium smelter in Iceland, local fisheries, and import/export companies. In addition, the port authority already has expansion plans and ample space for new industries (interview, operations manager Fjarðabyggð Ports, 26-04-2022). Furthermore, the existing port complex is at the right distance from urban areas and is not near environmentally sensitive areas. The fjord offers a safe harbour with sufficient depth and is capable of welcoming large vessels. The location of the fjord is located near existing hydropower and geothermal plants (Coopman & Halgrimsson, 2021). And in case energy producers would receive permission to build wind parks, the future port location would offer the ideal wind conditions with wind speeds up to 10,3 m/s. This number is even larger than the offshore wind conditions in the North sea. Also, wind parks could be built within 150 km of the future port complex (Coopman & Halgrimsson, 2021).

Experienced energy pioneers

In the 20th century, Iceland had already seen two energy revolutions. First, the country's enormous hydropower resources were utilized to create energy. Then, in the 1940s, geothermal water supplies were seized to heat all of Reykjavik's homes and generate a substantial percentage of the nation's power (Salameh, 2009). Both transitions contributed to a reduction of import dependency and fossil fuel emissions. Furthermore, Icelanders are generally quite ecologically sensitive, as seen by the country's effective recycling programs and clean air and water. Hydrogen has the potential to launch Iceland's third energy revolution in recent history (interview, director of business development Landsvirkjun, 10-05-2022).

Increased self-sufficiency of the island

In 2020, Iceland was ranked 15th out of 219 countries in terms of imports per capita. Per capita, Iceland imported US dollars 15,6 k worth of goods. In total, the top imports of Iceland are Aluminium Oxide ($455M), Refined Petroleum ($304M), and Carbon-based Electronics ($283M) (OECD, n.d.). Stakeholders mentioned that the recent developments in Ukraine at the time of writing this thesis and the volatile global markets as a result of the COVID-19 pandemic truly served as an eye-opener and are persuading policymakers of the need for self-sufficient markets (interview, director of employment and development Fjarðabyggð municipality, 23-02-2022). Stakeholders cited that the construction of a HIPC could be a game-changer because it would enable Iceland to export energy instead of importing it, but it would also allow Iceland to (re-)introduce production companies on home soil (interview, head of energy and green solutions Business Iceland, 26-04-2022). Examples are the production of Ammonia to be used for the Icelandic fertiliser industry to increase national food security and the production of e-fuels to replace the importing of fossil fuels. It would increase the national export revenues whilst decreasing the import costs.

Existing export partners
Iceland has a long history of trade with the Netherlands. In 2020, it imported mostly from the Netherlands ($621M), followed by Denmark ($565M), and Norway ($490M). With a total export of $931M in 2020, the Netherlands is also the most common destination for exports from Iceland. This is followed by Spain ($796M) and the United Kingdom ($517M) (OECD, n.d.). This makes it easier to set up a hydrogen export line to the port of Rotterdam to serve its large hinterland industry (interview, operations manager Fjarðabyggð Ports, 26-04-2022). The recent signing of a memorandum of understanding between the port of Rotterdam and the municipality of Fjarðabyggð, and the memorandum of understanding between the port of Rotterdam and the national energy producer Landsvirkjun, both intensify this strength. It promotes and scales up production and ensures a market.

Existing subsidy schemes for hydrogen projects
The construction of a full hydrogen port complex demands extremely high up-front investments. These expenditures will have to be made by multiple stakeholders such as energy producers, transmission system operators, hydrogen- and carrier producers, storage operators, and terminal operators. From the interviews, it became clear that the port authority cannot make use of national public support due to the fact that they are already financially independent and have sufficient resources to pay for a port themselves (interview, operations manager Fjarðabyggð Ports, 26-04-2022 & interview, head of harbour division Vegagerdin, 24-05-2022). However, these days more and more subsidy funding programs become available to fulfil the large capital expenditures. For example, one of the 48 actions described in Iceland's 2020 Climate action plan, is the issuing of green bonds (Government of Iceland, 2020). Also, with Iceland being part of the European Free Trade Association, stakeholders may apply for EU funding programmes and funds financed by the 2021 -2027 long-term EU budget and NextGenerationEU (European Commission, n.d.).

Emerging export possibilities
Next to the Icelandic ambitions of becoming carbon neutral by 2040 and fossil fuel free by 2050 (Government of Iceland, n.d.-a), many more exporting possibilities will arise due to the emergence of more and more zero-emission strategies in other nations. Hydrogen and hydrogen-related products will certainly be an important factor in reaching these targets so the demand will not decrease over time.

5.2.2. Weaknesses

Lack of long-term governmental vision
Although Iceland has the potential to generate vast amounts of energy, there is no long-term governmental vision in place that stimulates the production of hydrogen and hydrogen-derived products. The government is waiting for the private sector to feed them everything they need to know while the private sector needs stability and security from the government. Up to now, the only stimulus in place is the "2030 vision for H2 in Iceland" produced by the Icelandic New Energy company (Icelandic New Energy, 2019). The 37-slides document is considered a living document and only serves as an incentive toward a full-scale national hydrogen roadmap for a longer period of time. The document, however, has a short-term focus and does not include a widely-supported plan of action.

The lack of strategic unanimity has far-reaching effects on multiple governmental levels and business developers. Throughout the interviews, a couple of them became clear. Firstly, municipalities experience difficulties in formulating their own ambitions to invest in projects and issue local construction permits (interview, director of employment and development Fjarðabyggð municipality, 23-02-2022). Secondly, energy companies currently face difficulty in obtaining permits and licences for new renewable energy production sites due to rejected ratification of parliament (interview, director of business development Landsvirkjun, 10-05-2022). Furthermore, national companies base their own strategy on the playing field created by politicians. The absence of national clarity thus directly results in indecisiveness of key players (interview, head of harbour division Vegagerdin, 24-05-2022 & interview, operations manager Fjarðabyggð Ports, 26-04-2022). Fourthly, current fossil fuel industries could switch to multiple hydrogen variants and e-fuels. To serve whole domestic industries at scale, a roadmap should lead to a uniform choice of e-fuel (interview, operations manager Fjarðabyggð Ports, 26-04-2022). Finally, a roadmap should incentivise the construction of national hydrogen infrastructure (eg. pipelines, fuelling stations) to serve domestic markets.

One cannot base costly long-term infrastructure decisions on short-term support and authorization without any sense of direction. Considering no single company or organisation can control production, demand and infrastructure single-handedly, the government is tasked with a coordinating role that ensures market organisation, good infrastructure and regulations (van Wijk et al., 2019). It is responsible for a long-term vision that satisfies long-term needs. This weakness has an impact on all the other threats.

Little social acceptance

The application of hydrogen products for societal purposes are numerous. Hydrogen production could play a role in solving today's issues and thus impact Icelandic citizens. Throughout this research project, no representatives of inhabitants were interviewed. However, key stakeholders described their possible lack of support due to a couple of reasons.

Firstly, more power plants (geo, hydro, or wind) would be needed to produce hydrogen. The Icelandic people highly value their environmental beauty and want to limit every human intervention (interview, operations manager Fjarðabyggð Ports, 26-04-2022). This is partly due to a strong tourism industry. Secondly, the safety aspects of hydrogen production could be of concern for neighbouring communities (interview, operations manager Fjarðabyggð Ports, 26-04-2022). Thirdly, due to the abundance of new technologies, unawareness of the benefits and lack of information could lead to objections. Finally, support for the industrial (international) application of Icelandic energy is low (interview, director of business development Landsvirkjun, 10-05-2022 & interview, head of harbour division Vegagerdin, 24-05-2022). Environmentalists stress the prioritization of domestic energy use above export purposes, without upscaling the production capacity (Sigurdardottir, 2022a).

Absence of clarity in markets

The current hydrogen market is in its infancy and could take many different development paths. Current strong technological development affects the applications, the prices, and the quantities needed. The lack of certainty about the future leads to a true causality dilemma, experienced by hydrogen developers and hydrogen off-takers. Developers need a solid and long-term commitment to hydrogen purchase before spending extensive investments on constructing electrolysers, storage and transportation systems (interview, project manager business development Mitsubishi Corporation, 21-04-2022). Offtakers, on the other hand, need affordable and stable hydrogen sources before giving guarantees of purchase. This situation where the market decides the production has severe effects on the size of the port terminals, and the choice of the carriers.

Offering hydrogen at affordable prices can only be obtained when produced at a large scale and thus benefiting from economies of scale. Interviewed developers indicated that the Icelandic domestic market alone is currently too small to reach these economies of scale, so focusing on the export market is essential in lowering the hydrogen cost to make it competitive with other energy sources (interview, 21-04-2022, project manager business development Mitsubishi Corporation). On the other hand, the construction of a HIPC would need to benefit national objectives and serve the domestic market. Serving the domestic market will certainly increase national support for the project. Therefore a balance will need to be found between serving the export market and the domestic market.

In-depth knowledge to be gained

Building a large-scale hydrogen industrial port complex requires in-depth knowledge, a fair amount of experience, and existing industries. However, because of the novelty of hydrogen technologies, there currently is a shortage of technical knowledge among stakeholders. As a result, stakeholders are faced with difficulties in taking a position in the port development process and formulating an opinion. This leads to decreased involvement and potentially obstruction to the project. This observation was clearly highlighted during the interviews as interviewees indicated to find it hard to map their own and other stakeholder' attitudes, and describe their uncertainties due to insufficient knowledge (interview, head of EIA division Skipulagsstofnun, 13-05-2022 & interview, head of harbour division Vegagerdin, 24-05-2022 & interview, director of business development Landsvirkjun, 10-05-2022 & interview, director of employment and development Fjarðabyggð municipality, 23-02-2022).

The same can be said about the initiating actor, the port authority. Although the actor clearly supports the project, it lacks the know-how on developing a port on this scale and for these applications. It is dependent on (international) experts to assist in making the right investment decisions and going through the development process in a coordinated manner (interview, operations manager Fjarðabyggð Ports, 26-04-2022).

The eventual hydrogen producers take a central role in sharing knowledge about the requirements and choices to be made. However, because of their competitive position towards other developers, their knowledge is highly sensitive. Accordingly, they minimize sharing information with stakeholders other than the port authority. When setting up this research, this finding clearly emerged as the most prominent developer refused any form of interview due to the risks at stake.

The opposition of the tourism industry

On the contrary to the lack of knowledge in the chemical industry, Iceland's largest economic sector is the tourism sector. Before the COVID-19 pandemic hit, it accounted for 35% of the total value of exports. Between 2010 and 2018, the number of tourists have increased by 400%, resulting in the fastest growing industry in the country (International Trade Administration, n.d.). In 2017, the sector directly employed 14% of the total number of employees in the country (Statistics Iceland, 2017). The construction of new power plants and of an industrial port complex next to a fjord will affect the scenic views and environmental beauty of the country. It will thus impact the tourism industry. Therefore, throughout the development process developers will certainly experience resistance from environmental interest groups and the tourism lobby (interview, director of employment and development Fjarðabyggð municipality, 23-02-2022). It must be noted that the tourism industry might also benefit from domestic hydrogen production. It could decrease the dependence on imported fossil fuels and reduce emissions of their running ferries.

5.2.3. Opportunities

Accelerated energy transition

This issue is two-fold since the country (a) is challenged with becoming 100% renewable, and (b) has an inconsistent supply of renewable energy. Although approximately 85% of Iceland's entire primary energy supply is generated from renewable energy sources produced locally (Government of Iceland), the remaining 15% is fossil fuel-related. So far, the renewable electricity sector has not been able to replace the fossil fuel consumption used in industrial processes, road transport, agriculture, fisheries and waste management (Government of Iceland, n.d.-b). Iceland aims to reduce greenhouse gas emissions by 40% before 2030 and to achieve carbon neutrality before 2040 under the Paris Agreement (Icelandic Ministry for the Environment and Natural Resources, 2020). To realise these goals, black oil use in Icelandic territorial water has been prohibited from 2020 (regulations no 124/2015, Iceland). This incentivises the shipping industry to move towards the application of renewable energy sources. Icelandic hydrogen- and e-fuel production could serve as a solution in this regard.

Additionally, stakeholders indicated that seasonal shortfalls of the current power system are leading to a public discussion about an increased energy capacity (interview, head of energy and green solutions Business Iceland, 26-04-2022). The recent lack of electricity as a result of summer droughts has forced some industries and district heating plants to switch back to fossil fuels as temporary solutions for a period of four months (Sigurdardottir, 2022b). In this case, the hydroelectric dams clearly were lacking capacity. Using electricity to produce hydrogen in times of abundant renewable sources would have solved the long-term energy conservation problem and would have prevented switching back to fossils.

Increased economic development of the Eastern Region

The Eastern Region is one of Iceland's eight regions. Although the region has an area of 15.706 km^2 (15% of Iceland's whole surface area), in 2021 it only counted 10.850 inhabitants (3% of Iceland's population) (Statistics Iceland, 2022). Compared to the Capital Region in the West of the country, which counted 236.528 inhabitants in 2021, the East is geographically isolated and economically challenged. This can be seen from the fact the region is only accessible by two access roads. A recent event made the economic preference for the west clear. The last summer droughts lead to a shortage of electricity in the east. As a result, the electricity for eastern smelters, data centres and fishmeal factories was cut short (Landsvirkjun, 2021). The restriction was based on Article nr.9 of Act No. 65/2003 on Electricity. It describes that "although there is enough electricity in the east if there is not enough in the west, industries in the east will be cut short of electricity to provide for the west." (interview, operations manager Fjarðabyggð Ports, 26-04-2022). This burden is contrary to the potential for the region to prosper economically as a result of its natural resources and land surface availability. Hydrogen production could be a pivot in that sense. For the development of a hydrogen production facility, the East could thrive on the potential construction of a large wind park in the east and favourable port conditions. Therefore, stakeholders in the Eastern Region aim is to independently strengthen the eastern part by using their natural strengths and taking responsibility for the energy transition. Their aim to be a frontrunner in hydrogen production. It would stimulate the economy and is good for its reputation (director of employment and development Fjarðabyggð municipality, 23-02-2022 & interview, operations manager Fjarðabyggð Ports, 26-04-2022). It would generate more income for the municipality as a result of increased port fees. It would attract labour forces that have a reason to live in the region. Employees would have to be brought in considering the current employment rate is already high (interview, operations manager Fjarðabyggð Ports, 26-04-2022). It would attract technical knowledge that could benefit other industries such as local education and neighbouring factories. If the east would provide the rest of the country with hydrogen, the accessibility will increase as well.

Enlarged geopolitical influence
From a geopolitical standpoint, Iceland might benefit from hydrogen production. The nation would no longer be required to import fossil fuels, resulting in greatly improved supply security (interview, head of energy and green solutions Business Iceland, 26-04-2022). There are no negative geopolitical consequences associated with Iceland's production of hydrogen. If Iceland chose to sell hydrogen to Europe, favourable economic links might be strengthened. Furthermore, there are no substantial geopolitical concerns associated with Iceland exporting hydrogen to Europe (Pickford, 2021).

Creating green hydrogen certification schemes
Hydrogen can be generated in multiple ways. Green hydrogen is a form that is supposed to produce no greenhouse-gas emissions. With Iceland only producing green hydrogen, it offers a premium product that currently comes at a higher price but can be used to meet energy transition goals. Green hydrogen is physically equivalent to other kinds of hydrogen and will be blended with other forms of hydrogen and maybe other fuels, such as in a gas grid. Currently, there is no globally acknowledged administration system in place that distinguished the different forms of producing hydrogen. In order to determine if the given hydrogen is "green" according to the requirements, strong administration will be required. This administration could be done in the form of green hydrogen certificates that guarantee the origin of the hydrogen. Green hydrogen tracking systems are essential for encouraging and enabling green hydrogen usage (interview, director of business development Landsvirkjun, 10-05-2022 & interview, project manager business development Mitsubishi Corporation, 21-04-2022). Incentivizing enterprises to commit to utilizing green hydrogen, generating social engagement, and promoting consumer knowledge, such a tracking system has the ability to expedite the clean energy transition. The standardization of these certifications can also facilitate and encourage the growth of green hydrogen commerce and hasten the birth of a worldwide market. Certification may also be used to provide clear and detailed investment signals for the effective deployment of renewable energy in response to the demands of customers (such as location, logistics costs, need for infrastructure, etc.). For the development of a green hydrogen port complex, the creation of green hydrogen certificates would increase the demand for specifically green hydrogen.

Set up international treaties
Creating a hydrogen economy is a global endeavour and therefore requires international collaboration. National hydrogen strategies need to be coordinated for each other's benefit. The Dutch government is seeking for large scale hydrogen import from foreign countries. For the Icelandic government this offers an opportunity to explore a large export market and to benefit from existing Dutch hydrogen knowledge and experience in creating a national hydrogen strategy. Accordingly, setting up an Icelandic-Dutch hydrogen treaty or a government-to-government Memorandum of Understanding could foster the project feasibility.

5.2.4. Threats

Transforming hydrogen markets
Future demand is difficult to map, technology can change rapidly, and future government policies can steer the market in a certain direction. That hydrogen will play a crucial role in the energy transition is certain.

However, the form in which it will be transported and stored, and the form in which customers will want to receive it in the future, may well change over time (interview, project manager business development Mitsubishi Corporation, 21-04-2022). This applies to the Icelandic market as well as to the export market. The port authority has to choose specific carriers when developing the port complex and thereby attract specific developers. It is impossible to predict or direct which of these forms will ultimately be the most important because it depends on too many different factors. Therefore, at this stage, it's important to keep as many options open as possible, stimulate the development of various technologies, and be able to adapt over time to changing demands for specific carriers and hydrogen products.

Changing regulatory environment

To develop a hydrogen industrial port complex, additional large-scale energy production plants are needed. The interviews made clear that obtaining permits for these forms a source of uncertainty and, as a result, could form a threat. For two years now, national power companies must adhere to a master plan framework for submitting new projects. In different rounds, power companies can submit plans for specific locations. These plans are then assessed by four working groups focussing on different aspects of the plan. It is then up to parliament to approve or reject these plans. So far, four of the rounds have taken place. Parliament has not ratified a single new energy production plan during the last two rounds. Consequently, not everyone in Iceland agrees on this way of permitting. Therefore, politicians are considering implementing a new way of permitting geothermal and hydro plants and potentially intend to implement a specific permitting system for wind parks (interview, director of business development Landsvirkjun, 10-05-2022). The unclarity in permitting leads to uncertainty among all stakeholders, but especially among developers.

Emerging competitors

This phase of the hydrogen economy, where the number of large-scale hydrogen producers is still limited, offers the ultimate opportunity to benefit from the first-mover advantage by signing early offtake agreements. This applies to Iceland as an export nation as well as to the port developer in Fjarðabyggð. However, this advantage will reduce over time. New competitors could be of danger if they manage to offer hydrogen products at a lower price, in larger quantities, or with larger flexibility.

This competition can come from other Icelandic ports, focussing on the Icelandic market and/or export market, but also from other countries aiming to meet the European import demand. This threat can manifest itself in two ways. Firstly, Icelandic competitors may claim future energy production permits, and thereby limiting the expansion opportunities of the port of Fjarðabyggð. Secondly, foreign competitors may bring the price of hydrogen down as a result of lower energy prices. This could motivate importing countries to switch providers at the end of the purchase agreement, leaving the Icelandic export parties with large quantities of unsold hydrogen.

Negative media coverage

As described earlier, currently the social acceptance of the development of new energy production plants is low. Strong stakeholder involvement is therefore important. However, not every single stakeholder can be involved. Mostly the greater public must be convinced in such a way that they do not obstruct the project in the process of permitting and financing. The media is of utmost importance here. The power of the Icelandic media should not be underestimated because a negative attitude of theirs is a direct threat to the project.

Strong public blocking power

It is key to involve societal players from the very start in the process of developing the port. Their input should be taken seriously and education will be key. Not only could it increase domestic hydrogen markets, but it would also increase the chance of a successful port development significantly. One on the weaknesses already indicated the little social acceptance. This weakness could become a threat if not taken seriously. The Icelandic people have a strong voice in the permitting process as they are allowed to provide comments on all aspects of planning and the preparation of zoning plans (Skipulagsstofnun, n.d.) (interview, head of EIA division Skipulagsstofnun, 13-05-2022 & interview, operations manager Fjarðabyggð Ports, 26-04-2022). Historic events, such as the protest at the construction of the Alcoa aluminium smelter, prove the blocking power of the general public (Bosshard, 2003).

5.3. Resulting design brief

Now that the different strengths, weaknesses, opportunities and threats for the hydrogen production in Iceland are set, an all-encompassing objective for drafting a roadmap to develop the port can be defined.

The objective of the roadmap is to guide port developers in the process of realising a hydrogen industrial port complex in a chronological and step-by-step manner. Thereby, important aspects to consider are the absence of a national hydrogen vision, undefined hydrogen markets, little social acceptance towards the increased industrial activity, and limited in-depth technical knowledge. Eventually, the roadmap should lead to the creation of a port complex that:

- enables the production of hydrogen and hydrogen-derived products for domestic usage and export purposes;
- is commercially viable in all plausible futures by maintaining a competitive position;
- and fits in the vision and the overall spatial planning of the municipality of Fjarðabyggð and the national government of Iceland.

5.4. Chapter summary

Chapter 5 served as the first diamond of the double-diamond design process model and provides an answer to the third sub-question. The aim was to define the practical problem of the case study and draft the design brief as a starting point for the second diamond.

First, the results of the stakeholder interviews were discussed. Subsequently, a SWOT-analysis was performed with the following results:

- Strenghts: the availability of suitable area for a port complex of large scale, the energy pioneering nature of the people, the existing collaboration with the Port of Rotterdam (offering large export opportunities and knowledge sharing), the aspiration to increase self-sufficiency by replacing fossil fuel and fertilizer imports, and further growing subsidy opportunities.
- Weaknesses: the lack of long-term governmental vision, little social acceptance towards the construction of new power generation facilities for export purposes, an absence of clarity in the future hydrogen markets in Iceland, limited in-depth knowledge as a result of the novelty of hydrogen technologies, and a strong opposition of the tourism industry towards increased industrial activity in Iceland.
- Opportunities: an accelerated energy transition in Iceland, an increased economic development of the Eastern Region, an increase in Iceland's geopolitical position by exporting energy instead of importing, an increase in the demand for green Icelandic hydrogen due to certification schemes, the creation of an Icelandic-Dutch hydrogen treaty to foster a hydrogen economy.
- Threats: the potential transformation of markets once the hydrogen economy grows out of its infancy, a changing regulatory framework that could lead to surprises in the permitting and off take of hydrogen, emerging (international) competitors who could reduce the advantageous position of being amongst the first large-scale hydrogen developers, potential negative media coverage that has a large influence on the social acceptance, and the blocking power of the general public.

Finally, a resulting design brief was formulated with at its core the objective to guide port developers in the process of realising a hydrogen industrial port complex in a chronological and step-by-step manner.

6

Diamond 2: Integrated Hydrogen Port Design framework

In line with the methodology described in chapter 2, this chapter aims to formulate a solution to the design brief as described in section 5.3. By incorporating port planning aspects that were assembled in chapter 4 and lessons from the SWOT analysis, eight phases have been identified that should be run through in chronological order to come to a full hydrogen port masterplan. This chapter first describes the theoretical frameworks that were considered throughout this research project and were of influence in the creation of the final framework (section 6.1. Then, this results in a roadmap that can be found at the beginning of section 6.2. Thenceforth, the final framework is elaborated upon and applied to the Icelandic situation where possible further on in the section. Next, section 6.3 offers a narrative that describes practical recommendations for the Fjarðabyggð port master plan. Lastly, section 6.4 summarises the chapter.

6.1. Research journey as a basis for IHPD framework

Throughout this research project, multiple frameworks have been evaluated that could contribute to the formation of a roadmap. Eventually, these frameworks have led to the establishment of the final Integrated Hydrogen Port Design ('IHPD') framework described in-depth in the next section.

Quist et al. (2006) proposes a methodological roadmapping framework using participatory backcasting. The framework consists of five stages and four groups of tools and methods that can be applied to a case study. Commonly, backcasting is used in scenario creation for defining future visions and then sketching paths backwards from those ideas to the present (Dreborg, 1996; Holmberg & Robèrt, 2000). The concept can be applied to determine shorter-term activities for system innovation from a long-term vision. The essence consists of generating desirable sustainable future visions and turning these, through backcasting analysis, design activities and analysis, into follow-up agendas, planning for actions and realising follow-up activities. The product of backcasting is a strategy for achieving a sustainable vision of the future. This strategy is translated into a series of concrete suggestions for activities with a relatively short time horizon, which fit within the long-term vision (Quist et al., 2006). Backcasting is seen as a useful approach when there is a complex societal problem, need for major change, dominant trends influence the problem, externalities are not yet solved in the market and long-time horizons allow for other solutions to develop in time to solve the problem (Dreborg, 1996). In the case of hydrogen, the current regime with fossil fuels needs to be changed, thus hydrogen can play a role in solving the problem of climate change. Technological, economical, and societal changes have to occur before hydrogen becomes a part of the regime. However, discussions revealed that there was an obstacle to applying this framework to the hydrogen port case study. Due to a lack of a national hydrogen strategy and long-term vision set out by the Icelandic government, defining desirable future visions for the port authority would not be possible within the scope of this research. This gap has determined these factors as an imperative and formative starting point for the IHPD-framework.

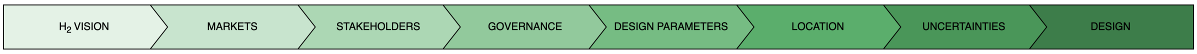
Further discussion resulted in the consideration of a systems-mapping framework. DeLaurentis and Callaway (2004) argue that decision makers within government and industry are facing problems of increased complexity. Solving them is complicated because, although tools are available, they are ineffective in their usage because their developers all speak different languages and have different expertise. Decision makers, on their part, lack the understanding of the proper method to assess if decisions to allow spending millions of dollars on a HIPC, execute a certain public policy, or develop a new piece of technology are wise for the nation and the globe over the next generation. Because existing tools operate at different levels and frames of reference, all with their own (sub)system, decision makers need a more detailed map to analyze the complex system. Therefore, the authors suggest taking a system-of-systems perspective. It allows for the inclusion of different types of aspects that are needed for the development of the HIPC. The goal of the system-of-systems approach is to recognize that the substance of the problem is most likely only seen from this higher vantage point, rather than to predict the future. Therefore, the framework has two key structures: system categories and hierarchy levels within those categories. DeLaurentis and Callaway (2004) identifies four categories that all emphasize one distinguishing characteristic of the system. Every category consists of components and sub-components. A hierarchy is used to break down the category and, accordingly, display the relative position of each component. However, in order to roadmap the development process of a HIPC, the defined system-of-systems perspective requires to include a third dimension: sequentiality. Within the four category hierarchies, a component of time is needed to determine the roadmap as a means of solution to the defined problem. This dimension should indicate when a particular component will have to be developed in contrast to the others and what time-related priorities come into play. This time-dependency will allow the development of the whole system in the right order. However, stakeholders confirmed this system-of-systems cannot be mapped at the moment as there are too many uncertainties about what the system should look like, what its size should be, and what products it should produce. In addition, due to the early status of the project and the sensitive information about the physical subsystems, it would prove impossible to collect the necessary data. These two reasons caused obstruction to applying the framework to the hydrogen port case study. Thus, DeLaurentis and Callaway (2004) not only showed the need for a uniform system map, it also helped to realise that the desired hydrogen port system in Iceland cannot be defined at this moment due to the lack of national vision and the consensus of the port initiators. Yet, this must be done at the start of the process. Therefore, a shared vision should be created by a consortium of initiators. It did also indicate the necessity to fixate the port governance model early on in the IHPD framework before drafting the rest of the system. Also, information sharing between multiple subsystems proved to be pivotal to mapping the system and using this map for decision-making.

The question arises about which other uncertainties exist and how to determine what actions should be put in place to reduce them. This can be approached using the framework by Eskafi et al. (2021) who have developed a structured framework to deal with uncertainties in the port planning process. The authors argue that port decision-makers are confronted with rapid, radical, and frequently unforeseen developments. Typically, judgments are taken at the outset of a project in a turbulent environment where the future is characterized by inherent ambiguity. However, it is difficult to make long-term decisions (e.g., port construction) in the face of uncertainty and long-lasting initiatives are more likely to be successful under unpredictable conditions when the planning process accounts for uncertainty. Therefore, the framework is based on three elements for identifying the uncertainties that may appear over the expected lifetime of the plan and incorporating them into the planning process. The first element is a stakeholder analysis to (a) identify the port stakeholders, (b) expose the aims of stakeholders and consequently determine the success of port planning, and (c) Identify the uncertainty around the actions and objectives of stakeholders and the various planning timeframes. The second element involves various strategies for methodically addressing the defined uncertainties. Throughout the third element, uncertainties are analyzed to find opportunities and vulnerabilities. Effective actions can then be planned in order to grasp opportunities and control vulnerabilities, and so deal with uncertainty. Despite the uncertainties surrounding the port's expected lifespan, port officials and decision-makers can proactively take the necessary measures. The framework would be well applicable for the case study in Fjarðabyggð. Nevertheless, the application of the framework is based on the uncertainties experienced by stakeholders. This caused complications as this research is hampered by mapping the positions of stakeholders and understanding the local constraints to the project. Also, the performed stakeholder interviews indicated the lack of knowledge concerning a project of this kind, resulting in a difficulty in detecting the uncertain developments. It can be concluded that the biggest uncertainties are still unknown at this stage of the project. This gap has determined that mapping uncertainties is key and should be an element of the IHPD-framework. However, it can only be done once the shared vision is set, the port governance model is fixated, an in-depth stakeholder analysis in a local context is done, and the location is fixated..

Considering the described difficulty of applying the aforementioned frameworks within the geographical and time constrain of this research, discussions led to a change of scope. Whereas the initial aim was to create a detailed roadmap, this study can only make recommendations on how to tackle this project in an effective manner. The aforementioned frameworks have been consolidated to meet the needs of this port development project at this specific stage. The rest of the IHPD-framework should be based on existing port development processes. Desk research identified the framework by Zheng (2015) to be the most relevant. The framework focuses on the system level and seeks to identify sustainable possibilities while creating socio-economic value. This may be accomplished by taking into account and combining the physical, environmental, governmental, and socioeconomic disciplines in order to identify the best site for these possibilities. It provides a framework for port planners to establish and maintain a balance between the economy, environment, and society in the present and future, resulting in a port that is sustainable and future-proof. The framework integrates pertinent elements from current sustainable concepts and completes the traditional framework's gaps. Another port planning framework deemed important is Ligteringen (2017). It served as inspiration for the for the IHPD-framework.

6.2. Final IHPD-framework

With the necessary foundation of the conventional port development framework and the appropriate aspects derived from stakeholder analysis and the frameworks described in Section 6.1, the new hydrogen port framework may be established and implemented in this section. In this concept, all phases of port development are considered vital components of the hydrogen industrial port complex. This framework shall henceforth be known as the Integrated Hydrogen Port Development (IHPD) framework. The framework consists of 8 phases (as to be seen below) that should be run chronologically to successfully develop the port. In broad terms, the first four phases treat strategic organisational aspects, the following three phases treat general design definitions, and the last phase treats the eventual design of the port. The detailed framework can be seen in figure 6.1. The squared boxes represent actions where something needs to be delivered whereas the tartan boxes represent decision moments where the port developer can choose from a list of options. The framework should be run through from the top to the bottom, following the solid arrows. The dotted arrows represent iteration cycles.



Before explaining the eight phases in depth and applying it to the Icelandic case study, an important remark must be made about the structure of the framework. The framework not only consists of the necessary port development elements, it also describes the suitable sequentiality between these elements. Ideally, one phase of the framework should be completed to provide a solid basis for the subsequent phase. The output of phase A serves as input for the subsequent phase B. It is about capturing decisions made to establish complete buy-in at the subsequent stages. It also ensures that if any decisions are reversed, the decision-maker can go easily back to the appropriate phase to reassess what the impact is. This gated-phase structure aims to lock in decisions that are made as the framework is followed to ensure the quality of output from one phase to ensure that any subsequent phase is based on correct information. However, whilst in this report the eight steps are shown happening sequentially, in practise it is likely that there will be certain action concurrently and there are times where there are iterations required.

The establishment of the appropriate sequence of elements is done intuitively by determining the prerequisites per step. Whenever a step is dependent on other steps, it should naturally be done once the other steps have been completed. Table B.1 in appendix B displays these prerequisites. Per step, the required information input is specified. Because the steps have been put in the correct order, it can be seen that, per step, the required information has been gathered in earlier on.

This can be exemplified by looking at phase 7 step 7.1 where uncertainties are mapped through elaborate discussions with stakeholders. Mapping and processing uncertainties at the start of the development process would be ineffective as relevant information would be missing. To discuss the topic, first stakeholders must be identified (step 3.1). Also the port functions must first be known (step 4.1). Additionally, the planning time horizons must be set (step 5.1) to carefully describe the uncertainties. The same holds for the selection of the location (step 6.3). Therefore, the above mentioned steps should be run through first before step 7.1 can be performed. Consequently, step 7.1 can not be done earlier than after step 6.3 Selection of most suitable location. In fact, the results of the interviews performed for this study (section 5.1) reveal the same. Stakeholders indicated to find it difficult to describe uncertainties at the premature stage and need more information to share their concerns.

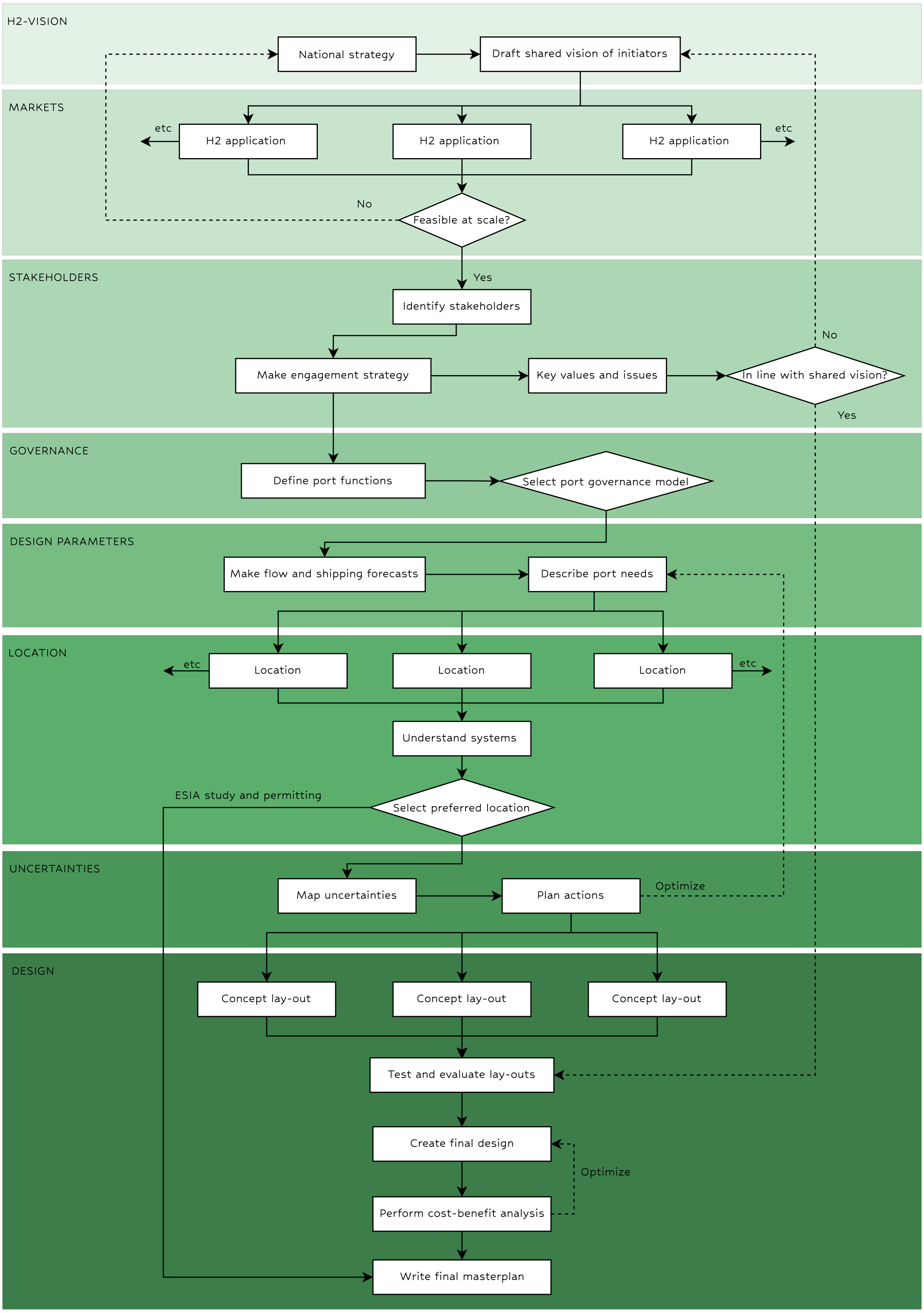
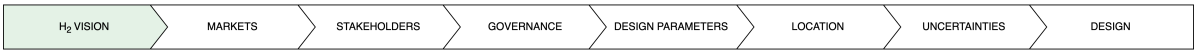


Figure 6.1: Final IHPD-framework as a roadmap for hydrogen port development

6.2.1. Define H2-vision

In phase 1, a pathway-leading vision should be created that motivates the construction of a HIPC and facilitates the decision process. This is a vital phase and influences the choice of all following phases. Therefore, it must be done at the very start of the process.



National strategy

Port projects can be initiated by anyone. However, the definition of a port complex is not just what is within the fence but is dictated by external factors crucial to designing the right port complex. Currently, the port authority is not only dependent on the government for permitting reasons, the government plays a key role in developing the hydrogen market. Hydrogen developers, who will operate in the port complex, are waiting for the market to guarantee offtake. Meanwhile, off-takers need conviction and support in their choice to transition from fossil fuels to hydrogen. Therefore, governments should take responsibility for managing market organization, adequate infrastructure, and laws, as no one corporation or organization can independently oversee production, demand, and infrastructure. By direct push, the government can change the pace but for that, a national hydrogen strategy is needed. Such a strategy should, have long-term visions, have clear deadlines, and have numbers as targets. These targets can be based on existing energy transition targets in Iceland and the EU. In the strategy, the targets should be aiming for specific industries and should state incentives to support market development through feasibility studies, subsidies, and pilot projects. It should also indicate plans for the construction of national infrastructures, such as roads for heavy duty hydrogen vehicles, pipeline construction, and charging stations. Eventually, the strategy should result in a regulatory framework that implements a permitting system that is designed for new power production facilities such as wind parks, hydro dams, and geothermal plants. This framework should also address the consideration between the permission to generate energy for export purposes and domestic purposes. Politicians set the playing field but are challenged with limited in-depth knowledge about the matter. Therefore, a hydrogen working group should be created to bundle experts with policymakers. The working group should involve representatives of different industries, the national power company Landsvirkjun, and players in the full supply chain. With regards to the latter, these could include international players such as importing hydrogen countries. Through government-to-government agreements or memoranda of understanding, international collaboration could help to strengthen the national strategy.

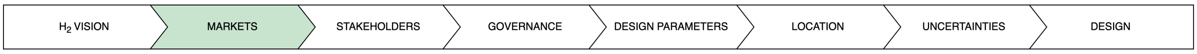
Shared hydrogen port vision

Consequently, based on the national strategy, port initiators such as the port authority, hydrogen developers, and energy providers should set up a consortium of the willing in which they draft their own shared vision as the basis of the future port project. Likewise, this vision for the port should be time bound and quantified to determine the initial port size and scalability. The vision should also address the role of external players such as port consultants and foreign ports who aspire to import Icelandic hydrogen. Additionally, the shared vision also serves informative purposes to include stakeholders early in the process. Through knowledge sharing, social acceptance can be increased from the start. Using the backcasting framework, as described in section 6.1, the long-term vision can be brought back to shorter-term activities.

On this basis, a definition of success may be formulated in terms of the intended results. This is necessary in order to improve decision-making and decrease uncertainty among the all involved in the planning process. Typically, the success of a project is determined by whether it meets a predetermined financial objective, such as decreasing lifespan costs or maximizing profits. Nonetheless, other requirements such as technical performance, sustainability, availability, safety, maintainability and flexibility, must be stated and satisfied throughout the port's lifespan.

6.2.2. Determining markets and carriers

Phase 2 can be seen as a feasibility study in order to find markets for the hydrogen developers in the port. Markets should be tested for their maturity in size and technology. If the scale of the markets is still too small, it can be an incentive for the national hydrogen strategy to initiate pilot projects to help the market grow. A suitable market is one that fulfils the goals of the national hydrogen strategy and the shared vision of port initiators.



Markets

It is in this phase where a trade-off must be made between production for the domestic market and for the international export market since it will determine the size of the port. Ideally, a combination of the two is made. Serving the export market enables it to reach economies of scale and thus reduces the final cost of hydrogen. It will also increase the geo-political status of the country, and attract the knowledge and expertise of international players. Serving the domestic market will however be needed to meet the goals of the national hydrogen strategy and increase domestic support for the project. Estimating the demand of the international market is a matter of finding international clients that are willing to agree on long-term purchase agreements. At this moment, exporting to the Port of Rotterdam is the most feasible option because it has the ambition to import 4 megatonnes of hydrogen before 2030 and already has a wide base of customers waiting. In Rotterdam, clients can be found that want to use hydrogen for refinery, fuel production, chemical production, and power generation. Estimating the size of the national market requires in-depth conversations with domestic industries that could use hydrogen to replace fossil fuels or use hydrogen to optimize production processes. The domestic markets determined throughout stakeholder interviews are:

- Heavy trucking;
- Public transport;
- Private transport;
- Public energy storage;
- Fertilizer production;
- Shipping industry such as ferry lines, fishing ships, and cargo ships;
- Fish plants that could use hydrogen for drying and milling of fish;
- Fish farms that use the byproduct oxygen.

On average between 2010 and 2020, Iceland has consumed 924 709 tonnes of crude oil imports per year (CEIC, n.d.). In order to replace the oil consumption, an alternative has to be found that provides an equivalent amount of energy. For hydrogen, this would require the production of 321 608 tonnes per year (Hydrogen Tools, n.d.). Regarding the fertiliser industry, in 2017 Iceland imported 16 924 tonnes of Nitrogen, Phosphorus, and Potash (Statistics Iceland, n.d.). This number has been relatively stable since 1977. Since ammonia can be directly applied to soil as a plant nutrient, a similar amount of ammonia would be required to replace the import of fertilizer (The Fertilizer Institute, n.d.). For 16 924 tonnes of ammonia, 338 tonnes of hydrogen would be required (preliminary study).

Other domestic industries do not seem to benefit from switching to hydrogen because they already run on geothermal heat or green electricity. Examples are aluminium smelters and the house heating industry. However, there are industries that could supply their residual products for the production of carriers. For example, the nearby aluminium smelter could supply about 560,000 tonnes of CO_2 annually. This could be used for the production of 817,600 tonnes of methanol annually using the latest technology (Carbon Recycling International, n.d.).

Therefore, the roughly estimated total domestic demand could go up to 321 946 tonnes of hydrogen per year. The total demand from Rotterdam before 2030 could go up to 4 000 000 tonnes of hydrogen per year. It must be noted that in reality, the Port of Rotterdam will not uptake this full amount from Iceland in order to diversify its importing streams to decrease dependency. The preliminary study showed that a 20 TWh power plant would be sufficient for the production of 420 000 tonnes of hydrogen per year (Coopman & Halgrimsson, 2021). In appendix C, calculations are made to determine the number of new energy plants required to reach these demands.

In that line, table C.1 shows the outcomes for rough estimates of the required new infrastructure. On the left, the total maximal domestic and export demand can be seen. It was calculated how many wind turbines, or geothermal plants, or hydro plants would be needed to meet the demand. The table is rather indicative and no summation of all the plants would be needed. In reality, however, a combination of a fraction of the different plants would be optimal to provide a constant supply of energy. For the number of wind turbines, the planned 7.5 MW turbines (Landsvirkjun, n.d.) and a capacity factor of 0,45 (Coopman & Halgrimsson, 2021) have been taken into account. For the geothermal plants, the current largest Icelandic plant was considered with a capacity of 303 MW (NA Energy Staff Writer, 2021) and a capacity factor of 0,87 (Ragnarsson et al., 2021). For the hydropower plants, the current largest Icelandic plant was considered with a capacity of 690 MW (Visitegilsstadir, n.d.) and a capacity factor of 0,85 (Coopman & Halgrimsson, 2021).

Market	**Yearly hydrogen demand [tonnes H2/year]**	**Energy required [TWh/year]**	**Wind turbines [-]**	**Geothermal plants [-]**	**Hydropower plants [-]**
Maximal total domestic demand	321 946	15,33	519	7	3
Maximal demand from Rotterdam before 2030	4 000 000	190	6 427	83	37

Table 6.1: Roughly estimated energy plant requirements

Carriers

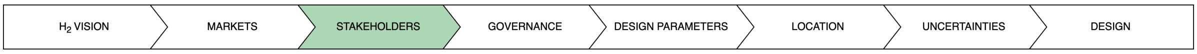
This phase should also clarify the form in which the hydrogen is needed. Although the choice of carrier mostly depends on the demand from the market (as a function of the final price per kg of hydrogen and specific wishes) there are a couple of aspects to take into consideration, such as safety, technology readiness level, and terminal investment costs. In practical terms, it is also a matter of the specialization of the available hydrogen producers. The exact details of the different hydrogen carriers can be found in section 3.6 but generally, the various methods of transporting and storing hydrogen each have benefits and downsides. The production of liquid hydrogen requires a great deal of energy, specialized ships for transport, and infrastructure. This is counterbalanced by the fact that it no longer has to be "loaded and unloaded." On the other hand, ammonia (NH3) is an extremely poisonous chemical, necessitating extensive safety precautions for the transport and storage of hydrogen in ammonia. This is counterbalanced by the fact that ammonia is a material with which the industry has extensive expertise and, like hydrogen, is available for immediate use in a variety of manufacturing processes and as a maritime fuel. The latter also holds for methanol. However, its drawback is that the expenses of unloading hydrogen from the methanol carrier are comparatively large. The downside of LOHCs (such as DBT and MCH) is that the hydrogen carrier must be returned in order to receive a new load of hydrogen. Additionally, it requires a great deal of energy to unload, and large carriers create issues in terms of cost and safety. This is counterbalanced by the fact that existing infrastructure may be utilized and the carriers are reasonably simple to manage.

Usually, the choice of carriers also depends on the importing side of the supply chain. However, when only exporting to Rotterdam, this is no criterion considering that the Port of Rotterdam will be ready to import any form of hydrogen.

It is hard to anticipate or determine which of these types will be the most significant in the long run since it depends on too many variables. Real experience will reveal which carriers are the most desirable in the future years. Technological advancements, the level of cost reduction of the various technologies, the volume that can be delivered, and the final usage will all play a role. Currently, it would not be prudent for society or businesses to select one or two particular hydrogen carriers. Given that each choice has its unique qualities, it is anticipated that several forms would be utilized over time. Through a multi-criteria analysis, the port authority can set priorities for specific carriers but it is important to remain flexible to accommodate for changes in the future.

6.2.3. Stakeholder analysis and engagement

Phase 3 concerns the execution of an in-depth stakeholder analysis and the formulation of a stakeholder engagement strategy. There are multiple persons, groups and organisations that have to be taken into account when developing the HIPC. These groups or organisations are called stakeholders. The definition of stakeholders used in this report is the definition of Nutt and Backoff (1992) applied to the Fjarðabyggð harbour board: stakeholders are all parties who will be affected by or will affect the Fjarðabyggð harbour board's strategy (Nutt & Backoff, 1992). The stakeholders need to be involved in the process because they are affected by or can affect the development of the new HIPC. Analysing these involved stakeholders can help to decide how to engage the stakeholders in the process. A stakeholder analysis focuses on the resources and inter-dependencies of the actors involved (Hermans & Thissen, 2009). It looks at the stakeholder environment to maximize cooperative potential and minimize the threat of obstruction (Freeman, 2010). A failure to attend to the information and concerns of stakeholders is a kind of flaw in thinking or action that too often and too predictably leads to poor performance, outright failure or even disaster (Bryson, 2007). For this reason, it is important a stakeholders analysis is done prior to the port planning. Stakeholder analysis is utilized to determine: port stakeholders, stakeholders' objectives, and uncertainties around stakeholders' activities and objectives. Nonetheless, the difficulty in port master planning remains: how to prioritize the major stakeholders in the planning process for effective and timely participation in order to satisfy their objectives and resolve any conflict. This can be done through the following steps.



Identification

The first step in analyzing and engaging stakeholders is to identify those who have been granted stakeholder status according to the definition described above. Through brainstorming with the project initiators and the rest of the consortium, primary and secondary stakeholders can be identified. However, this brainstorming group may lack the skills and resources necessary to uncover all stakeholders. Therefore, an inadequate list of stakeholders results in an incomplete analysis of stakeholders. To maximize the validity of the stakeholder analysis for successful engagement, a wide variety of stakeholders must be considered. In actuality, an exploratory approach should be used to not only identify the widest possible variety of stakeholders but also to find dormant or latent stakeholders who may have a specific stake and effect on the project. The snowball sampling technique can be used in this regard. In essence, already identified stakeholders are asked to add missing stakeholders to the list. This process should be continued until no further stakeholders are suggested. Only then, the list is comprehensive enough to move on to the next step.

This research applied the method for the hydrogen port project in Fjarðabyggð. In consultation with the port authority and an Icelandic port expert, a list of stakeholders was drafted and eight main stakeholders were identified. Consequently, these eight were interviewed and asked to add other stakeholders to the list. This resulted in a list of 27 stakeholders that can be found below. Due to the time constraint of this research, the other 19 stakeholders could not be contacted. As can be seen in the table, the stakeholders were grouped into four main groups: internal stakeholders, external stakeholders, legislation and public policy stakeholders, and community stakeholders. Respectively, the internal and external stakeholders are entities that impact or are impacted by the port development. Further descriptions can be found in appendix D.

Category	Group	Stakeholder
Internal	Port authority	Harbor committee
		Port director
		Employees
	Municipality	Town council
		Customs
		Planning and building office
		Infrastructure, environment and asset management office
		Environmental office
		Fire brigade
		Utility supplies
External	Associations	Associations of industries
		Federation of Icelandic industries
		Association of fisheries companies
		Icelandic association for search and rescue
		the Agricultural association of fisheries
		the Port Association of Iceland
		the Icelandic regional development institute
		Innovation center Iceland
	Environmental interest groups	Icelandic Environmental association (Landvernd)
	Shipping lines and shippers	
	Companies & industries	Fishmeal factories
		Insurance companies
		Steel smelters (Alcoa)
		Fuel importers and distributors (N1, Skeljungur)
	Energy and water suppliers	Energy grid operators (Landnet)
		Energy producers (Landsvirkjun)
	Terminal users	Hydrogen producers (CIP, Shell, Mitsubishi)
		Storage and handling operators
Legislation and public policy	the Environment Agency of Iceland	
	Consumer agency	
	the national energy authority	
	the Icelandic transport authority	maritime security
		port installation and maritime navigation
	the Icelandic coast guard	
	the Icelandic Road and Coastal Administration	
	the national planning agency	
	ministries	ministry of foreign affairs
		ministry of environmental and natural resources
		ministry of finance and economic affairs
		ministry of industries and innovation
		ministry of transport and local government
Community	small neighboring markets	local stores
	landowners	
	neighboring residences	
	press/media	
	local fisherman	

Table 6.2: Full list of identified project stakeholders

Engagement strategy

Once stakeholders are identified, the next question is how to engage them.The stakeholder engagement strategy will give the port authority more information about what stakeholders need to be engaged in the process and how this should be done. Both stakeholders that are influenced positively as stakeholders that are influenced negatively should be considered. The advice can be obtained on the basis of the power-interest-attitude-grid as formulated by Murray-Webster and Simon (2006). Such a figure shows an overview of the categorized stakeholders based on their interests, attitude and power towards the situation. The power scale shows the actor's potential to influence the outcome of the process. The interest scale measures the extent to which the actor will be active or passive. The attitude, however, displays whether the actor will support or resist the process (Murray-Webster & Simon, 2006). Ranking the stakeholders per grid cannot be done single-handedly as it is no exact science but rather depends on the perspectives and experiences of the other stakeholders. Therefore a survey should be sent to representatives per group.

For this research, the following three representatives were asked to complete the survey: the municipality of Fjarðabyggð, the national power company Landsvirkjun, and the Icelandic road and coastal administration. The survey format can be found in appendix E. The results were bundled which led to the creation of the power-interest-attitude-grid in figure 6.2. Due to the time constraints of this research, only the stakeholder groups could be mapped. It must be noted that it is advised to map every single stakeholder in this manner to reach an optimal stakeholder engagement strategy. Per category, an engagement strategy can be formulated depending on the local conditions, the time available, and the tools at hand. General suggestions are elaborated in the following paragraphs.

Saboteurs These influential, active blockers, should definitely be closely involved, because of their large power and large interest. They need to be engaged in order to disengage blocking from those actors. It would be positive to transform the saboteurs into saviours.

Saviours These influential, active backers, should get attention to make sure they attend to their needs. They are on the side of the port authority and have high interest, high power and high attitude. So they will need to be involved for sure. The saviours are the parties that should be kept as active backers. Also, they can be used to create a positive attitude towards the plans of the port authority. This might help persuade other parties.

Irritant The insignificant, active blocker, should be engaged to sabotage their block behaviour. Also, they should be changed into friends. These can be converted into friends by actively listening to their feedback on public information and publicised processes.

Friend These insignificant, active backers can be used to persuade other actors that are not so positive about the situation. Friends have low power, high interest and a positive attitude. Collaborating with them would help the situation. The port authority does not have to do anything specific with this actor.

Acquaintance These insignificant, passive, backers need to be kept informed without collaborating in an intensive manner. Throughout the process, they might turn into friends if their needs are met more.

Time bomb These powerful, passive blockers need to be understood to to ensure that they do not have a major negative impact on the project. Because of their low interest, negative attitude, or alternatively influential characteristic, they need to be 'defused before the bomb goes off'.

Sleeping giant These powerful, passive backers need to be engaged in order to awaken them and benefit form their positive attitude.

Trip wire The insignificant, passive blocker has low power, low interest and a negative attitude. So those stakeholders will not be that important. However, they will need to be observed to make sure they do not change in an actor that blocks the situation.

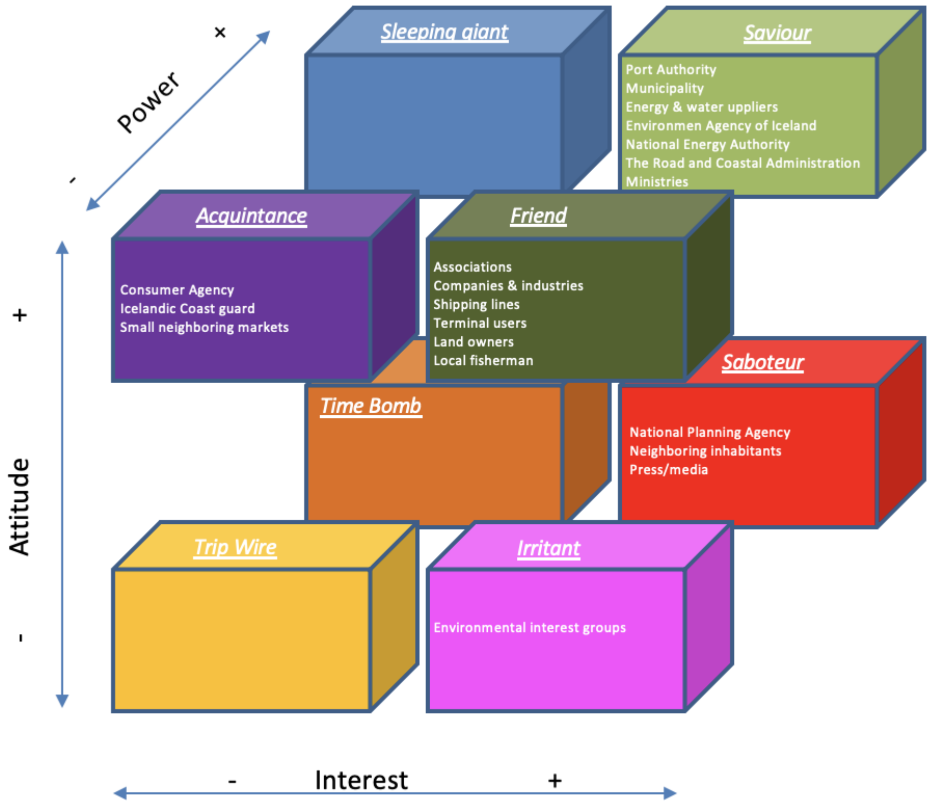


Figure 6.2: Stakeholder identification using the power-interest-attitude-grid

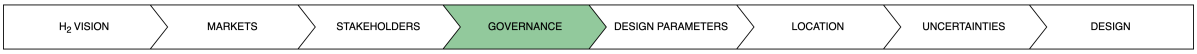
The next step is to identify the key stakeholders. These should have a say in the earlier-defined shared hydrogen vision to increase cooperation and facilitate the development process later on. It is up to the initiators or the consortium of the willing to determine the amount of selected key stakeholders. In general, key stakeholders should have significant power and high interest such as saviours and saboteurs. In this research, the key stakeholders were identified early in the process to conduct stakeholder interviews for data collection. These stakeholders can be found in section 5.1 and were selected after consultation with the port authority.

Select key values and issues

All identified stakeholders have their own agenda and preferences for the project. These can be expressed using values. As certain values are contradictory, it is hard to take into consideration the values of all stakeholders when designing a port. Therefore, only the selected key stakeholders should be interviewed to determine their values, objectives, and issues. Consequently, the bulk of values can be ranked according to prevalency and importance. From this should come a small selection of key values. The same can be done for the issues. The issues form the basis of the following negotiation rounds about design parameters. The selected key values will serve as the basis for selection criteria later on in the process. If the key values are not identified in an early stage, the design optimisation, later on, will take a lot of time. To align key stakeholders, the selected key values should be compared with the drafted shared vision. The shared vision may need to be adjusted accordingly.

6.2.4. Determine port organisation

In phase 4 the port organisation is specified. Before planning and designing, it is vital to identify the functions and comprehend the organization. For the economic and financial choices to be made as part of the development process, both variables are crucial. Since they are dependent on the core qualities and the wishes of the involved key stakeholders, these decisions should not be made before the stakeholder analysis.



Port functions

A port's primary role is to provide facilities for receiving, dispatching, and effectively handling goods from and to the many vessels of various sizes that will call at the port in the future. Equally critical are the industrial, logistical, and distribution operations that contribute to the port's value creation (Taneja, 2013). Regardless, different types of ports can be distinguished: import/export of a local market, port of entrance of a large region, bulk and industry port, or a container transhipment port. Serving the purpose of producing, storing, distributing, and exporting hydrogen, the port authority would clearly develop an industry port.

Within every type, a port can take on multiple functions. A port is a collection point that can perform four different general functions, which are:

- Traffic function: the port serves as a node in the transportation network, linking water and numerous land routes. Traffic in and out of a HIPC could include trucks, trains, pipelines, and ships.
- Transport function: ports serve as hubs for a variety of cargo flows. In the case of a HIPC cargo includes the hydrogen itself and its derivatives.
- Industrial functions: ports attract activities related to the production of cargo and to the needs around the handling of it. In the specific case of a HIPC this is the production of hydrogen itself, the production of its derivatives, and operational activities such as ship repair.
- Commercial and financial function: producing and trading in cargo such as hydrogen and its derivatives demands. Therefore, a port could serve as a buying and selling authority and could attract banks (van Koningsveld et al., 2021).

During this step it is essential to further define what these functions should look like in more detail depending on the shared vision, the national hydrogen strategy, and the involvement of stakeholders. In the case of a HIPC, the industrial functions are essential. The choices made in phase 2 determine the set-up of the port.

Port governance model

After carefully defining the port functions, the question remains of how this should be governed. Ports could be governed in multiple ways and section 4.3 has described the differences among the port governance models.

The functions and responsibilities should be divided among those who are best capable of bearing the risk and have the most experience and knowledge. The port authority of Fjarðabyggð has stated they want to build the port themselves at all costs to control and decide on the actions to be taken. Choosing a public port is a wise decision because the port authority closely collaborates with the municipality, and as such, has a higher chance of experiencing support from the (local) government. This can be expressed in financial resources, permits, and the construction of public infrastructure for the port. In addition, the port authority has more experience in developing ports in Iceland than a private (foreign) party. In this way, the port can be used for pilot projects and to attract new developers in the interests of the rest of Iceland.

In the case of a public port, the port authority has to choose between the service port model, the landlord port model, and the tool port model. The landlord model would be best. The port authority would own the land and give concessions to private sector companies for the production of hydrogen and carriers, and the provision of cargo handling and storage. The port authority's role would be to optimise investments by creating an attractive environment for private companies to invest in superstructure while the port development company focuses on common infra. As such, the port authority can generate a sustainable income from a mix of land leases and port dues. The provision of electricity and water for the electrolysers should be done by one of the three national energy companies as only they have the license to produce energy in Iceland. Besides, generating electricity is not the core business of a port authority or a hydrogen developer.

In the case of producing, selling and exporting a new product such as hydrogen, developers face many insecurities and risks. Technological immaturity, future demand insecurity, and supply instability, amongst others, reflect on the to-be-made decisions. The supply chain characteristic of a HIPC leads to dependencies between its elements. The accompanying risks can be labelled as chain risks, which is the probability of an event threatening other parties, who are affected by negative consequences not directly related to their own actions. An event can cause a chain reaction impacting the whole production process of a hydrogen producer (Beusenberg & Fasten, 2010). For that reason, private developers will want to reduce the chain risk by controlling most of the supply chain without sacrificing profitability.

Assuming multiple carriers (thus multiple hydrogen producers) will be required to serve a wide variety of requirements from clients and to be flexible for future technological developments, it is recommended to develop a port where all functions can be served. A hydrogen producer and exporter will always want to minimize supply chain risk by controlling the full chain development including its own terminal and jetty.

Once a first hydrogen plant developer is already settled, the second developer does not want to depend on its competitor and will prefer to build its own infrastructure. This phenomenon would continue if more developers are welcomed. However, one terminal and jetty would suffice to serve multiple producers. Therefore, it would be wise to attract an independent third-party logistics provider for a common user facility. This way, hydrogen producers in the port can outsource of their logistics (tank storage and handling) to the third-party logistics provider to focus on their efforts and investments in production.

Such a multi-user industrial port complex has the benefit of sharing common-user infrastructure and logistics facilities. It will also make better use of available land, minimises environmental and social impacts, and reduces overall logistics costs. It will also help to attract other industrial activities (such as fertiliser production) and logistics activities (such as refuelling stations for mooring ships). The end vision is a mature market with multiple players and segments thereby maximizing flexibility and competition and minimizing the final hydrogen price. In figure 6.3, an overview of such a port model can be seen. The facilities in blue would be privately operated whereas the facilities in red would be publicly operated according to the landlord port model.

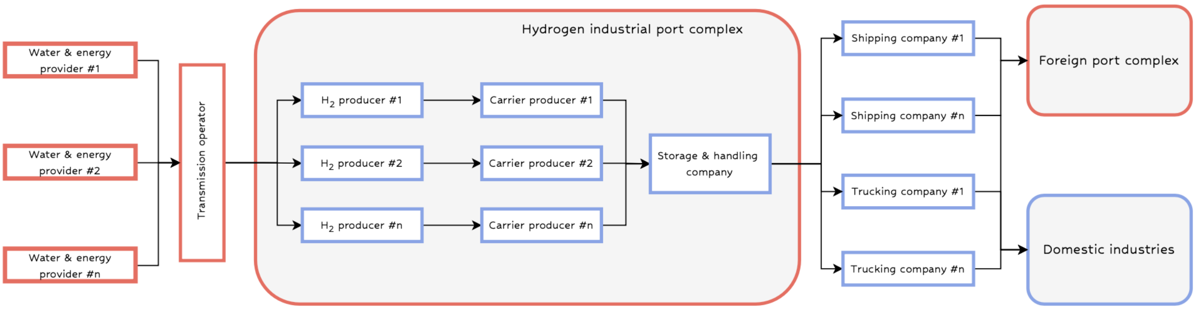
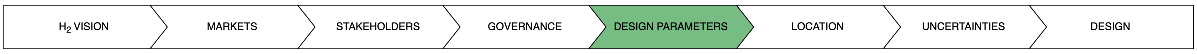


Figure 6.3: Hydrogen industrial port complex model

6.2.5. Define project design parameters

Phase 5 is the starting point of the actual port planning. In order to determine the most suitable location and work out multiple alternative plans, objectives and port needs have to be fixated. These are based on long term forecasts and the wishes of the port authority.



Cargo flow and shipping forecasts

In phase 2 of the IHPD-framework, feasible hydrogen markets have been determined. However, not every future offtake is equally ready for hydrogen receiving. Some industries might first require a pilot phase whilst others are ready for large scale offtake. Therefore, cargo flow and shipping forecasts should be linked to the design life of the port. The planning strategy is coupled with a predefined planning time horizon. A planning time horizon is defined as “the farthest time that uncertain developments are addressed” (Eskafi et al., 2021). There is no widely acknowledged conventional or explicit view of time extension in terms of specific short-, intermediate-, or long-term perspectives (Nordlund, 2012). However, table 6.4 shows an indicative example of three different time horizons. Long-term, medium-term, and short-term strategies are typically interconnected. Masterplans serve as the framework for medium-term plans, which in turn serve as the foundation for short-term initiatives. Time horizons should be linked to the national hydrogen strategy and the shared port vision. It should also be related to regional development plans and contract durations between energy producers and hydrogen developers, and between hydrogen producers and off-takers.

Type	Time horizon	Components of planning
Long-term	>20 years	Master plan
Medium-term	5-20 years	Phases of a master plan
Short-term	1-5 years	Minor layout changes

Table 6.3: Examples of time horizons

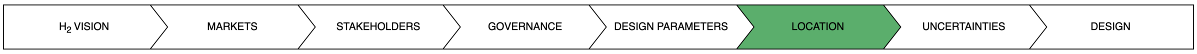
Once these are set, the forecasts for throughput can be made to provide clarity on the amount of hydrogen needed at this moment in time and the potential changes over time. These are conducted by transport economists. Generally, these definite port projections of expected future developments are based on historical trend analysis and expert opinions. Considering hydrogen ports are a new phenomenon, probabilistic studies are not an option. In that case, forecasting should be done through the use of scenarios to depict a spectrum of anticipated developments. The scenarios should be constructed using bottom-up methods that are drawn upon the expectations of the identified industries. The following stage is to determine the number and size of ships required to transport the various types of carriers. This needs knowledge of how the shipping line will handle the various transactions that result from cargo predictions. The master plan requires periodic updates in which the actual throughputs are compared to the initial expectations. Consequently, the initial predictions should be revised and the original phasing should be changed. The master plan should be adaptable enough to accommodate variations in economic development and transport pattern changes.

Define port needs
Following the objectives, cargo and shipping forecasts, and choice of carriers, a full list of project needs can be specified. These should be based on port user needs and port location needs. Port user needs should be collected from the shipping lines, hydrogen producers, and storage and handling operators. Port location needs depend on neighbouring communities and industries, energy and water providers, and key stakeholders. Eventually, this full list of functional requirements leads to planning elements. Using design formulas, the principal dimensions of the port's wet and dry regions are established. The planning elements should cover the following facets:

- Dimensions of the approach channel, turning circle and other water areas in the port;
- Dimensions of the jetty for different carriers;
- Dimensions of terminal areas;
- Infrastructural connections;
- Service area and buildings;
- Land required for industries;
- Safety and environmental requirements, including safety distances for the handling of dangerous cargo (Ligteringen, 2017).

6.2.6. Fixate location

Phase 6 is about choosing the most suitable location according to the defined port needs and objectives. As part of the design process, the significance of the location decision should be highlighted. This is considered the framework's foundation, as the location, design, and operation of a port are intricately interwoven. By this time the greater region is probably known as the initiator has a preference and is oftentimes regionally bound. However, within this area, there are often several possible locations available. First, all locations have to be identified, then their systems must be analyzed. Only then the best option can be chosen.



Find physical suitable locations
Now that the port's design characteristics are established and the area of study is specified, the possible physical sites may be narrowed down. This pre-selection is needed since conducting research on too many sites in the next stage would demand too much time and resources. A physically acceptable location is one that satisfies all, and if not most of, the stated design requirements while having the least negative physical environment consequences. The locations can be found based on existing literature, expert advice, and site visits. When identifying locations, review to what extent the physical environment will negatively impact the proposed port. In the case of a HIPC the distance from the energy provider, a safe shelter for the plants, and the time required to be on the open sea is key in this regard. Thereafter, all visible suitable locations need to be systematically checked for impacts caused by the environment on the design criteria (that already include uncertainty reducing actions).

As was mentioned in section 1.1.3, for the case of Iceland, a study was undertaken which concluded the good port location to be in the Reyðarfjörður on the island's East coast. The area offers a wide range of advantages, including: an existing port complex, a safe harbour with sufficient depth, existing expansion plans, ample space for industries, the required distance from urban areas, planned wind parks, hydropower-and geothermal plants nearby, and it is not located near environmentally sensitive areas. However, around Reyðarfjörður, there are multiple options. These should all be analysed with the specific defined design requirements in mind.

Understand the systems

The earlier defined port design parameters are basically limitations for the amount of potentially suitable locations for the proposed port, since not all locations are able to fulfil the needs and objectives of the port. Therefore, multiple disciplines should be studied to determine the optimal placement of the port. Broadly speaking, the following disciplines should be borne in mind here: physical factors, environmental factors, governance factors, and socio-economic factors (Schipper et al., 2015).

A physical analysis should provide more insight into the site conditions. Aspects to research include topography, land cover, soil conditions and geotechnical characteristics, climate and meteorological conditions (wind, rainfall, fog, temperatures), bathymetry, wave conditions, currents and horizontal tide, water levels and vertical tide, sediment characteristics and transport, water and air quality, salinity, seismic conditions, and noise. An environmental analysis should provide information on the potential impact of the port on the surrounding environment. Aspects to consider include protected areas, fauna and flora types and diversity, endangered species, sensitive habitats, and ecology (marine, coastal, and terrestrial). Also, a governmental analysis is of importance. Here, it is important to understand aspects such as relevant regulations and standards (both international and national), and the national and local governmental situation. This will influence the permitting process and the financial contribution. Last but not least, a socio-economic analysis should be performed about the current situation and the projected situation in the area. Aspects to consider include infrastructure and connectivity, nearby businesses (industries, fisheries, agriculture and livestock), population and community social structure (including vulnerable groups and indigenous populations), labour market and sources of income, land use and planned developments, and cultural heritage/religious sites.

Note that these disciplines are general and need an interpretation that is dependent on the area conditions at hand. Also, in the event that the identified locations are close to each other, there may be overlap in the interpretation of these studies.

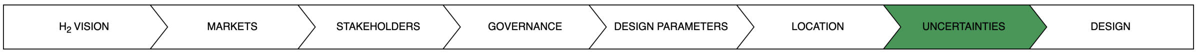
Select the most suitable location

By examining the broad influencing elements in each discipline's study, it becomes evident what possibilities and obstacles the proposed port would encounter when deciding on a site. By including the key stakeholders in these studies, it becomes clear what their problems and priorities are at each site. All gathered information should be categorized into location-specific threats. The site with the fewest negative effects from the criteria and the greatest prospects for the port might be deemed the most ideal. It is up to the port planner and port authority to decide which location that is.

This is also the part where the Environmental Social Impact Assessment starts. The ESIA process should be performed parallel to the design process in order to early identify the positive and negative impacts caused by project implementation. This is assessed through an analysis of the effects resulting from interaction between environmental and social components and the various activities of a project and its development. Jurisdictions in most countries around the world require an ESIA to be undertaken before authorization (for example, permitting, licensing, planning consent) for certain types of projects is granted. National legislation often varies between countries, so it is vital to establish the local requirements prior to embarking upon the ESIA process.

6.2.7. Map uncertainties and plan actions

Phase 7 aims to optimize the flexibility in the port design by addressing the uncertainty throughout the port development at an early stage. Section 4.1 described ports as complex socio-technical systems that have to be planned under volatile circumstances. Due to the complexity of a port system and the uncertainties associated with its expected lifetime in a dynamic environment, uncertainty must be accounted for before the design phase. This is done by first identifying them and consequently defining actions to decrease them. These actions result in more planning elements.



Map uncertainties

Carefully describing uncertainties helps to find the most suitable remedies for vulnerabilities and objectives for opportunities. Because uncertainties can manifest themselves through different developments, all developments should be considered. For example, a fluctuating demand for hydrogen can be defined as both a demand that diminishes over time and demand that increases over time.

The more uncertain developments are defined, the better the ultimate port design. It is impossible to map all concerned uncertainties single-handedly as there are multiple perspectives on the port development. Therefore, both the earlier-on identified stakeholders and multidisciplinary experts should be consulted on their perspectives. Interviews are recommended because they enable the port planner to explain the decisions made throughout the previous steps. This information is essential for stakeholders to brainstorm about their questions and worries.

The uncertain developments should be coupled to the time horizons because they are unique within a temporal horizon. Without a planned time horizon, every assumption about unknown future events becomes susceptible during the course of the project's existence. Only unpredictable events that occur within a specific time frame are considered susceptible. The same can be said about port functions. Every uncertain development should be linked to the earlier-defined port functions.

Consequently, the described uncertainties should be defined according to their level of uncertainty. The level of uncertain development expresses the degree of knowledge and information about the development of uncertainty. Walker et al. (2010) defined four levels of uncertainties that can be defined between the range of complete certainty and total uncertainty. Level 1 uncertainty is a circumstance in which one confesses that they aren't certain, but they are unwilling or unable to quantify their level of uncertainty in any way. Level 1 uncertainty is frequently addressed with a basic sensitivity analysis of model parameters, which assesses the effects of tiny changes in model input parameters on model outcomes. When probabilities are employed to indicate the possibility or plausibility of uncertain options, it is referred to as level 2 uncertainty or statistical uncertainty. Level 3 uncertainty describes a circumstance in which one can think of a lot of plausible options but can't decide which ones are most likely. The deepest level of recognized uncertainty is Level 4 uncertainty. We only know that we don't know in this circumstance.

The uncertainties identified throughout this research are the lack of knowledge about industrial processes, the scale and the infrastructure needed, the everchanging hydrogen-related technologies, the support of society and government, certification schemes, market demand, safety and environmental regulations, and competitive (international) hydrogen ports. However, because the previous IHPD-framework phases have not been worked out yet and because of the lack of awareness of the hydrogen industrial port complex among stakeholders, no more uncertainties could be identified.

Plan actions

Within the context of the planning objectives for the short-, medium-, and long-term, a variety of alternatives should be produced to address the unpredictability of future events. This can be done through a full port SWOT analysis. This can be completed on the basis of the system analyses that were performed in phase 6. The analysis should be in-depth, location-specific, and should take infrastructural port elements into consideration. It must be noted that the analysis of section 5.2 focuses on a hydrogen economy in a greater Icelandic context. Therefore, it could be used as a basis, but should be worked out in more detail for the port project of Fjarðabyggð. The results of the SWOT analysis and the uncertain future developments will lead to fundamental assumptions. These then can be formulated as opportunities and vulnerabilities.

To manage the fundamental assumptions, it is necessary to prepare effective actions. These measures are supposed to minimise vulnerabilities and maximise opportunities. There are two fundamental approaches to developing a vulnerability and opportunity plan: either by taking immediate action (during the planning and design process) or by planning actions in advance that may be implemented in the future if needed. Taneja (2013) defined the four categories of actions depending on the type of uncertainty and the level of uncertainty:

- *Seizing action*: an activity done to exploit reasonably definite opportunities. The necessary steps should be performed immediately. An example of such an action is attracting additional markets with attractive services (in terms of price or quality) because of the increased competitive position of the port or because of the construction of new infrastructure. Offering the extra space requires accounting for flexibility in the planning process.

- *Shaping action*: action taken now that is intended to remove the cause of a certain or uncertain vulnerability, either by reducing it or changing its nature. Planners act to ensure that the vulnerable event does not take place or to steer events towards a preferred scenario. Proactive shaping acts seek to influence external factors. An example of such an action is influencing policymakers in future regulations.

- *Mitigating action*: a measure adopted within the present planning cycle to solve a plan's virtually inevitable negative consequences. Prepare the fundamental plan for probable harmful consequences and attempt to strengthen it in this way. An example of such an action is building a highway around the port to avoid expected road congestion or already investing in extra storage areas for future increments in hydrogen export. Or if growth in port activities increases air pollution (environmental concern), a mitigating action could be increasing the use of renewable energy (instead of fossil fuel) at the port.

- *Hedging action*: a strategy for spreading the risk of a plan's extremely unknown undesirable impacts within the current planning cycle. These activities anticipate undesirable consequences on the fundamental plan by making a backup plan, hence increasing the plan's robustness. Defining hedging activities necessitates visualising the probable consequences of a long-term development. An example of such an action is defining new profitable functions for land that becomes vacant after the closing down of terminals. This way the large vulnerability could become an opportunity. Or if rapid growth in H2 production, increases the cargo flow, and thus vessel traffic (in the fjord), then a hedging action to deal with this uncertainty can be managing/improving/rescheduling vessel traffic through the fjord for your port as well as the neighboring port (aluminum smelter).

After these actions are determined, they should be included in the list of planning elements. This way the port needs are optimized.

Action	**Likeliness**	**Type of uncertainty**	**Moment of acting**	**Objective**
Seizing	Fairly certain development	Opportunity	Take action now	Take advantage of fairly certain opportunity
Shaping	(Un)certain development	Vulnerability	Take action now	Take away the cause and steer towards preferred scenario
Mitigating	Fairly certain development	Vulnerability	Prepare for future	Reduce potential adverse effects of fairly certain vulnerability
Hedging	Highly uncertain development	Vulnerability	Prepare for future	Spread and reduce highly uncertain effects of vulnerabilities

Table 6.4: Examples of time horizons

6.2.8. Create concept design

Phase 8 is about the creation of the actual port design. This is the creative part. So far, the design parameters are known, the location is set, and the system parameters of the location are known. Different concept layouts should be worked out. These should be tested and evaluated to create a final design. The evaluation of lay-out alternatives takes place at different stages and can be done using monetary and non-monetary approaches. The distinction is that non-monetary approaches assign a score to the plan's quality, but monetary methods translate these scores into monetary values. First, a screening of basic sketch plans should be done, then an assessment of the most promising options (non-monetary evaluation), and lastly a financial and economic feasibility study (monetary evaluation) of the chosen masterplan layout should be performed. The latter should be performed to evaluate the feasibility of the port objectives. When the results are positive and the permits are allocated following the ESIA study, a final master plan can be written.

Concept layouts

Based on the system parameters, different alternative layouts must be made. Through brainstorming, engineers can come up with planning measures that respond to the defined location-specific threats (as defined in phase 6). At this point, alternative layouts are merely conceptual drawings and sketches based on design rules. The alternatives should take into account the different key values as defined by the key stakeholders. Probably there are no one-size fits all solutions and thus every alternative should have different priorities.

When designing the ports, special attention should be paid to regulations and standards. These differ per carrier. For ammonia, regulations already exist and are applied worldwide. Therefore, it is not expected they will change a lot over time. Regarding LOHCs, no regulations exist at the moment. On the other hand, due to similarities with diesel-like cargo, it may be anticipated that the safety of handling, shipping, and storage of LOHC can be ensured with little modifications to existing standards. Concerning liquid hydrogen terminals, the regulations are also still in their infancy. For now, the European Industrial Gases Association Doc 06/19 and Doc 224/20 are relevant. However, these are only recommendations and the usage is not binding. Other standards important for the storage of liquid hydrogen are ISO/TC 220 on "Cryogenic vessels" and CEN/TC 268 on "Cryogenic vessels and particular hydrogen technology applications."

The alternatives should also describe specific development phases. These should be based on the defined uncertainties and different forecasts. More phases allow for more flexibility in time. However, more phases also result in higher costs. The cost assessment per alternative will be an important selection criterium. Therefore, rough estimates are important to move on to the next step.

Test and evaluate layouts

The subsequent testing is focused on assessing the technical feasibility, possible ecological and social effect, and cost estimates of planning measures in the conceptual layout options that have been established. The different planning measures are intended to limit treats in the system and all come with advantages and disadvantages. These should be tested for their technical feasibility and impact.

Then, the many alternatives should be evaluated to determine the optimal choice. A non-monetary approach is preferred at this stage because it compares the in-depth feasibility and impact of the different alternatives. As an evaluation tool, a Multi-Criteria-Analysis (MCA) is advised and frequently employed. It pertains to an evaluation that assigns a total value to the design choices by applying different weights to various criteria. In this way, the tool may assess a larger variety of elements for which it is challenging to quantify the consequences and/or represent them in monetary terms. MCA is also beneficial in instances where various stakeholders place varying values on the impacts. Therefore, one should use the established key values as criteria. It is common to use sub-divisions of the primary key values to represent all port planning disciplines. In essence, the port planner assigns a relative score to all (sub-)criteria per alternative. Per criterium, these score allocations can be done in a qualitative and a quantitative manner. In parallel, every (sub-)criterium is coupled to a specific weight to define its importance. Multiplying the scores by the weight yields an overall score for the suggested choice that may be compared to other options' scores. The MCA technique has the disadvantage of requiring significant subjectivity in determining the weights, however, the entire computation may be redone with alternative weights to examine the sensitivity of the result to the weights used. Regarding the costs of the alternative, these can either be used as a single criterium in the process, or they can be used as a separate evaluation tool. In the latter case, the selection of alternatives can be made on the basis of the highest MCA value over costs ratio. In this manner, a little higher cost level may be justified if the alternative's value is higher. Once the port planner is pleased with the options and their evaluation, the client will be advised of the alternative with the highest score.

Create final design

Once the best alternative has been distinguished, it should be worked out in more detail. Before design and engineering teams work out the details, the initial alternative can potentially be optimized by making small adjustments or even combining multiple alternatives. In an iterative manner, the MCA score might be ramped up. Otherwise, initial sketches, rough design estimates, and preliminary cost assessments should be worked out until the necessary level of specificity is reached.

Perform cost-benefit analysis

The final design serves as the basis for the final investment decision of the involved investors and the initial consortium of the willing. Therefore, its financial feasibility should be assessed by means of a monetary evaluation. This can be done through a (commercial) cost-benefit analysis (CBA). This is a purely financial analysis. When stakeholders such as the (national) government or international financing institutes want to assess the overall effect on society, a social-cost-benefit analysis (SCBA) can be performed.

The CBA is a systematic and rigorous process for evaluating the benefits of a given project. The CBA approach is reasonably simple to implement because it takes only the investor's anticipated cash flows as input. Throughout the course of the project, the capital expenditures, operating expenses, and income should be put together and discounted to account for the fact that the value of money fluctuates over time.

The SCBA has a similar framework, but instead of basing the decision just on the profitability for the investor, it considers the larger advantages to the nation or area as a whole. This is accomplished by first identifying the status quo, that is commonly described as the condition without a port. Consequently, a comparison is conducted between the scenario with and without the project in terms of performance.

Write final masterplan

Eventually, the concluded shared vision, port design with multiple phases, and plan to serve the distinguished markets should be consolidated in a long-term final master plan. This document should be a comprehensive and flexible road map that outlines the port's future expansion and development. The master plan must be revised every 5 to 10 years, during which the actual throughputs are compared with the original estimates, the latter is altered, and the original phasing is evaluated and revised accordingly (Ligteringen, 2017). Also, the (inter)national regulations regarding (hydrogen) ports might have changed. All reasons to evaluate the uncertainties and adapt the planned phasing structure of the port. Thus, the lifespan of the master plan might be extended and a continuous planning process may be achieved. This is seen in figure 6.4, where the installation of Phase 2 infrastructure must be accelerated since new throughput predictions indicate a greater increase.

The final masterplan serves as input for the final investment decision, where multiple work streams come together into a go/no go decision. The ESIA must be completed and the right permits, licenses, and planning consents must have been awarded. As regards stakeholders, there mustn't be any major opposition to the project, there must be agreements with the clients, and there should be a continued stakeholder engagement throughout the next construction- and operation phases.

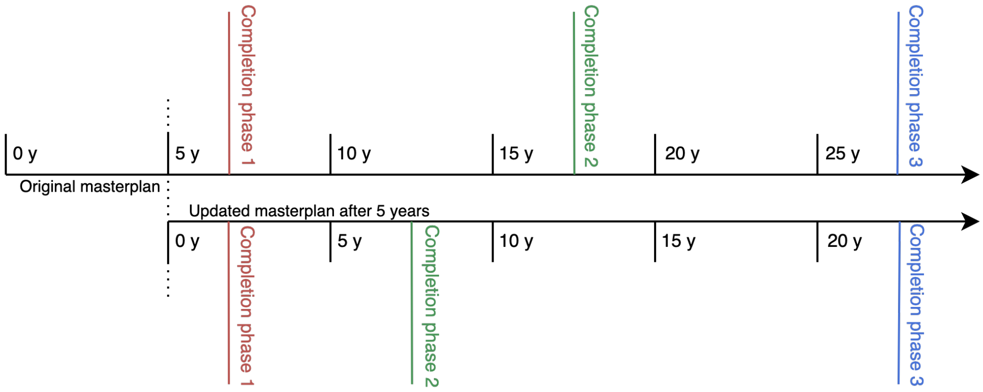


Figure 6.4: Illustration of updating master plan

6.3. Narrative for HIPC master plan

The previous section has extensively elaborated on the development process of a HIPC. As was described, investing in a port requires the composition of a master plan. This is a delicate process that involves expertise and approvals from various disciplines. A master plan can not be written single-handedly without iterations. Whilst explaining the IHPD-framework in section 6.2, suggestions were made about considerations per step. Taking these considerations in mind, this section offers a narrative that describes practical recommendations for the Fjarðabyggð port master plan.

Considering the port authority of Fjarðabyggð is the primary initiator, the location of the port complex should be bordering to the north side of the fjord of Reyðarfjörður on the island's east coast. Section 1.1 outlined the advantages of this particular location. The most outstanding one is its proximity to the open sea, which benefits the export to foreign countries. As can be seen in figure 6.5, there are three features that frame the borders of the port; the living area of Fjarðabyggð in the west, the Alcoa aluminium plant in the middle, and the Hólmanes nature reserve mountain in the north.

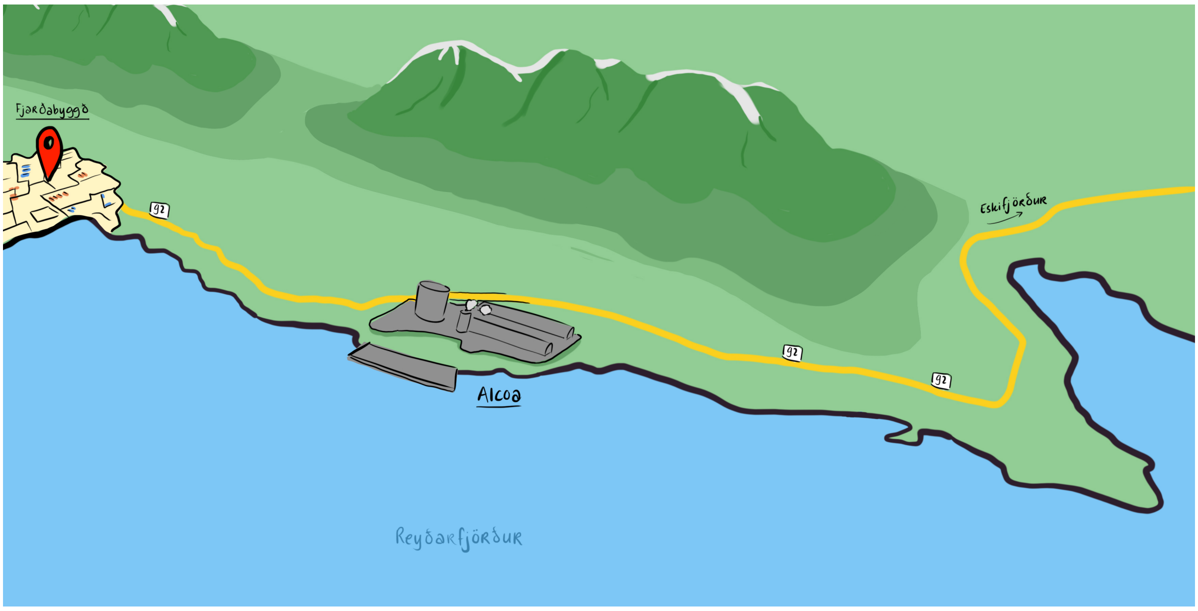


Figure 6.5: Map with current situation that contours the available port area

To start and stay ahead of competing (inter)national ports, it is key to maximise production as fast as possible. However, to ensure flexibility and grow with the market- and governmental-related developments, the port should be constructed in three phases. The first phase will set up the export to meet the existing foreign demand, and initiate pilot projects to develop domestic markets. The second phase will upscale production for proven domestic markets. During the third phase, production will be maximized for growing foreign demand.

Phase 1: Short-term

The first phase will produce hydrogen to meet a share of the demand from Rotterdam and to set up pilots for hydrogen market development in Iceland. If the port starts producing for export, it can benefit from the existing export partners who can guarantee a long-term purchase as a foundation for the HIPC. It also allows for educational purposes by attracting experts who can share in-depth knowledge. Furthermore, the lessons learned from developments of markets abroad serve as direct input for fine tuning the national strategy and developing national markets.

Meanwhile, pilot projects will be set up as the first step in Icelandic hydrogen markets. This reduces the absence of clarity in markets and allows for cooperation with Icelandic industries. The pilot projects will create an open environment of education to stimulate stakeholder engagement and increase social acceptance. It is important to involve the media in this phase to stimulate awareness of the benefits of hydrogen production. The following three pilot projects will be essential:

- a fuelling station for the first fishing ship on ammonia;
- a fuelling station for the first public transport bus on hydrogen;
- small-scale fertilizer production for nearby farmers;

In the first phase, only one terminal developer and hydrogen carrier will be chosen to reduce complexity and minimize the risk of public opposition. The size of the port will be in line with the minimum requirement to benefit from economies of scale to offer hydrogen at the lowest price. The share of hydrogen for the pilot projects will be put to a minimum.

The carrier of choice will be ammonia. Because it is expected to become a global shipping fuel, it can be directly used by the fishing ship pilot. It can also be used for the fertiliser pilot. Furthermore, because the technology already exists, it can immediately be produced at a reasonable scale.

For the supply of energy for hydrogen and ammonia production, new wind farms will be constructed nearby in allocated wind areas. There is a potential to generate up to 1,000 MW of onshore wind energy (Coopman & Halgrimsson, 2021). In this phase where the amount of hydrogen production is still relatively small, new geothermal- or hydro power plants will not be necessary. In addition, wind farms can be built in a shorter period of time.

Although only one carrier will be produced in this phase, the jetty and storage facilities will be designed in such a way that they can also facilitate larger quantities and other carriers in later phases. As such, in the longer term, only one jetty is needed and the master plan is flexible enough for future uncertainties.

The land allocation of the first phase hydrogen port can be seen in figure 6.6. The jetty is being built east of the Alcoa factory to keep incoming ships out of sight of the living area. For fast ship loading, storage facilities will be placed close to the jetty in a central location. Because of the poisonous character of ammonia, they will be placed far away from the nature reserve and living area. They will be placed next to the already existing industrial base of Alcoa.

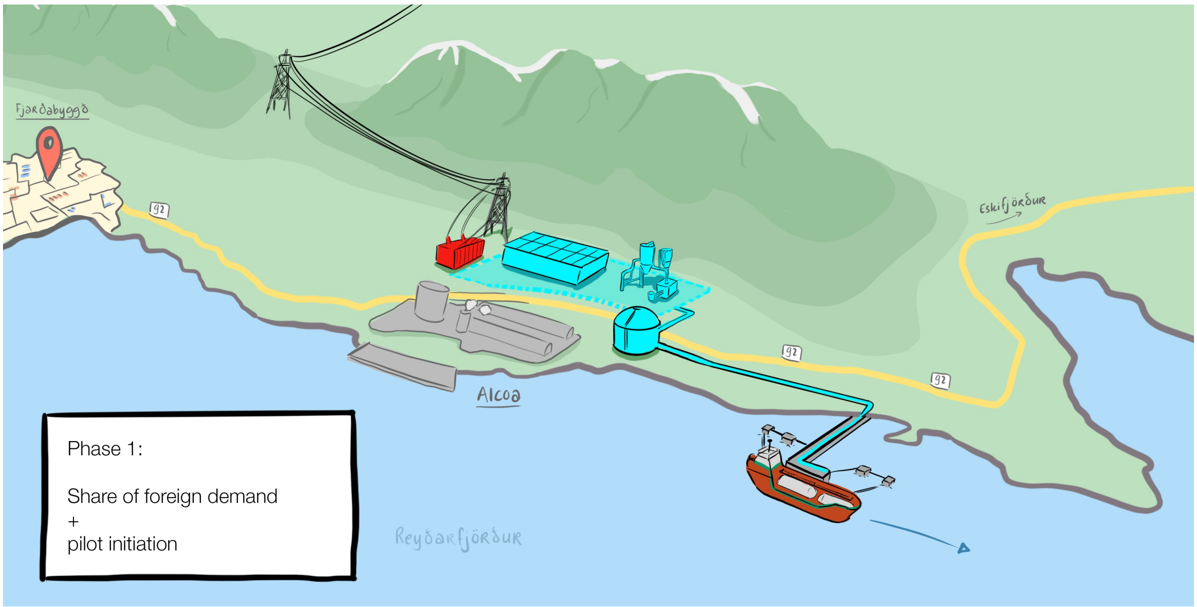


Figure 6.6: Phase 1 of hypothetical HIPC master plan

Phase 2: Medium-term

The second phase will upscale production for domestic purposes without compromising on the production for export. This should enlarge the social acceptance and increase the self-sufficiency of the island. By this time, the national strategy will have more shape and the pilot projects will have yielded more insights into concrete applications of hydrogen for Icelandic users. The government will have permitting and subsidy schemes in place and will be able to steer the choice of carrier. This means that the necessary public infrastructure can be built across the country. Examples are fuelling stations for heavy trucking, public and private transport, and ships. Also, national distribution pipelines and shipping lines can be constructed.

This enables the markets, as discussed in 6.2, to fully grow. Not only the direct domestic users of hydrogen will be served in this phase. Also, emphasis will be put on the byproducts of hydrogen production. Oxygen released can be used for fish farms and applications can be found for the heat released during the carrier conversion. Unfortunately, the Alcoa aluminium plant will not be an off-taker of hydrogen. However, the CO_2 emissions released in their process can be used for methanol production in the HIPC.

Up-scaling production demands more hydrogen production terminals and more energy supply. New terminals will be built that will either also produce ammonia or another carrier. This will depend on the wishes of the Icelandic customers, the latest technological developments, and the guidelines of the national strategy. With current insight, liquid hydrogen seems to be a good option because the re-conversion to gaseous hydrogen is a simple process without residual product at the end of the supply chain. Also, compared to LOHCs, it requires no transporting back of recycled toluene. Therefore, it will be more feasible to transport through pipelines.

The new terminals will be built within the same port complex to minimise the impact on neighbouring communities and nature, and benefit from the already existing storage and cargo handling facilities. In case the domestic markets prove to be of such scale that hydrogen production needs to be doubled, then there will not be enough space to develop even more wind farms in the vicinity of the port. Other energy plants will be developed in the form of hydro power or geothermal power.

The expansion plan can be seen in figures 6.7. Considering the existing jetty was built for any type of carrier and is capable of servicing additional visits, no new wet infrastructure will have to be built. However, storage capacity next to the jetty will have to be increased but this has already been taken into account initially. Assuming that local support for domestic hydrogen production will increase for this phase, the port will be further expanded towards the village.

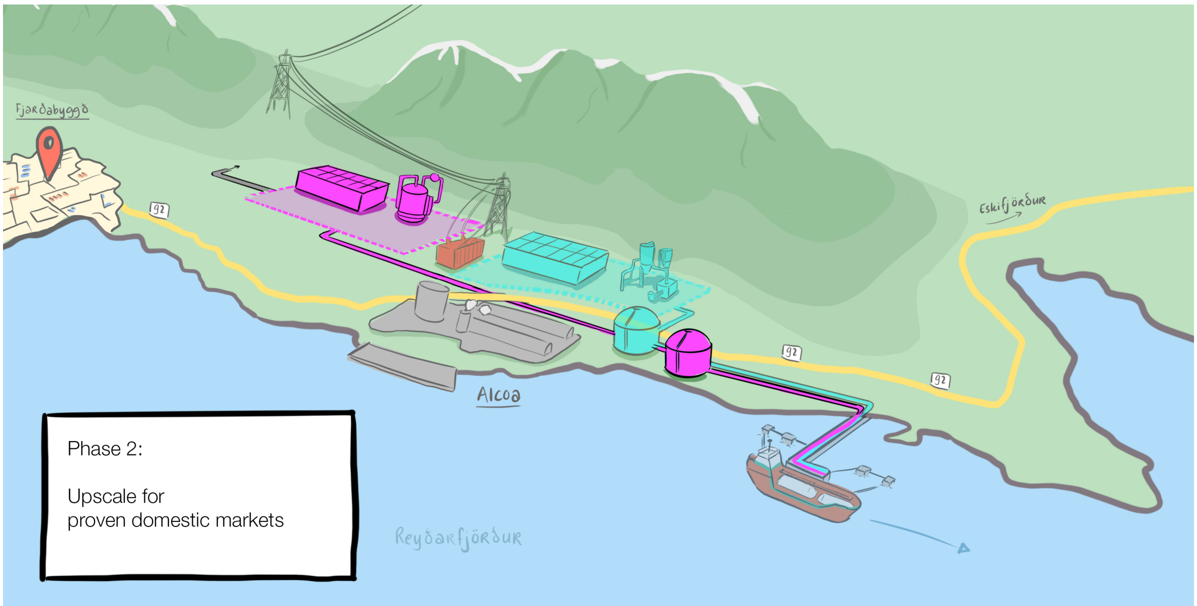


Figure 6.7: Phase 2 of hypothetical HIPC master plan

Phase 3: Long-term

During the third phase, the production capacity will be scaled up once again. This time to meet the expected growth in foreign demand. While the (smaller) domestic demand will remain fully supplied, all remaining available land and energy resources can be used to enlarge the Icelandic geopolitical influence, contribute to a global energy transition, and increase the economic development of the Eastern Region and Iceland as a whole. If the hydrogen production is maximised, a share of the hydrogen will be stored separately for seasonal shortfalls of the current renewable energy sources. This way a continuous supply of hydrogen can be guaranteed.

Once again, the expansion plans will take place in the same port complex for the earlier-mentioned reasons. Also, the existing jetty will suffice to meet the increment in hydrogen volumes and the storage facilities will be enlarged close to the jetty. The new terminals will be built next to the existing ones. The enlarged layout can be seen in figure 6.8.

As for the choice of carrier, this will depend on the technological status and the price comparison of the different carriers by that time. However, with the current knowledge, DBT will be a good option as it is not toxic and flammable. Considering the new terminal will come closest to the village, the latter argument is of importance. In the case of DBT, also new storage facilities will have to be built to unload and store the H18-DBT next to the jetty.

Also for this phase, new power plants will have to be built in the form of hydro dams or geothermal plants. The maximal hydrogen production volumes will depend on the surface requirements of the terminals, and the scale and amount of new energy plants that the government authorises.

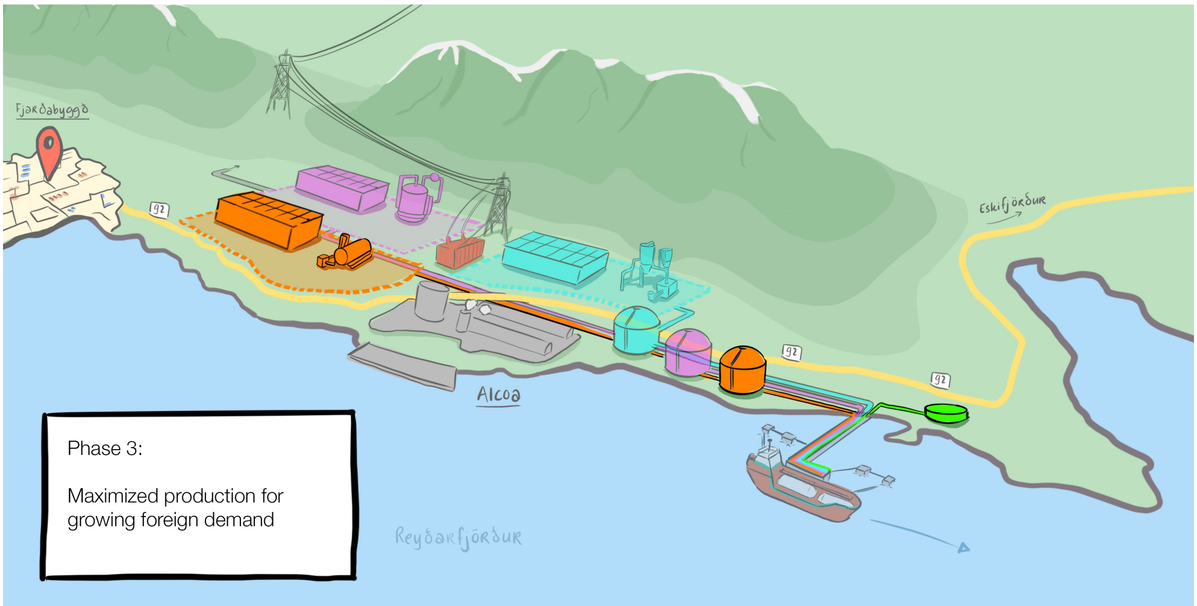


Figure 6.8: Phase 3 of hypothetical HIPC master plan

Final HIPC

The final result is a multi-user industrial port complex that has the benefit of sharing common-user infrastructure and logistics facilities. This will allow for making better use of the available land, minimising environmental and social impacts, and reducing overall logistics costs. It will also help to attract other industrial activities (such as fertiliser production) and logistics activities (such as refuelling stations for mooring ships). The end vision is a mature market with multiple players and segments thereby maximizing flexibility and competition and minimizing the final hydrogen price. In figure 6.9, an overview can be seen of the final port lay out. Three terminal can be distinguished that all produce a different carrier. The separate area for storage tanks allows for an independent operator to run them.

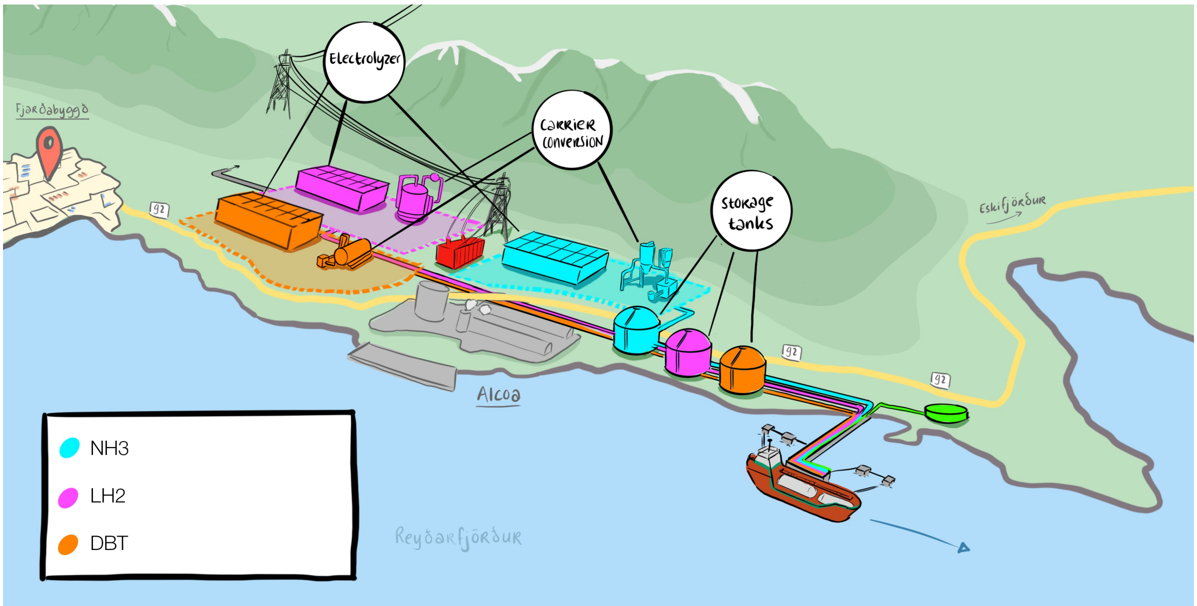


Figure 6.9: Final lay out of hypothetical HIPC master plan

6.4. Chapter summary

Chapter 6 was the second diamond of the double-diamond design process model and contains the problem solution to the design brief. The solution is a framework that directly serves as an answer to the main research question.

The chapter started by evaluating multiple frameworks that could contribute to the formation of a roadmap. Three different approaches were considered but due to the preliminary stage of the case study, the approaches seemed not the right solution to the design brief. However, these frameworks did lead to the establishment of the final IHPD-framework that was clarified in the subsequent section.

The IHPD-framework not only consists of the necessary port development elements, it also describes the suitable sequentiality between these elements. The sequence runs through eight phases with each multiple steps. These steps were explained and applied to the case study where possible.

Finally, a narrative was written about a potential master plan draft that consists of three phases. The first phase will set up the export to meet the existing foreign demand, and initiate pilot projects to develop domestic markets. The second phase will upscale production for proven domestic markets. During the third phase, production will be maximized for growing foreign demand.

7

Discussion

Chapter 5 and chapter 6 together formed the double diamond design process model. It served as a body for the empirical and analytical part of this research. However, throughout the study, several points were raised that require additional reflection. Section 7.1 reflects on the results on this research before section 7.2 lists research limitations.

7.1. Reflection of results

Firstly, before building the IHPD-framework, chapter 4 highlighted complicating factors concerning the construction of a new port or the expansion of an existing port. Developing the system is complex because of its many components and accompanying interactions. Initially, this research aimed to use existing literature such as DeLaurentis and Callaway (2004), for mapping the complex system. However, these frameworks have proven to be too static and not capable of fully defining the system at this stage of the project, where multiple decisions concerning the system layout still ought to be taken. Thus, a more dynamic approach was needed to incorporate opportunities and threats perceived by stakeholders to facilitate the making of these decisions. In fact, determining how stakeholders will behave in the system is a factor that could be contributed to the DeLaurentis and Callaway (2004) framework. Future projects are recommended to start with a SWOT analysis to dynamically indicate the contours of the desired system before they are further worked out in a static manner using DeLaurentis and Callaway (2004) to increase the understanding of the greater system amongst all involved stakeholders. It will prompt stakeholder engagement and reduce miscommunication due to a lack of knowledge.

Therefore, to come to a design brief as the basis for the IHPD-framework, a SWOT analysis was performed. The results were quintessential in understanding the current greater system in which an Icelandic hydrogen port would have to exist in. The results of the stakeholder interviews were used to identify several strengths, weaknesses, opportunities, and threats, which were influential in the sequentiation of the IHPD-framework. For example, there is a lot of potential to produce hydrogen for the domestic market because Icelanders are true energy pioneers and have proven to be willing to find more sustainable energy solutions. The market study is therefore addressed early on in the framework. At the same time, the export market is growing. As such, this issue must also be addressed parallel with the domestic market because the size of the port and the energy needed will have to be divided between the two. However, the shortcoming of the SWOT-analysis is that the four categories are kept separate from each other and no solutions are suggested that could improve the system by combining the categories. The Weihrich (1982) framework could be used for this. It suggests a tool for using important relationships between the aspects in the four SWOT categories, namely the TOWS matrix. Four different solution spaces can be created by answering the following four questions; Can we seize opportunities because we have our strengths? Can we eliminate threats with our strengths? Are there opportunities that compensate for weaknesses? Are there threats that are driven by weaknesses? Retrospectively, these solutions would not have influenced the sequentiation of the framework but it must be noted that this may be the case in future other projects. Additionally, in terms of port designing, this leaves an unexploited opportunity. Therefore, port planners are advised to perform an in-depth TOWS analysis on top of the SWOT analysis before drafting the master plan.

Thirdly, this research attempted to use back casting methodologies such as Quist et al. (2006). These use desirable future visions as a starting point for determining short-term concrete actions. This study revealed the lack of a desirable Icelandic future vision and the inability to determine the best option academically. The choices to be made are purely political. It is up to politicians to evaluate the economic benefits vis-a-vis the environmental consequences of new power plants. However, this research has shed light on the essence of a unified national hydrogen vision. Only once the direction is set, back casting principles can be applied to hydrogen port projects.

Moreover, literature reviews highlighted the need for incorporating uncertainties in the planning process as early as possible. Using Eskafi et al. (2021), effective remedies can be determined to reduce uncertainty. However, this framework was constructed for port expansion projects where the context was set and the plans determined. In those instances, stakeholders already dispose of the knowledge to point out their concerns and uncertainties. This is different from a greenfield hydrogen port. Stakeholder interviews proved the unawareness of Icelandic port stakeholders about plans for hydrogen projects. As a result of the lack of context and hydrogen-related knowledge, no particular uncertainties could be mapped at this moment. Therefore, it is important to first define a shared vision with the consortium of the willing as a way to share knowledge and create a context before consulting stakeholders about their project-related uncertainties.

Fifthly, the construction of the IHPD-framework was inspired by existing port development frameworks such as Ligteringen (2017) and Zheng (2015). However, the main differences between regular port development and hydrogen port development must be pointed out. The most significant difference with ordinary ports is an increased level of uncertainty due to the novelty of the products and markets. Therefore, this framework necessitates more steps and includes stakeholders at an earlier stage. Where regular ports already have defined cargo streams and can immediately start with flow forecasts, a hydrogen port relies on a national strategy and co-creating new markets. Because the hydrogen economy is still developing, a hydrogen port should factor in a lot more flexibility to change over time. Therefore, the IHPD-framework extensively focuses on incorporating uncertainties. Another big difference is the fact that a hydrogen port complex will not import goods for hinterland purposes but rather only produce and distribute. Furthermore, hydrogen ports should take into account more safety aspects because of the handling of toxic and explosive goods and should take into consideration changing laws and regulations. These factors form a gap in the literature that was filled by means of this research.

Furthermore, when determining the markets and carriers in Phase 2, two extra aspects should be highlighted. Firstly, this research has considered the combination of hydrogen for the export market and hydrogen for the domestic market. However, it should be noted that a third possibility exists of attracting foreign markets to Iceland for its cheap hydrogen (just like the aluminium smelter industry in Iceland). Not only would it create jobs, it would also offer the very long-term commitment of hydrogen purchase. Secondly, the price comparison, as displayed in section 3.6, showed that LOHCs and ammonia are the most cost-competitive but once the scale increases, LH2 also becomes cost-competitive. It must be noted that this was based on the full supply chain, including shipping, import storage, and export storage. If hydrogen is directly used in domestic applications, these costs might differ. On the other side, the costs primarily depend on the scale of production and thus rely on the scale of export. Therefore, it is recommended to run alternative cost calculations to determine the most cost-competitive carrier for domestic usage once the scale of hydrogen production is determined for export and domestic usage.

Also, although executed thoroughly, the Double Diamond method has limitations when employed in situations where the design of a system is required. The solution presents itself as a linear process whereas, in reality, design is an iterative process that requires a continuous reappraisal of context and options. To address this limitation, the final IHPD-framework includes revision steps which make the process iterative and thus satisfy modern design methodology.

Finally, this study confirms the complexity of port development in general, and more specifically, of hydrogen port complexes. This study adds insights to the field of knowledge by offering the necessary steps required to develop a successful port master plan. In this respect, sequentiality is important in order to optimise the process of data gathering and evaluation. However, it is imperative to acknowledge that the results were based on a single case study. In future projects, determining where to start and how to proceed will remain a complicated factor. The question, therefore, arises to what extent the phases and their sequentiality in this framework are replicable for other locations. Are the sequentialities universal or bound to Iceland? Although no hard conclusions can be made for other locations as they would all require their own analysis to determine the phases and sequentiality, it is estimated that the framework is applicable in a general way. However, not all phases might be of the same importance to other locations. This can be illustrated by looking at key variables such as public versus private, national versus private energy production, and customer fixed vs unknown. In case a port would be initiated by a private developer who wants to export hydrogen to a predetermined destination, then the shared vision will be more easily drafted and less dependent on the national strategy. However, the national strategy will be of equal importance as input to serve as a guarantee for support. Similarly, the markets, carriers, and governance model will be determined more clearly. Whenever, the energy can also be produced privately (say through solar panels), then the stakeholder engagement phase will be shorter. Yet, it should be done at the same moment in the sequence. For a private port, the social contribution would have to be less than for a public port, resulting in fewer efforts being spent on social cost-benefit analyses. Nonetheless, the sequencing of the phases should not change when comparing the variables above with the case study of this research.

7.2. Research limitations

This thesis study encountered several restrictions and obstacles. These are discussed below and must be considered when evaluating the data and conclusions of this study.

- Firstly, as briefly mentioned before, this research is based on a single case study. This enables to delve into a complex matter in its natural environment but limits generalised conclusions for other cases.
- Secondly, this research was performed in the Netherlands without any visits to Iceland. This limited the local contextual understanding of the case study and might have restricted the researcher from going into more depth. Especially identifying stakeholders, understanding the existing port infrastructure, and sensing the Icelandic sentiment toward hydrogen were challenging.
- Thirdly, there was a clear language barrier during the stakeholder interviews. This has strained the understanding and responses of the Icelandic stakeholders and has restricted the research from going into more depth.
- Fourthly, data collection has proven to be complicated. Of the 14 contacted stakeholders, six refused to have an interview. The three main reasons were: that the stakeholder did not support the idea of hydrogen production in Iceland, that the stakeholder did not want to speak because there was no additional project information available and that the stakeholder did not want to share information because of its sensitivity at this phase of the project.
- Fifthly, the interviewed stakeholders lacked both in-depth knowledge about hydrogen and contextual information about the project. Therefore, the project had to be discussed as being a hypothetical project. In the end, however, this made no difference as the IHPD model stands with success and is otherwise unaffected by stakeholder knowledge.
- Finally, due to time constraints and the limited scope, this research was not extensively validated. Therefore, it is recommended for future research to validate the IHPD-framework using other case studies or expert interviews.

8

Conclusion

In this chapter, the answer to the main research question is presented (section 8.1) and recommendations for the next steps are offered (section 8.2).

8.1. Answering research questions

One of the challenges to boosting the hydrogen economy is the lack of infrastructure to produce it, store it, and transport it in large quantities. The construction of infrastructure requires good coordination and significant investments. Port authorities play a key role in that regard as they bring together the necessary stakeholders of the whole supply chain. However, they are challenged with defining a long-term strategy to convince investors and other decision-makers. The many uncertainties, limited technological knowledge, and unknown societal demands constrain the development of a port masterplan. Because no hydrogen industrial port complex was constructed before, the main objective of this thesis is to fill this gap of knowledge. Hence the following main research question was posed:

> *"What does the development process of a greenfield integrated green hydrogen industrial port complex look like for the port of Fjarðabyggð?"*

The summaries to chapters 3, 4, and 5 respectively served as answers to the three sub-questions of this study. These are the basis for the following answer to the main research question.

Green hydrogen is a novel way of storing energy that currently accounts only for a small fraction of total hydrogen production. In combination with renewable energy sources, it has the potential for efficient energy export and long-term storage. In practice, the supply chain is a convoluted, inefficient process, due to current demand and usage. However, this can be highly optimized to make hydrogen a viable and efficient fuel for storage in Iceland itself and export to the port of Rotterdam. Thus, the construction of a green hydrogen industrial port serves as a solution to multiple, both global and national, threats such as global warming and the geopolitically sensitive import of fossil fuels. The recent oil and gas price increases, due to the situation in Ukraine, are pressing eye-openers to the urgency of the matter. With its wide range of applications, hydrogen is the best substitute for fossil fuels.

This research has shown that the development of such a system is not a technical challenge but rather depends on strategic decision-making. Where regular port development projects, such as a container terminal expansion, are a direct answer to changing market conditions, hydrogen ports are faced with extremely higher uncertainty in markets. This has an impact on the scale of production and the choice of hydrogen carrier. The chicken and egg causality problem of existing markets that will only switch to hydrogen if there is ample availability at a low price and producers who will only start producing hydrogen at enough demand must be broken through by a solid political strategy that stimulates both sides and gives them a direction. Added to this is the fact that hydrogen production in Iceland is only possible if more energy plants are built by the national energy companies, which requires political approval. Without a national strategy, it has proved impossible in this study to properly map out the desired system because there are simply too many uncertainties, the scope reaches beyond the feasibility of a master thesis, and the system design requires contextual insights. Therefore, it has been decided to road-map guidance for the creation of a long-term master plan in the form of an 8-phase model. This so-called Integrated Hydrogen Port Development framework is an interconnection of important components involved in the project.

The framework starts with creating a national hydrogen strategy and defining a shared vision amongst the port initiators as the basis for the future port project.

Consequently, the right markets and carriers must be chosen. Here a balance must be found between production for the domestic market and the production for the export market. Ideally, a combination of the two is made because the export market enables it to reach economies of scale and thereby reduce the final cost of hydrogen, while the domestic market should be served to meet the domestic climate ambitions. Identifying export markets is a matter of finding existing industries through collaboration with other ports such as Rotterdam. On the other hand, the domestic industry still has to be created. Therefore in-depth conversations should be held with the following industries: heavy trucking, public transport, private transport, fertiliser production, shipping industry, fish plants, and fish farms. It was estimated that the yearly domestic hydrogen demand could reach 322 kilo tonnes and the total annual hydrogen demand from Rotterdam could reach 4 000 kilo tonnes. The choice of carriers will mostly depend on clients' wishes but when designing the port, special attention must be paid to each carrier's specific safety requirements.

In phase 3, an in-depth stakeholder analysis must be done and a stakeholder engagement strategy must be written. The identified key stakeholders must be interviewed to define key values as design- and evaluation criteria later in the process.

Next, in phase 4, the port organisation should be specified in terms of port functions and port governance model. For the port of Fjarðabyggð, the landlord model came out as the best option. This way, the port authority would optimize investments by creating an attractive environment for multiple private companies to invest in superstructure while a neutral port development company focuses on common infrastructure to minimise duplication of infrastructure investments. The port authority would generate income through land leases and port dues.

Phase 5 assembles design criteria. Here flow- and shipping forecasts should be done, and port user- and port location needs should be collected. This list of functional requirements leads to planning elements. Using design formulae, the principal dimension of the port's wet and dry regions can be calculated.

Phase 6 then focuses on choosing the most suitable location for the design parameters. This is done by pre-selecting multiple locations, before analysing their physical systems. During later studies, physical factors, environmental factors, governance factors, and socio-economic factors should lead to location-specific threats. The site with the fewest adverse effects from the functional requirements and the greatest prospects for the port may be deemed the most ideal. This is also the starting point for the ESIA process to obtain the right permits, licenses, and planning consents.

The 7th phase aims to optimise flexibility by upfront addressing uncertainty. Carefully describing uncertainties helps to find the most suitable remedies for vulnerabilities and objectives for opportunities. To determine appropriate measures, either seizing-, shaping-, mitigating-, or hedging actions should be planned.

Finally, in phase 8, the actual port can be designed. Multiple layouts should be made that respond to the location-specific threats and align with the port's needs. Consequently, the preferred alternative (or a mix of) should be chosen through a Multi-Criteria-Analysis. The earlier defined key values should be used as evaluation criteria. Then (social-)cost-benefit analyses should be run to evaluate the added value of the port. Eventually, the concluded shared vision, the port design with multiple phases, and the plan to serve distinguished markets should be consolidated into a long-term final master plan to serve as a comprehensive and flexible roadmap that outlines the port's future expansion and development. The final master plan serves as basis for the final investment decision. The ESIA must also be completed and the permits, licences and planning consents must be received.

Despite the limitations of this research, the researcher believes the aforementioned framework contributes to the field of research because the discussion showed that the model could be applied to other locations in future projects. It is now up to the government of Iceland and the port authority of Fjarðabyggð to follow the IHPD-framework to make a socio-economically attractive case that can meet the domestic and international demands. It is advised to act better sooner than later to get ahead of international competition and secure a share of the world's largest import ports that takes the lead in realising a global hydrogen economy.

8.2. Recommendations

In the future, the framework can be further improved and applications of the framework can be explored. Improving the level of detail and framework validation can increase the overall reliability. In addition, there are several topics that the dissertation is limited to. The topics out of scope remain highly relevant and should be thoroughly investigated prior to the construction of a final proposal. This section discusses practical next steps and recommendations for possible future research as listed below:

- In this study, only one case was analysed. To further develop and validate the IHPD-framework, the theory would have to be applied to other cases (with different contextual circumstances) too. A lot can be learned from its successes and barriers.
- The credibility of the created framework could be increased by doing more stakeholder interviews during the next research.
- The validity of the framework should also be enhanced by interviewing experts in the industry.
- Further research should enhance the framework so that it may also be applied to brownfield situations. This will be extremely useful as it is anticipated that for some hydrogen carriers, no new terminals will be developed, but rather current terminals will be modified.
- This research indicates that flexibility in planning is required to meet the many uncertainties ahead. This can be reached through the construction of multiple different carriers instead of one, through building in a modular way to allow for later adaptations, or through development in multiple phases. However, in the IHPD-framework, flexibility is not rewarded monetarily, despite the fact that it might be enormously profitable. It is therefore recommended to investigate the valuation of port flexibility to a greater extent.
- Because of the research limitations as described in section 7.2, it is recommended to perform further case-related research in an Icelandic setting by either travelling to Iceland or collaborating with an Icelandic researcher. It goes without saying that an Icelandic person doing the research would be optimal.
- Section 4.2 briefly highlighted the parallel process of doing Environmental and Social Impact Assessments (ESIA). The IHPD-framework has not taken these into consideration. Therefore, incorporating the ESIA factors could be a topic for further research. As this is subject to national, regional, and/or local authorities, doing multiple case studies is recommended.
- This study investigates four hydrogen carriers (Ammonia, DBT, MCH, LH2). Yet, additional carriers, including methanol, ethanol, formic acid, and sodium borohydride, have been omitted. To provide a more complete picture, these hydrogen transporters should be incorporated into future research.
- Due to limited project information and in-depth hydrogen knowledge among the interviewed stakeholders, few uncertainties could be identified in this research. This would change after having gone through the first 6 phases. Further research could be done into the typification of specific hydrogen port-related uncertainties to further detail and concretise phase 7 of the developed framework.
- This research discussed literature on systems mapping. Due to the novelty of hydrogen ports, systems mapping theories could not be applied at this stage. However, once the Icelandic port has been constructed, it would be very valuable to map the system for future hydrogen port development projects.
- The framework should be extended so that multi-modal transport scenarios may also be addressed. This would be of added benefit because these scenarios are likely to arise in the future.
- Possible technical advancements within the supply chain components of the carriers require more study. For NH3, a very well-developed supply chain can already be established. However, the supply chains for LH2 and LOHCs are still in the development phase. Consequently, there is a great possibility for technical innovations in these supply chains that might drastically influence the choice of carrier. Studying the influence of technological development on the phasing of a port could strengthen the IHPD-framework.
- This research demonstrates the importance of a national hydrogen strategy. Further research could be done into the essential information required for port development and the impact of such a strategy on a port development project.
- The choice of hydrogen carrier is not easy as numerous elements have to be taken into consideration. This research suggested a MCA as a tool. However, such a tool is subject to subjectivity and does not include learning from previous projects. Therefore, through research, a tool could be developed to assist in carrier decision-making.
- The IHPD-framework was developed for hydrogen-producing, exporting port complexes. However, the importing port has been left out of the picture. Further research could be done into the development process of an importing port or a combination of the two.
- This research displayed the reluctance of the local population to support industrial expansion. The origins of these opinions must be further investigated as the local population are key stakeholders and could resist the fluid implementation of the project. Further studies could be performed on engagement strategies as such.

9

Reflection

This chapter covers the discussion of the personal process of writing this master thesis by means of a self-reflection. As one does not simply learn from experience, but from reflecting on experience. Section 9.1 first runs through the process before section 9.2 concludes with a couple of personal takeaways. Finally, section 9.3 offers a few points for future students to take consider while writing a thesis.

9.1. The practical thesis process

I approached my thesis with an open mind, without knowing precisely what I wanted to concentrate on. While orienting, I had an elaborate list of topics I a) unquestionably wanted to learn more about and b) deemed interesting enough to uphold my zest throughout the thesis trajectory. I was equally looking for a timely topic with which I could feel like I was making a contribution. Eventually, the combination of port development and hydrogen production stood out in that regard. Whilst narrowing down the topic and speaking with various firms, I stumbled upon the paradox of the hydrogen industry being eager for more research but simultaneously overloaded with work and struggle to find the time to supervise students. This resulted in an extensive search process and a delay of four months. However, the offer of the Port of Rotterdam was worth the wait and I was ecstatic that I was given a chance to delve into this topic. Looking back, I indeed made the right choice, and I'd like to portray three chronological key moments that deserve reflection.

The first key moment was right after the kick-off meeting. Leading up to the start of the research, I had already done a fair share of literature research and wrote a rather elaborate research proposal based on theories of back casting. The rigorous scientific foundation and the clearly defined direction enabled me to convince both myself and the committee of my approach. However, on the assumption that my research had to be academically sound, I forgot about the applicability to practice. I soon realised I did not know how to work my plan out for the case study and I would have to look at my topic from a different perspective. It required a more agile approach of analysing the practical problem before finding the correct academic answers.

The second pivotal moment occurred after I had changed scope once again. Because bridging the gap between the practical Icelandic context with academic frameworks seemed impossible, I developed the urge to include an Icelandic port researcher in my committee. This led to a bundle of new expectations and steering directions, resulting in more confusion about what to do and how to do it. The bigger picture became blurry and it felt like my own thesis became more a matter of project managing, rather than doing the actual research. However, only after having downsized the graduation committee and re-aligning the expectations, I realised that I had learned from the experiences of involving other people. In fact, bundling the different angles led to the solution that eventually answered my main research question. Although I had described my research as iterative beforehand, it was only then that I found out what the diverging and converging components of design truly meant.

The final fundamental moment took place before the green-light meeting. I had worked out my suggested new framework and written my report. Although I was satisfied with the result, throughout the entire process, I was anxious the result would not meet the expectations of my supervisors. With my tails between the legs, I handed in my report and was counting on the disappointment of my supervisors. Per contra, the supervisors commented that this was quite precisely in line with their expectations and that they were sufficiently content with the result. It made me realise that, due to the individual nature of this thesis, I had filled in the expectations of others by myself. Unfortunately, this has caused a gnawing feeling throughout the whole period. In hindsight, I should have spoken up about these feelings to discuss a more realistic portrayal of expectations. After all, the supervisors have been at the side-line throughout the entire process and do not solely base their expectations on the end-result.

9.2. Lessons for personal development

Truth be told, writing this thesis was not an easy task for me. But is anything ever which challenges you and brings you out of your comfort zone? On a more relevant note, I am happy with the result and I learned a lot from the process, as difficulty creates an opportunity for self-reflection. The previous section highlighted some challenges faced throughout this process. This section covers a few personal points I will take along to my professional career.

- *planning:* I learned that my strengths can be found in planning and preparing for work to be executed. Compared to my peers, I felt I was always well-organised and had clear planning. After every change of scope, planning was always the first thing I did.
- *perfectionist*: although cliché, I realised I can be slightly too perfectionist. That is why it took me so long to decide on a suitable subject. Furthermore, because I aspired to write accurately from the start, I often suffered from writer's block. However, this often also resulted in very long and detailed descriptions, which sometimes was unnecessary. Unfortunately, when I didn't receive the results I anticipated, it often led to frustration. In the future, I should embrace imperfections in an attempt to learn from them and polish them to the desired result instead of requiring the perfect result from the start.
- *choices*: I am quite impressionable about the expectations of others. This has challenged me at times to make up my mind and choose my own path. I realise that, at times, I was too fixated on the bigger picture and avoided going in a specific direction. During my next projects, I should embrace choices early on and trust that making choices eventually will result in a more convincing and unique narrative.
- *team player*: I struggled quite a bit with the individualist approach of having to trust the process. Deep down I had faith in myself and was confident that things would fall into place eventually, but I was doubtful whether the process was going to get me there, not least because I was the one in charge. My strengths come out better when I work in a team and can constantly discuss with the people around me.
- *emotions*: because this thesis was the single and last project of my degree, it not only took all of my time for the past year, it also occupied all of my thoughts. I struggled with stopping a constant stream of thoughts. Every minute of the day, random thoughts popped up, often leading to long ruminating behaviour. At first, I tried to stop this by writing down all my thoughts immediately. This proved to be a good yet temporary solution. In the long run, this only accumulated into many stand-alone notes without any further context and applicability. The ruminating eventually also started to express itself emotionally. These emotions often obstructed logical reasoning and seeing the bigger picture. This thesis process taught me ways to deal with these emotions. By means of mindfulness and meditation, I eventually managed to decrease the rumination and balance my emotions. This is definitely something I plan to continue doing throughout my professional career. I learned that I am only capable of breaking bigger problems down into smaller manageable chunks when my mind is in balance.

9.3. Lessons for future thesis students

The previously described experiences could contribute to the successes of future students. Therefore, this section summarises a few tips for the thesis students of the future.

- Choose a subject you are passionate about but don't stare yourself to pieces and embrace discovering new interests.
- Create an environment where expectations can easily be made explicit from both sides.
- Trust the graduation process. Eventually, everyone will get through it.
- Maximise structure and rhythm to organise the thought process and maintain a balanced life. Setting both small and big deadlines helps in this regard.
- Start writing as soon as possible. This visualises your progress and keeps you motivated.
- Prioritise your mental well-being by continuing to do social activities, sports, and meditation (or what gives you peace).

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A

Stakeholder interviews

A.1. Onepager for interviewee

Thesis research by Sief Andriopoulos
On behalf of the Technical University in Delft and the Port of Rotterdam

Introduction
Nowadays, climate change is at the centre of the daily debate. While recent effects of climate change have refuted the last arguments of climate change sceptics, many governments have set their targets on the 2015 Paris agreement and renewable energy projects are being constructed rapidly to replace fossil fuels. However, the main disadvantage of renewable energy generation is its intermittent character, resulting in a mismatch between energy supply and demand. Hydrogen generation as a means of energy distribution and storage is seen by many to be a viable solution to this challenge. It can be produced using renewable energy sources, including hydro-, wind-, wave-, solar-, biomass-, geothermal energy, and non-renewable energy sources like coal, natural gas, and nuclear power. It may be stored as fuel and utilised in vehicles, power production systems employing fuel cells, internal combustion engines, and turbines. Therefore, hydrogen is considered a flexible energy carrier because it can be produced by any energy source and can be converted into various energy forms.

Opportunity statement
In general, one of the challenges to boosting the hydrogen economy is the current infrastructure need. Building hydrogen supply chain infrastructure (power supply, production plants, storage facilities, trans-shipment) needs strong coordination. Significant investment is involved with substantial risks. A dependable supply chain is one in which all the components are adequately integrated. The creation of a Hydrogen supply chain, using sustainable energy, necessitates thorough design, planning, and optimisation approaches. Iceland has a great potential to develop abundant green hydrogen. To realise this, it will be necessary to develop a long-term strategy to attract potential developers and align stakeholders. Prior to creating the strategy, research must be undertaken to define system requirements, future scenarios, and thereby develop a road map. This roadmap should take into account the interests of all stakeholders. The ultimate goal of the roadmap is structuring the decision-making process. The roadmap must include decision moments, actions and phases, and serve as a guide to making a hydrogen supply chain a reality. Before creating the roadmap, an overall perspective is needed to understand local needs and constraints, to sketch out the system requirements and develop a design brief. By means of interviews and desk research, the entire system will be mapped, taking into account the different stances of stakeholders and port developers. My research will focus on a hypothetical new hydrogen port facility in Iceland that incorporates functions such as production, storage and export, and uses electricity supply, water and local employment as a key input. The final applications are manifold.

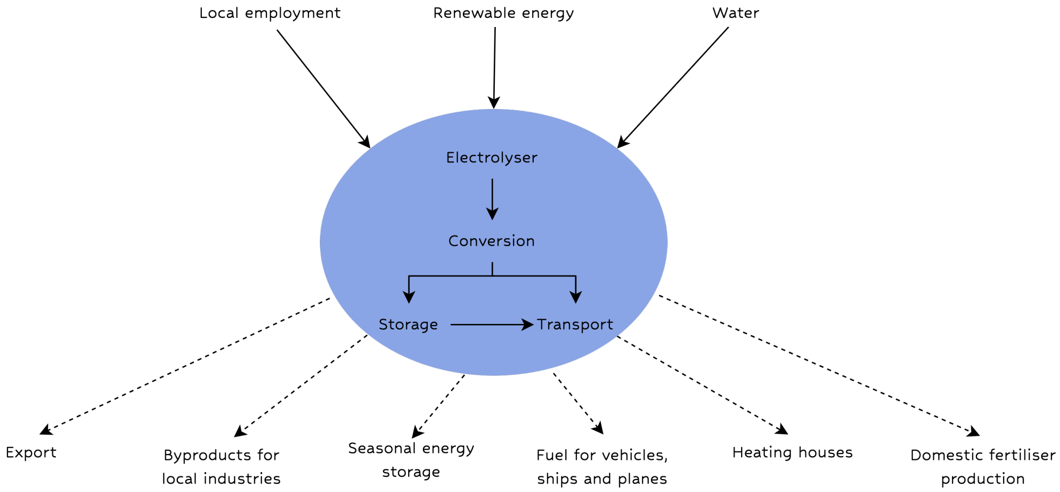


Figure A.1: Schematic overview of port complex for interview onepager

Interviews

The objective of the interviews with stakeholders across the supply chain, and in the local and national community, is to collect information on several key aspects:

- their opinion of the hydrogen port development;
- their knowledge about the system;
- their requirements to make it into a successful project.

The interview will be structured in a way that the interviewee has a chance to explain by first talking about their stance on the development of the hydrogen port, before talking about their knowledge of the system in different categories. Broadly speaking, the interview will address the following questions:

- Under what conditions do you support/ object to the construction of a hydrogen industrial port complex?
- What general requirements does the port/system have to fulfil in your eyes?
- What are the physical components of the system?
- What technical requirements are essential for designing the system?
- Which operations are necessary to operationalize the system?
- What local markets/industries could be benefitting from hydrogen production?
- What permits do you need to develop such a system?
- Is there a governmental policy in place that allows for the development of such a port?

A.2. Interview protocol

General information

- interviewer: Sief Andriopoulos
- contact details interviewer: j.andriopoulos@student.tudelft.nl - +316XXXXXXXX

- interviewee: XXX
- contact details interviewee: XXX
- organisation interviewee: XXX
- function interviewee: XXX

- date: XXX
- location: XXX
- duration of interview: XXX

extra questions what permits will need to be obtained what will be bottlenecks in the esia here? what components does the esia have?

Introduction (10 minutes)

To start off, I will shortly introduce myself.

- Master Construction Management & Engineering as part of the faculty of Civil engineering at the Technical University of Delft in the Netherlands.
- Currently in the final phase, for which I have to do this 6-month research project.
- Am performing this research in the form of an internship at the Port of Rotterdam authority because of their aim to realize a global hydrogen economy. However, you must know that my research is of independent nature and has an academic focus. Also, the research into a hydrogen port for Iceland is merely hypothetical and no concrete plans for an actual hydrogen industrial port complex exist so far.

Before we continue with your introduction, more information about the research and the actual interview questions, I would like to set some conditions for this interview.

- I would like to record this interview for processing purposes. Will you allow me to record this interview to ensure validity? -> YES on tape?
- If anything is unclear or if I am going too fast, please feel free to interrupt and tell me to slow down or repeat.
- Also, feel free to take as much time to think as you want.
- Your answers will be treated confidentially, so answer freely.
- Anonymity is guaranteed; recordings are deleted and are only viewable by my supervisor.
- Do you have any further questions beforehand?

In that case, I would like to ask you to briefly introduce yourself.

- What is your name?
- Where do you work?
- Could you tell me a bit more about the organisation?
- What is your function there?
- Could you tell me a bit more about the current port (numbers, facilities)?

Then, I would like to ask you a bit more about your awareness of, or involvement in, hydrogen-related activities in Iceland.

- Are you aware of the advantages and disadvantages of hydrogen as an energy carrier?
- Are you familiar with the idea of a hydrogen port complex to produce, store and export hydrogen?
- Are you involved in setting up a hydrogen economy in Iceland? If so, in what way and at what moment in the process?

Topics (45 minutes)

Q1. Do you support the creation of a hydrogen industrial port complex in Iceland? Is it attractive to you?

  - why?
  - if yes, what added value does it offer you?
  - if yes, what are the biggest steps that need to be taken?
  - if yes, what are the most important decisions that have to be taken?
  - if no, which part are you against?
  - if no, a new industrial port or hydrogen in general?
  - if no, traffic, safety, economic uncertainty, nature conservation?
  - if no, when would you reconsider?

Q2. Under what conditions could you support the idea?

  - what is the use of a hydrogen port complex for you?
  - would it be an extension of the current port?
  - what type of collaboration? landlord model,...?
  - would you share storage and export facilities with other developers?
  - what are your interests?

Q3. Who do you depend on in taking your actions and who depends on you?

  - why?
  - in what way?
  - also the other way around?

Q4. As i understand, currently there is no excess energy. Could this port only be build if the wind law changes? What is the law and what does it say?

Q5. According to you, what are uncertainties in the planning of a hydrogen industrial port complex and how could you deal with them?

  - increasing demand?
  - technological innovation?
  - increasing vessel sizes?
  - uncertain markets?

Q6. What general requirements does a port/system have to fulfil in your eyes?

  - technical requirements?
  - for commercial contracts?
  - for operating the system?
  - costs?
  - safety?
  - maximize production?
  - minimize land usage?
  - own provision vs export?
  - social requirements?
  - environmental requirements?
  - would you choose for 1 carrier or go for multiple? Why?
  - would you rather have centralized or decentralized electrolysers? why?
  - would you choose for 1 carrier or go for multiple? Why?
  - what is the prioritization?

Q7. What local markets/industries could be benefitting from hydrogen production? (What are the byproducts that could be used locally?)

  - housing industry?
  - nearby housing needed for external labour employees?
  - waste heat produced by electrolysis for district heating?
  - local labour forces?
  - the industry with the need for hydrogen in their processes?
  - synthetic ammonia for the fertiliser agriculture industry? is it going to grow? now importing?
  - filling stations for vehicles, trains, (fishing)ships?
  - oxygen (produced by electrolysis) for the steel and cement industry?

Q8. What (local or central) governmental policies are in place that allow/counter the development of such a port?

  - what is the impact of local/ national elections?
  - new wind law?
  - who influences these changes? environmental groups? lobby groups?
  - how could this be mitigated?

  - at what level? what government?
  - what would have to change?
  - over what period of time could this change?
  - and specifically for onshore windfarms? what needs to change to develop this?

Q9. What decisions need to be taken before the final investment decision?

Q10. What permits do you need to develop such a system?

  - national law or regional law?
  - new wind law?
  - environmental? what are the components of an EIA?
  - safety?
  - land allocation?
  - water allocation?
  - planning? on what timescale?
  - who issues these permits?
  - what influences these permits?

Closure (5 minutes)
I see we have gone through the planned duration of the interview and I think we have covered all topics, so this might be a good moment to wrap up. Do you have any comments or issues you would like to raise that you feel may not have been covered during the interview? Do you have any further questions for me? May I contact you again to follow up? (Are you interested and motivated ?)

As part of this research, I would also like to talk to other potential stakeholders that could be involved in or could have some useful input, in the planning of such a hydrogen port development. Do you have any suggestions on who I could contact? Can you introduce me?

Thank you very much for your time, your participation is greatly appreciated. Should you have any further questions, please do not hesitate to contact me by mail or telephone. May I note your details for further contact? (name, mail, phone number)

Extra: interjections
- Why?
- What do you mean by that?
- Could you tell me something more about…?
- Could you specify?
- Is that a general characteristic?

B

Sequentiality of the IHPD-framework

A fundamental characteristic of the IHPD-framework is its specific chronological order. Table B.1 on the next page displays the information input per step. The left two columns are the eight phases with corresponding steps. The right two columns specify what information is required for the concerned steps and in which step this information is obtained.

Phase	Step	Required information	From step
1. H2-vision	1.1 National strategy	-	-
	1.2 Draft shared vision	National targets and regulatory framework	1.1
2. Markets	2.1 Markets	National targets	1.1
		Shared port vision	1.2
	2.2 Carriers	National targets	1.1
		Shared port vision	1.2
3. Stakeholders	3.1 Identify stakeholders	Markets	2.1
		Carriers	2.2
	3.2 Make engagement strategy	List of stakeholders	3.1
	3.3 Determine key values	Shared vision	1.2
		Key stakeholders	3.2
4. Governance	4.1. Define port functions	Shared vision	1.2
	4.2 Select port governance model	Shared vision	1.2
		Key stakeholders	3.2
5. Design parameters	5.1 Make flow and shipping forecasts	Markets	2.1
		Carriers	2.2
	5.2 Describe port needs	Shared vision	1.2
		Key stakeholders	3.2
		Flow and shipping forecasts	5.1
6. Location	6.1 Find physical suitable locations	Port needs	5.2
	6.2 Understand the systems	Suitable locations	6.1
	6.3 Select most suitable location	Key values	3.3
		System understanding	6.2
7. Uncertainties	7.1 Map uncertainties	List of stakeholders	3.1
		Port functions	4.1
		Time horizons	5.1
		Selected location	6.3
	7.2 Plan actions	List of uncertainties	7.1
8. Design	8.1 Make concept layouts	Key values	3.3
		System understanding	6.2
		Actions for uncertainties	7.1
	8.2 Test and evaluate layouts	Key values	3.3
		System understanding	6.2
		Concept layouts	8.1
	8.3 Create final design	Preferred layout	8.2
	8.4 Perform cost benefit analysis	Shared vision	1.2
		Final design	8.3
	8.5 Write final masterplan	Shared vision	1.2
		Time horizons	5.1
		Final design	8.3
		Cost benefit results	8.4

Table B.1: Required information input per step of the IHPD-framework

C

Required energy plant calculation

Phase two of the IHPD-framework covers the determination of markets and carriers. This appendix covers the calculation of the number of plants required to meet the maximal hydrogen demand.

Calculating the energy demand

The preliminary study showed that a 20 TWh power plant would be sufficient for the production of 420 000 tonnes of hydrogen per year (Coopman & Halgrimsson, 2021). This means that 1 TWh power plant could produce 21 000 tonnes of hydrogen per year.

Maximal domestic demand

Section 6.2 explained that 321 608 tonnes of hydrogen per year is required to replace the current crude oil imports in Iceland. When adding the extra 338 tonnes of hydrogen per year to replace the fertilizer imports, the roughly estimated total demand could go up to 321 946 tonnes of hydrogen per yer. This would mean an energy demand of 15,33 TWh per year.

Maximal demand from Rotterdam before 2030

The total demand from Rotterdam before 2030 could go up to 4 000 000 tonnes of hydrogen per year. This would mean an energy demand of 190 TWh per year.

Calculating the production capacity

The hourly production capacity of renewable power plants can be calculated by multiplying the optimal power generation per hour with its capacity factor. This number should also be multiplied by 365 days and 24 hours to determine the yearly production capacity.

Yearly production capacity of wind turbines in Iceland

For the number of wind turbines, the planned 7.5 MW turbines (Landsvirkjun, n.d.) and a capacity factor of 0,45 (Coopman & Halgrimsson, 2021) have been taken into account.

$$7,5MW * 365 * 24 * 0,45 = 29.565MWh/year$$

Yearly production capacity of geothermal plants in Iceland

For the geothermal plants, the current largest Icelandic plant was considered with a capacity of 303 MW (NA Energy Staff Writer, 2021) and a capacity factor of 0,87 (Ragnarsson et al., 2021).

$$303MW * 365 * 24 * 0,87 = 2.309.224MWh/year$$

Yearly production capacity of hydro plants in Iceland

For the hydropower plants, the current largest Icelandic plant was considered with a capacity of 690 MW (Visitegilsstadir, n.d.) and a capacity factor of 0,85 (Coopman & Halgrimsson, 2021).

$$690MW * 365 * 24 * 0,85 = 5.137.740MWh/year$$

Calculating the number of plants required

The number of plants required can easily be calculated through dividing the demand by the production capacity per plant.

- Wind domestic: $\frac{15{,}33 TWh/year}{29566 MWh/year} = 519$
- Wind Rotterdam: $\frac{190 TWh/year}{29566 MWh/year} = 6427$
- Geo domestic: $\frac{15{,}33 TWh/year}{2309224 MWh/year} = 7$
- Geo Rotterdam: $\frac{190 TWh/year}{2309224 MWh/year} = 83$
- Hydro domestic: $\frac{15{,}33 TWh/year}{5137740 MWh/year} = 3$
- Hydro Rotterdam: $\frac{190 TWh/year}{5137740 MWh/year} = 37$

Market	**Yearly hydrogen demand [tonnes H2/year]**	**Energy required [TWh/year]**	**Wind turbines [-]**	**Geothermal plants [-]**	**Hydropower plants [-]**
Maximal total domestic demand	321 946	15,33	519	7	3
Maximal demand from Rotterdam before 2030	4 000 000	190	6 427	83	37

Table C.1: Roughly estimated energy plant requirements

D

List of identified stakeholders

Phase 3 of the IHPD-framework consists of the identification and engagement of stakeholders. This was applied to the case study in Iceland. The identification resulted in the following list of categorised stakeholders.

Internal

I1 Port Authority: is in charge of the operation of the harbor fund and all development of port areas. The Fjardabyggd port forms an independent business unit within the municipality's institutional system. The guiding principles of the port authority is that all customers are provided with excellent service in all areas of port operation. Their aim is to grow in size, increase income, and take a leading role in hydrogen export and distribution.

I2 Construction Division: handles the day-to-day management of the harbor on behalf of the port authority and is therefore in line with the interests of the initiator. The division manager is the head of the port's employees, handles communication with stakeholders, and cooperates with the Property, Planning and Environment Committee. Their aim is to execute the decisions taken by the Port Authority and operate the multiple ports in the best possible way.

I3 Town Council: is in charge of institutions and companies on behalf of the town, acts on behalf of the municipality and looks after the interests of the municipality and its residents. Their current goal is to build the HIPC in order to increase the economic activity in the town and boost the reputation of the Eastern region. However, upcoming elections might change this goal.

I4 Property, Planning and Environment Committee: deals with asset management, utilities, service and equipment centers and traffic and traffic safety issues. They formulate the town's policy regarding structures and their supervision, nature conservation and environmental issues. Their aim is to enable the construction of the port while taking into account environmental and safety aspects.

External

E1 association of industries

E2 federation of icelandic industries

E3 association of fisheries companies

E4 Icelandic Aquaculture Association: represent all Icelandic fish farmers in one unified organization in order to safeguard their mutual interests. Fish farmers could be benefitting from the hydrogen production by using the by-product oxygen.

E5 Port Association of Iceland

E6 Icelandic Regional Development Institute: promote rural settlement and economic activity, with special emphasis on the creation of equal opportunities for all inhabitants to employment and habitation. In accordance with its function it prepares, organizes and funds projects and provides loans with the aim of bolstering regional settlement, boosting employment and encouraging innovation in business and industry.

E7 Iceland Renewable Energy Cluster: joint platform for companies that together manage the energy resources of the country. The main role of the cluster is to increase competitiveness of its members and represent what they have to offer. The energy cluster represents all stakeholders of the energy sector value chain.

E8 European Sea Ports Organisation: ensures that seaports have a clear voice in the European Union, represents the common interests and promotes the common views and values of its members to the European institutions and its policy makers. Their goal is to create understanding of policy initiatives

E9 Icelandic environmental association (Landvernd): aims to safeguard Icelandic nature from the increasing demand of energy for heavy industry. It runs a number of educational programs, its lobbying takes place at all levels, and it is active in writing reviews on parliamentary bills and motions and on local, regional and national planning of municipalities and the government.

E10 shipping lines: currently running shipping lines aim to increase their amount of trips. However, currently they can not carry any hydrogen-related product. It therefore is a race to pioneer in this new sector. It could be a new business that increases their fleet. Besides, the growing pressure on fossil fuels for the marine industry will force the shipping lines to using e-fuels.

E11 insurance companies

E12 Municipality Credit Iceland: is a limited liability company owned by all Icelandic municipalities to offer financing for municipal borrowing needs. Its objective is to secure loans on favourable terms to Icelandic municipalities, their institutions and enterprises for projects of general public interest.

E13 aluminium smelters (Alcoa): use local renewable energy sources to produce alimunium and export it. Their plants are located next to the existing port infrastructure and use the port to inport the raw product and export the aluminium. Their goal is to increase production and reach carbon-neutrality. Currently, their process still produces carbon-emmisions. These could be used in the production of methanol. Aluminium smelters would not be competing for electricity as they have a 40-year contract with fixed price and supply.

E14 energy grid operator (Landsnet): Landsnet is the only operator. It owns and operates the whole transmission system and has the exclusive right to construct new facilities. It is a public company that is owned by the four big energy producers. Their goal is to serve the energy producers.

E15 energy producers (Landsvirkjun): in total, Iceland has four energy producing companies. Landsvirkjun, the national power company, is the largest and the only one operating in the Eastern region. It's goal is to maximize the value of Iceland's renewable energy sources is a sustainable and efficient manner. The company intends to produce more energy for the purpose of hydrogen production. This intend is confirmed after signing a Memorendum of Understandig with the Port of Rotterdam to explore all possibilities.

E16 fuel importers and distributers (N1, Skeljungur): aim at providing fossil fuels for the transport and fishing sector. They could play a significant role in distributing hydrogen and e-fuels for the Icelandic market.

E17 hydrogen plant developers (CIP, Mitsubishi power): aim to build and operate the plants and maximize production. Before investing in the costly infrastructure, they need the commitment from long-term offtakers.

E18 fishmeal factories: produce ground powder made from cooked fish, used for fertiliser and animal feed. The large factories currently use large steam cookers and conveyer belts, run on fossil fuels. The numerous Icelandic factories could be benefitting from the applications of hydrogen.

E19 cruise lines: aim to maintain their accessibility to the existing port and attract more tourists to the area, and on the other side also increase using green fuels. The creation of an industrial complex could reduce the attractiveness of tourists. However, the cruise industry is a pioneer to reduce emissions and environmental impact using green fuels and could be a large offtaker.

E20 storage companies: are specialised in the storage and handling of large amounts of liquid or gaseous chemical products. They serve as independent player to provide a common user facility. They aim to maximalize their storage capacity and amount of calls to increase revenues.

E21 international import terminals (Port of Rotterdam): aim to import large amounts of cheap hydrogen and aim to set up long-term supply chain with exporting ports.

E22 international offtakers: aim to import cheap hydrogen. They are of importance to reach a large scale of hydrogen production, which will lower the overall price.

Legislation and public policy

L1 the Environmental Agency of Iceland (Umhverfisstofnun): operates under the direction of the Ministry for the Environment and Natural Resources. Its role is to promote the protection as well as sustainable use of Iceland's natural resources, as well as public welfare by helping to ensure a healthy environment, and safe consumer goods.

L2 consumer agency (Neytendastofa): is one of the governmental agencies in Iceland which is entrusted with market surveillance of business operators, good functioning and transparency of the markets in respect to safety and consumers legal rights as well as enforcement of legislation adopted by the Icelandic Parliament for protection of consumers health, legal and economical rights. This agency will look after the safety aspects of using hydrogen for domestic markets.

L3 the National Energy Authority (Orkustofnun): exists to advise the Government of Iceland on energy issues and related topics. They license and monitor the development and exploitation of energy and mineral resources. They regulate the operation of the electrical transmission and distribution system and they promote energy research.

L4 the Icelandic Transport Authority (Icetra): is responsible for the administration and supervision of aviation, maritime and road traffic safety and the safety and supervision of transport infrastructure and navigation systems. For this port case, Icetra is responsible for preparing and publicizing the adoption of new maritime legislation. It also publishes marine safety training materials and promotes training in other ways. It is responsible for port state control of foreign merchant vessels in Icelandic ports.

L5 Icelandic Coast Guard: is a law enforcement agency that is responsible for search and rescue, maritime safety and security surveillance, and law enforcement in the seas surrounding Iceland.

L6 the icelandic road and coastal administration: is a state run institution in Iceland whose purpose is to construct and maintain roads and infrastructure (land and sea) in rural areas and between urban areas.

L7 National Planning Agency (Skipulagsstofnun): is responsible for the administration and implementation of the Planning Act of the Ministry of Infrastructure. Its goal is to give advice on planning issues, assist local authorities in preparing spatial plans and to review and approve spatial plans produced by local authorities. Additionally, it is also responsible for preparing the National Planning Strategy on behalf of the Minister of infrastructure, and it oversees the mplementation of the EIA and SEA and provides guidelines on environmental impact assessment.

L8 ministry of foreign affairs: safeguards the interests of Icelandic citizens, companies and consumers by facilitating access to international markets and strengthening free trade. They could be important to set up Memoranda of Understanding and Memoranda of Agreement between the Icelandic parties and international parties.

L9 ministry of environment and natural resources: is responsible for most matters concerning environmental protection and nature conservation.

L10 ministry of fiance and economic affairs: is responsible for the state's financial and economic affairs, for which it formulates policy and prepares plans and budgets.

L11 ministry of industries and innovation: is responsible for state supervision and involvement in industry and innovation.

Community

C1 private landowners: aim is to either keep their land or sell it for the highest possible price. When the land is owned by the municipality, the interests are different.

C2 small neigboring markets: aim to increase profits from tourists and local habitants.

C3 neigboring residences: their aim is to seek dialogue with the municipality to preserve the surrounding nature, keep the industry out of sight, and maintain a safe living environment.

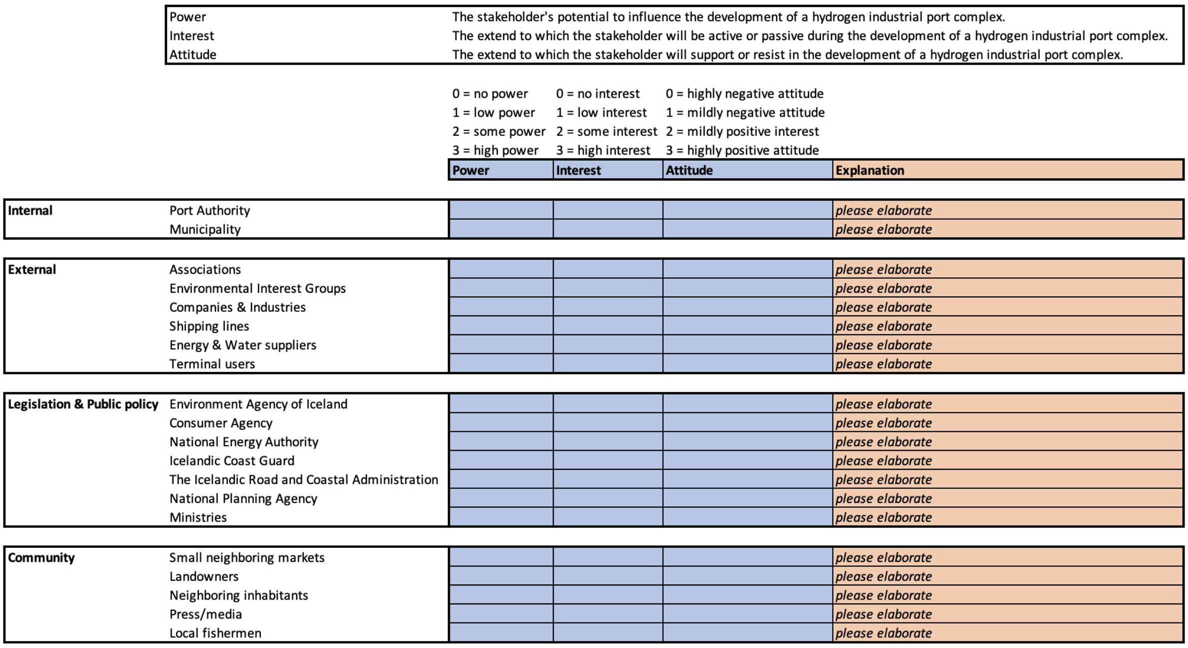
C4 press/media: aim is to inform the general public about the most recent developments. Internationally, this could attract business opportunities. Locally, their work could lead to societal support or protest.

C5 local fisherman: use neighboring ports to run their business. The construction of a HIPC leads to an increase in large vessel calls, impacting their passage. However, they could be benefitting from running of green fuel production.

E

Survey for stakeholder mapping

The following survey was sent to 3 key stakeholders to map the other stakeholders.



Power	The stakeholder's potential to influence the development of a hydrogen industrial port complex.
Interest	The extend to which the stakeholder will be active or passive during the development of a hydrogen industrial port complex.
Attitude	The extend to which the stakeholder will support or resist in the development of a hydrogen industrial port complex.

0 = no power	0 = no interest	0 = highly negative attitude
1 = low power	1 = low interest	1 = mildly negative attitude
2 = some power	2 = some interest	2 = mildly positive interest
3 = high power	3 = high interest	3 = highly positive attitude

		Power	Interest	Attitude	Explanation
Internal	Port Authority				*please elaborate*
	Municipality				*please elaborate*
External	Associations				*please elaborate*
	Environmental Interest Groups				*please elaborate*
	Companies & Industries				*please elaborate*
	Shipping lines				*please elaborate*
	Energy & Water suppliers				*please elaborate*
	Terminal users				*please elaborate*
Legislation & Public policy	Environment Agency of Iceland				*please elaborate*
	Consumer Agency				*please elaborate*
	National Energy Authority				*please elaborate*
	Icelandic Coast Guard				*please elaborate*
	The Icelandic Road and Coastal Administration				*please elaborate*
	National Planning Agency				*please elaborate*
	Ministries				*please elaborate*
Community	Small neighboring markets				*please elaborate*
	Landowners				*please elaborate*
	Neighboring inhabitants				*please elaborate*
	Press/media				*please elaborate*
	Local fishermen				*please elaborate*

Figure E.1: Stakeholder identification using the power-interest-attitude-grid

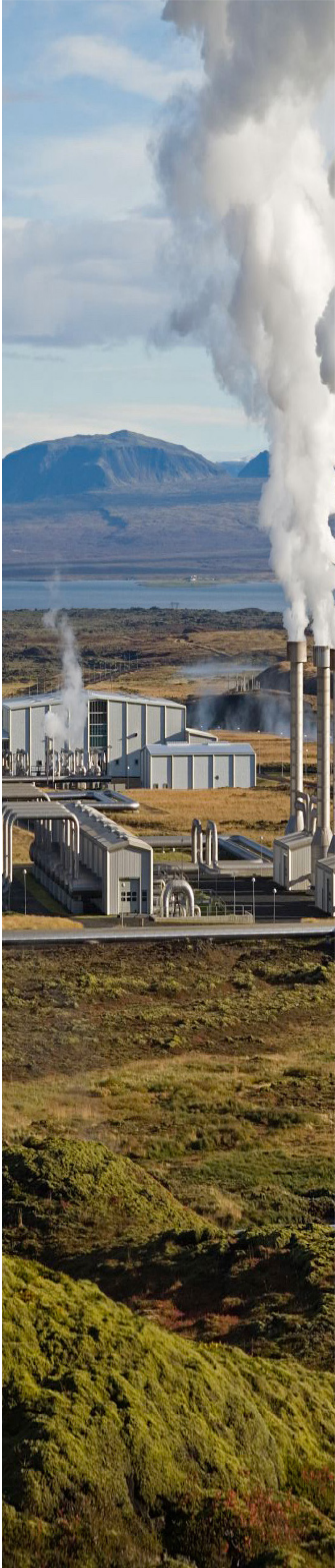
Notes

Roadmapping a green hydrogen industrial port complex

The world is faced with an unprecedented need for transitioning toward a more sustainable and durable way of energy provisioning to meet the climate ambitions and reduce fossil fuel dependency. Hydrogen generation as a means of renewable energy distribution and storage is argued to be a viable solution to this challenge because this flexible energy carrier can be produced by any energy source and can be converted into various energy forms. The energy carrier is critical for decarbonising heavy industries, heating, and transportation.

A lack of port infrastructure to create, store, and transport hydrogen in significant amounts is one of the obstacles to developing the hydrogen economy. Infrastructure development needs effective coordination and substantial expenditures. In this sense, port authorities play a crucial role in bringing together all the relevant parties in the supply chain. However, creating a long-term plan to convince investors and other decision-makers presents a hurdle.

This research aims to provide a roadmap to assist port authorities in navigating through the development process of developing a green hydrogen port complex. The resulting generic roadmap is applied to an Icelandic case study. However, because no future port environment is the same, this roadmap should be suited to the specific conditions at hand. In case you have further comments, please let me know. Otherwise, enjoy your reading.



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