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ABSTRACT

What is the potential of the Norwegian Hydrogen Market? Using secondary data from hydrogen industry reports and conferences, this paper provides a conceptual analysis of the Norwegian market situation and defines the means and measures to achieve this potential. Our research finds that hydrogen could be considered a viable alternative to Oil and Gas as one of the Norwegian most valuable resources in the future. However, to reach that point, the investing perspectives need to change in the private sector, through venture capital, as well as the public sector, as the government strongly influences investing trends in Norway. The market characteristics will also have to be considered as the local market is limited in size: partnerships and inter-country cooperation will provide access to bigger markets preventing the issue. The Norwegian market infrastructure is also particularly favorable to the development of hydrogen. If the government increases its involvement in the industry and measures are taken to lessen the risk of hydrogen development, Norway can become the hydrogen leader of tomorrow.

DEFINITIONS

Blue Hydrogen (see Appendix A): Blue hydrogen is hydrogen produced using natural gas and refinery fuel gas, and where the CO_2 that is released during production is captured and stored using CCSs (Equinor, 2022).

Grey Hydrogen (see Appendix A): Grey hydrogen is hydrogen created from hydrocarbons without capturing CO_2 (Equinor, 2022).

Green Hydrogen (see Appendix A): Green hydrogen is defined as hydrogen produced via electrolysis using power sourced from renewable sources such as offshore wind farms or solar power (Equinor, 2022).

Fuel Cells: A fuel cell uses the chemical energy of hydrogen or other fuels to cleanly and efficiently produce electricity (Office of Energy Efficiency & Renewable Energy, 2022).

Offtake Contract: Offtake agreements are contracts to purchase all or a substantial part of the output or product produced by a project (Thomson Reuters, 2022)

Private Capital: Private capital is capital that does not come from an institutional source such as a bank or government entity or any public entity.

China Five Year Plans: The Chinese Five Year plans are roadmaps provided by the government which provides guidelines and details about all aspects of development over the next five years (*Issue Brief - China's 14th Five-Year Plan | United Nations Development Programme*, 2021).

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INTRODUCTION

What innovations will enable the energy transition?

The nature of innovations and their impact on society as a whole have intrigued us throughout our studies. With climate change being at our doorstep, we wanted to study the processes that attempt to solve such overarching problems.

Technological innovation appeared to us as an interesting topic and we noticed how academia has extensively researched the field of innovation management (Chesbrough, 2003). However, we observed how certain aspects of innovation management and the transition period lacked material. We first established it as our first identified literature gap. Unfortunately, building a framework for research around the topic proved to be particularly challenging due to its purely theoretical approach. Hence we decided to seek a business partnership for our thesis which would bring practical reasoning to our analysis. BI Innovation is a sub-entity of BI Norwegian Business School which operates on the non-academic side of innovation with the university. It links up the academic activity of the university with various innovative businesses around topics such as circular economy, hydrogen, offshore wind, and more.

Hydrogen in particular has become a crucial aspect of the energy innovation and transition discussion (European Commission, "Supporting clean hydrogen", 2022). The topic became relevant for us through a class we had with Per Ingvar Olsen on energy transition which made us create a report about maritime hydrogen and how it could provide a long-term solution for the energy transition of the maritime sector. Yet, despite its apparent potential, Norway did not appear to us as a clear leader in that transition. The issue reminded us of our initial interest in transition periods and how technologies can be slower to progress on their innovation life-cycle. In addition, we believe that sustainability is a critical topic of study for social researchers in the years to come and the energy transition aspect of hydrogen plays an important role in achieving climate neutrality in the future.

The importance of hydrogen analysis was specifically shown by BI Innovation's interest in partnering with us to discuss hydrogen in our innovation transition research. They believed our thesis could bring reciprocal benefits to their hydrogen innovation projects and our future career developments. The partnership synergizes with our current program of study: Master in Innovation and Entrepreneurship. Our interests in overall innovation discussions and energy industry analysis made the cooperation increasingly relevant. Our newly found aim was to provide an overview that could help industry actors and improve the understanding of Norway's potential and why it has not been achieved yet. Creating a conceptual research paper to bridge the information about the various aspects of the industry and the literature appeared to us as a strong contribution to academia and industry.

Having all of the previously mentioned considerations in mind, we created the following research questions:

1. *What is the potential of the Norwegian Hydrogen market?*
2. *What means and measures are necessary to achieve this potential?*

To answer the research questions, we pursue the following structure: we first discuss the relevant literature for our conceptual analysis, then we explain our research design and methodology, afterward, we analyze secondary data and information available about the hydrogen industry in Norway and we conclude with a discussion on our findings and the means for Norway to achieve its hydrogen potential.

Most of our master thesis limits fall on the collected secondary data and analysis part (see Research Design and Methodology). We believe it might also be limited by the Norwegian setting and we explore the European hydrogen environment when required. Lastly, we are careful with causal inferences made during the study as they must be analyzed carefully and generalized properly (Walker, 2005).

LITERATURE REVIEW

I. Innovation Core Theories

1. Innovation management and types of innovation

Innovation management is a diverse topic that encompasses the management of change and innovation processes, starting at the initial stage of idea generation and leading to its final stage of diffusion and adoption. Today the concept of innovation is widely used and embedded in our language, even so, that it might be on the verge of becoming a cliché (Trott, 2017). However, the concept of innovation can be viewed and translated in several different ways. Understanding the notion is vital for any organization to better react to opportunities, penetrate a market, grow, survive and essentially be successful (Tohidi & Jabbari, 2012). It is important to highlight that innovation isn't a standard process, there are different ways to create value depending on the size and stage of a company (Landry, 2020). Innovation can not only be applied to products and services but several areas such as organizational processes, structure, form and values. In his study of The Innovator's Dilemma (1997) Clayton Christensen differentiates between three main types of innovation: sustaining, disruptive (low-end disruption) and revolutionary (new-market disruption).

Sustaining innovation (also called routine innovation) is described as a process that aims to improve existing capabilities in existing markets (Satell, 2017). The capabilities can include performance, price or incremental changes. When sustaining innovation takes place the problem and what skills are required to solve it are well defined and understood. Christensen (1997) describes sustaining innovation for an organization as "an effort to provide better products than their competitors and earn higher prices and margins". This type of innovation provides incumbents with a continuous advantage as they listen to customer feedback and insight to develop superior products such as Apple (Landry, 2020). However, this process also creates an opportunity for competitors to develop products and enter the low-end of the market with more favourable pricing.

As opposed to sustaining innovation, disruptive innovation is dramatic and game-changing and it happens when there is a shift in technology and the continuous innovation of existing products doesn't help (Satell, 2017). According to Christensen (1997), disruptive innovation either originates in low-end or new-market footholds. Low-end disruption occurs when a company uses a low-cost business model to enter the bottom of an already existing market and claim a market segment by delivering more-suitable functionality (Cote, 2022). As the incumbents of the market tend to chase higher margins in more-demanding segments, the low-end segments are usually overlooked and the incumbents tend not to respond too strongly. Entrants then move up-market and start delivering the performance that incumbents' mainstream customers require, while they preserve the advantages that drove their early success. Consequently, low-end disruption creates a situation where incumbents are more motivated to flee the market rather than "putting up a fight" against the competition, which makes it an important tool for new entrants (Cote, 2022).

As far as new-market disruption is concerned, it occurs when a business creates a new segment, a category in an existing market or even a new industry to reach underserved customers (Sampere, 2016). Through novel measures, businesses turn products and services into more affordable and accessible to a greater population of people (Landry, 2020). Similarly to low-end disruption new-market disruption competes with existing players of a market by targeting customers that incumbents are not interested in. However, new-market disruption can be a powerful tool for growth for incumbents as well if they navigate well through this path. To successfully implement new-market disruption organizations need to recognize first that established players have more time to react to changes in the business environment, provided that they are willing to look past their current customer base (Gilbert, 2003). Furthermore, it is essential to develop or restructure an organization so that it is capable of serving new customers.

2. Innovation life cycle

There are several theories and academic models describing change, but one is particularly relevant to innovation which is centred on the S-curve. The technology S-curve is a graphic representation of disruptive, radical and incremental innovation (Collins & Lane, 2019). The model is a useful framework for describing the substitution of old and new technologies on an industry level

(Christensen, 1992). However, it is important to highlight that the S-curve serves as a way to trigger discussions and assumptions and not as a magic forecasting tool.

The model visualises technological evolution and suggests that technologies go through an initial period of slow growth which is followed by a steep acceleration phase as the technology matures until it reaches its stabilisation phase, the plateau (Sood, 2010). Over some time the given technology reaches its limit of usefulness and competitive advantage and there can be a change in technology which results in a new S-curve. (Collins & Lane, 2019). The gap between the S-Curves - which is often referred to as the discontinuity period - can vary given the type of innovation. In the case of disruptive innovation, it can involve elements from the previous technology meaning that the S-curves can overlap. Regarding radical innovation, it fulfils the same need as the previous technology, however it is based on different knowledge and practice, meaning there is a gap between the S-curves (Collins & Lane, 2019).

The S-curve model is a useful analysis tool when measuring progress, evaluating performance or making strategic decisions. However, in contrast to the dominant view in the literature, some argue that technological evolution doesn't resemble an S-curve. Empirical findings suggest that the path of technological evolution rather follows "a series of irregular step functions" which is better approximated with multiple S-curves than with a single one (Sood, 2010). Furthermore, in his work (1992) Clayton Christensen also extensively focuses on the limitations of the technology S-curve. He describes how the plateau of S-curves is a firm-specific rather than a universal industry phenomenon (1992). According to Christensen, it occurs due to the lack of progress in conventional technologies as opposed to the natural maturity progress of technologies.

Similarly to the S-curve model, the Technology adoption life cycle examines the evolution of technology and innovations. The framework was introduced by Geoffrey Moore in his book Crossing the Chasm (1991). It builds on the social theory of the Diffusion of Innovations among individuals and organizations by Everett Rogers (1962) and it aims to explain why companies with high-tech, disruptive products often have difficulties reaching and succeeding in the mainstream market (Kylliäinen, 2022). The evolution of technology and the market are interdependent as the technology adoption depends on the performance of the technology and the rate and phase of adoption affect technology evolution. If the competition is serving the mainstream market we are likely to be facing a decreasing phase of technology evolution and a shift to a new curve is expected to happen.

Geoffrey Moore's concept of crossing the chasm is based on the classic bell curve and it visualises the adoption process of new technology over time (Sridharan, 2017). The technology adoption life cycle starts with a handful of innovators and early adopters, which then moves on to the dominant mainstream market of early - and late majority customer groups and finally reaches the most change-resistant customer group of laggards. Since all customer groups have different price sensibilities and are also driven by different motivations to adapt to technology, applying unique marketing strategies to the various groups is necessary for success in the market.

According to Geoffrey Moore, the chasm exists between the early adopters and early majority customer groups and crossing it is a challenging dilemma for businesses. The chasm exists as customers mostly trust references that belong to their adopter group (Sridharan, 2017). In his work Moore (1991) argues that to successfully cross the chasm, the key is to target and secure the beachhead market in the mainstream market to create a reference base. Once the niche market is secured businesses can move forward and capitalise on additional market segments and essentially reach overall domination in the market.

3. The evolution of innovation models

After discussing the various types of innovation, the evolution of technology and its customer adoption process, we must take a closer look at innovation process models that are an essential element of innovation management. Innovation models provide a comprehensive framework to identify, develop, implement and commercialise ideas (Bureau, 2020). The literature on innovation management features several conceptual models that describe how organizations develop or should develop new products and services (Verworn & Herstatt, 2002). The process of innovation at the firm level has evolved quite significantly over the decades from simple linear and sequential models to more advanced and complex models ("Innovation Model Analysis", 2022). In his work Towards the fifth-generation innovation process (1994) Roy Rothwell documents five shifts or generations in innovation processes based on their complexity. Each generation of innovation process aimed to address the limitations of their predecessors and integrate current new practices into their framework.

Regarding the first generation of innovation process, models describe innovation as a process of discovery that proceeds by a linear sequence of phases. The model focused on the idea that technological innovation is pushed through extensive research and development, thus this generation of innovation process models is also referred to as the push era (Bureau, 2020). In the view of the linear model, innovation begins with new scientific research which then advances sequentially through the stages of product development, manufacturing, marketing and concludes with the sale of new products, services or processes. One of the advantages of the phase-review process was the reduction of technical uncertainty, furthermore - as each phase was consistently monitored - the approach ensured that the tasks were complete (Verworn & Herstatt, 2002). However, one of the main flaws of the process was that the emphasis fell only on the development phase of innovation and not on the whole process from the idea generation to its launch (Verworn & Herstatt, 2002). As a result customer feedback and expectations were also disregarded.

The third generation of innovation models overcame several limitations and shortcomings of the previous two linear models as they attempted to describe the complexity of innovation. Third-generation models gained prominent acceptance during the period of high inflation and demand saturation in the economy when companies were forced to adopt strategies of consolidation with an increasing emphasis on scale and experience benefits (Rothwell, 1994). One of the main advancements was that innovation models paired technological innovation with market needs and they aimed for a balance between technology pull and market push (Bureau, 2020). In 1986 Kline and Rosenberg proposed a systemic model called the Chain-Linked model which is often contrasted with the linear model of innovation (Micaëlli, Forest, Coatanéa & Medyna, 2014). According to Kline, innovation is not necessarily driven by new knowledge, instead, the process starts with the identification of an unfilled market. To successfully implement an innovation, feedback loops are key in the process. While third-generation innovation models formed a non-linear feedback loop, “the stages in the process made the model sequential” (Bureau, 2020). The Coupling or Chain-Linked models are also characterised by the interaction between science, technology and the marketplace ("Innovation Model Analysis", 2022).

Regarding the fourth and fifth generation of innovation processes, models move away from the sequential approach and emphasise that technological innovation is cross-functional by nature and often multi-actor (Buyse, 2012). Following the work of Rothwell (1994), innovation model researchers indicated that open innovation represents the newest wave or generation of innovation models ("Innovation Model Analysis", 2022). Open innovation is believed to be an alternative to conventional innovation processes that best represents the complex system and characteristic of innovation and it aims to create a continuous culture for innovation within a company (Stefanovska Ceravolo, Polenakovikj & Dzidrov, 2016). According to Henry W. Chesbrough (2003), in the model of open innovation, a “company commercialises both its own ideas and innovations from other firms and seeks ways to bring its in-house ideas to market by deploying pathways outside of its current business”. In the view of the open innovation model, the centralised approach to R&D has become obsolete and useful knowledge has become widespread (Chesbrough, 2003). According to the model, outside knowledge can originate from suppliers, competitors, scientists, etc. (Stefanovska Ceravolo, Polenakovikj & Dzidrov, 2016).

II. Innovation Processes

1. Creation and maintenance of an innovation process

The innovation process is highly dependent on the initial environment the industry or the firm is navigating in (Salter & Gann, 2003). The relations between the firm, the projects, the regulatory framework, the supply side, and the supporting infrastructure are key aspects that need to be discussed when looking to innovate (Salter & Gann, 2003). These differences in factors and aspects lead to different innovation models to describe different “building blocks” to manage them (Kasztler et al., 2012)

The first aspect innovations could be differentiated with are whether the innovation is a process innovation or a product innovation (Utterback & Abernathy, 1975). The two types, while related, differ in the innovative object. Product innovation is the introduction of a new good with improved characteristics while process innovation is the implementation of a new production or delivery method, also significantly improved (Utterback & Abernathy, 1975).

The second aspect in which innovation could be differentiated is their respective impact on the market: incremental or radical innovation. Incremental innovation is an innovation that is smoothly introduced in an industry or market – often by being an improved version of an existing product or process - while the radical innovation disrupts the current industry with its clear differentiation points compared to the existing offering (Clark & Henderson, 1990).

The third aspect that differentiates innovation is their interactions with their external environment. A closed innovation process only takes in internal information and keeps only internal interactions while an open innovation process interacts with the external environment, often with the lack of secrecy of the former one (Chesbrough, 2003).

Depending on these different building blocks (Kasztler et al., 2012) innovations thus take different aspects and forms and interact differently with their internal and external incumbents (Salter & Gann, 2003).

2. Diffusion of technological innovation

Now that we have established what are the types of innovation and their characteristics, discussing the way firms diffuse their innovation with their characteristics is the next logical step (Kasztler et al., 2012).

As discussed in an open innovation process (Chesbrough, 2003), a firm that interacts with its external environment will tend to diffuse its innovation faster due to its preexisting relationship with the said external environment (Chesbrough, 2003). Analyses have shown that companies tend to adopt innovation processes or roll out innovative solutions more if they improve their interfirm relations (Pennings & Harianto, 1992).

Additionally, supporting technologies and infrastructures will prove to be essential in the proper diffusion and roll-out of an innovation (Salter & Gann, 2003; Pennings & Harianto, 1992). It has become increasingly important for companies to have certain control over all of their innovation processes and especially their enabling technologies (Teece, 2018). The complementary innovations that organise an iterative innovation process became so important that the lack of them would eventually lead to market failure (Teece, 2018). The necessity for complementary innovations, unfortunately, led innovators to overly rely on the supply structure and the innovation agenda of the supplier (Robertson et al., 1996).

Researchers have also focused on the different patterns of innovation diffusion that could be observed. On one hand, it became important to understand the timing of the introduction of the innovation (Dekimpe et al., 2000), if a firm was at the implementation stage of its technology (Rogers, 2003) or if a firm was at the confirmation, full adoption of the technology, stage (Dekimpe et al., 2000). On the other hand, it became essential to understand what scale the innovation diffusion was operating on. Researchers have particularly focused on the international aspects of innovation diffusion (Douglas & Craig, 1992), however, most researchers struggled to go beyond within-country diffusion patterns and their interactions with a limited number of industrialized countries (Dekimpe et al., 2000).

3. Barriers and incentives to innovate: the public sector

In an innovative firm environment, there also are multiple incentives and barriers at different stages which could help or block future innovation opportunities (Salter & Gann, 2003; Kasztler et al., 2012). One of the major barriers or incentives to innovate has often been the public sector (Halvorsen et al., 2005).

The differences or similarities between the public and private sectors in rolling out innovation are particularly interesting considering the hydrogen focus – which leads to an extent to energy discussions – of the thesis. The questions of diversity, funding intensity, value creation, etc. differ completely depending on the sector (Halvorsen et al., 2005). Energy, while operated by private and public actors, often benefits the public sector first (Dalpé et al., 1992). Indeed, innovations are essential for value creation for citizens, industry, and government (Hope, 2012; Agarwal et al., 2021).

The relation with the public sector becomes apparent when observations show that policies push or hamper innovation (Kivimaa & Rogge, 2022). This leads to innovations relying on policy experimentation or changes to be able to be pushed further in some cases (Salter & Gann, 2003; Halvorsen et al., 2005; Kivimaa & Rogge, 2022). Furthermore, the public sector has often pushed funding and research capital to fuel innovation (Fleming et al., 2019). While the overall industrial spending remains majorly reliant on the private sector for investments, public funding has been shown to improve industrial competitiveness and overall entrepreneurial success for various innovations (Fleming et al., 2019).

4. Transition period between innovations

The transition periods between innovations are equally important in the discussion of innovation processes (Abernathy & Utterback, 1978). The definition of a specific innovation defines itself as you transition to it. Initially, an innovation might appear as a rough process but as the innovation starts building up, it becomes clearer what its objectives and offerings are (Abernathy & Utterback, 1978). “Are management actions sufficient to sustain the transition?” (Abernathy & Utterback, 1978), “[Is the supporting infrastructure] ready for innovation?” (Salter & Gann, 2003) are questions that appear during the transition and should be answered if the innovation intends to be successful.

It is also important to talk about the time when studying evolution or innovation transitions (Agawarl et al., 2002). Indeed, timing conditions, the model and the framework of the innovation, especially the potential transformation of the barriers and incentives, could determine early if the innovation project is deemed to fail (Agawarl et al., 2002).

Transition periods thus often are started or ended by a dominant design of the innovation, moderated by industry constraints and current technological possibilities (Tushman & Murmann, 1998). They act as a transition point in the larger technological life cycle (Foster, 1986). They frequently end the current innovation cycle and will thus initiate the subsequent cycle of incremental change (Tushman & Murmann, 1998).

Transition periods also observe a two-step innovation mechanism. Once a technology has been adopted, a transmission process, a “reverse product cycle” (Barras, 1986) arises in the various industries the innovation was implemented in to reverse engineer the innovation and adapt to the current environment it’s navigating into its innovative solution (Salter & Gann, 2003). Improving current delivery systems and service quality (Process Innovation (Utterback & Abernathy, 1975)), then leads to further product innovations through the generations of new products or services (Barras, 1986) which then leads to further process innovation, in a repeating cycle.

During the transition period, competition becomes quite intense between industry actors. Co-opetition then becomes an intriguing case because of the overlapping markets in a rapidly changing industry with matched resources (Gnyawali & Park, 2011). It has been demonstrated that cooperation between firms is very helpful to address transition periods and further stimulates the market into more innovative mechanisms (Gnyawali & Park, 2011).

III. Collaboration

1. IORs with technological collaboration in the focus

There has been a steady increase in the number of Inter-Organizational Relationships (IORs) formed in the last decades. IORs encompass a wide selection of collaborative agreements including strategic alliances, joint ventures, networks or cross-sector partnerships (Parmigiani & Rivera-Santos, 2011). Broadly speaking, IORs can be defined as an established relationship between a focal organization and one or more other organizations for the common achievement of their goals and objectives (Levine & White, 1961). Scholarly work in this area typically focuses on specific forms of collaboration, thus it is rather difficult to build a holistic understanding of why organizations engage in different types of collaborative activities (Parmigiani & Rivera-Santos, 2011). However, general driving factors for such agreements can be characterised by three main approaches: cost-related collaboration, resources-based collaboration and relational collaboration where actors engage in synergistic collaborative practices and it is centred on the community as a whole (Capdevila, 2014).

Regarding technological collaboration, theories range from purely economical to ones that entirely discount price and cost considerations (Dodgson, 2018). However, when assessing the various theories we can conclude that technological collaboration is a significant feature of industry and industrial innovation, and it provides a necessary incentive for technological and organizational learning (Dodgson, 2018). Furthermore, collaborative innovation networks can help discover new market opportunities, capitalise on market conditions and improve the performance of their technological innovation (Jialu et al., 2021). Therefore, we argue that technological collaboration occurs - or shall occur - when the nature and environment of technological innovation are characterised by complexity, turbulence and high levels of uncertainty (Dodgson, 2018). Moreover, technological innovation is rarely created and marketed by a singular organization or individual as it requires complex interactions to match resources that are often spread out amongst several actors.

2. Alliance formation and partner selection

Many scholars have emphasised the importance of partner selection processes as a critical requirement for the success of IOR agreements. Throughout its history, different research streams have dominated the field of partner selection in alliance formation. For a long time, empirical research has focused on the notion that partner selection is based on social capital considerations (Baum et al., 2010). Current frameworks on partner selection heavily draw on Granovetter's notion (1985) of structurally embedded exchange which focuses on how an organization's existing pattern of relationships both enables and constrains its future partner selection. To reduce risk Gulati & Gargiulo (1999) suggested relying on exchanges in two forms of social capital: past ties and third-party ties (Baum et al., 2010; Gulati & Gargiulo, 1999). As organizations tend to repeat their past interactions and thereby increase their familiarity with other firms, they can better predict the benefits and downsides of collaboration with a given partner. As a result, taking into account third-party exchanges increases the likelihood of selecting an appropriate partner for an organization.

During the last decade, different but complementary views and models have been at the centre of academic discourse. In 2009 Mitsuhashi and Greve introduced the Matching Theory, where they emphasise two critical matching criteria in alliance formation: market complementary and resource compatibility instead of social capital considerations. In their study, they have found evidence that alliances with 'matched' partners improve their overall performance and survival chances (Mitsuhashi & Greve, 2008). Furthermore, they have highlighted that networked firms, rather than isolated firms, have exhibited a better match quality. Building upon this model, Baum et al. (2010) introduced a concept that completely disregards social capital considerations or strategic motives and it rather emphasises complementary knowledge stocks as a formation criteria, the idea that an organization's knowledge base must be fit for joint learning and thus mutual innovation. Interestingly they have found that this simple model adequately replicates conduct, network structure, and contingent effects of network position on performance observed and discussed in the empirical literature (Baum et al., 2010).

3. Collaboration management

Alongside finding the appropriate partner(s), several factors influence the mechanisms and thus the performance of IORs. Such factors include the level of interpersonal trust, cultural differences, leadership, control or the quality of communication between partners. In an increasingly turbulent and dynamic market environment, an organization's ability to develop and successfully manage its relationship with other firms is viewed as a key competence and a source of sustainable competitive advantage (Batt & Purchase, 2004; Teece et al., 1997). While many firms perceive that they are in total control of such relationships, most eventually discover that they are also influenced by the control of other organizations and that a network of firms cannot be centrally directed (Batt & Purchase, 2004). As a result, rather than aiming to control the relationships with their partners, organizations must learn to focus on the interactions that take place - both internally and externally - between companies within their collaboration efforts.

4. The role of trust in IOR dynamics

Several research papers and studies reveal the importance of high-level interpersonal trust between partners in IORs. Despite the high interest among academics, the theory of trust is still developing and a widely accepted definition is yet to emerge due to the complex nature of this concept (Seppänen et al., 2007) However, inter-organizational trust is commonly described as the extent to which members of one organization hold a collective trust orientation toward another organization (Zaheer et al., 1998). There are several positive effects of a high-level trust in IORs among others that it facilitates more open communication, information sharing and conflict management (Blomqvist, 2002). Furthermore, trust is believed to be a critical component of collaboration management as it is seen to increase predictability, adaptability, strategic flexibility and pave the way to collaborative innovation (Seppänen et al., 2007). Moreover, it is also seen to reduce transaction costs such as governance costs or internalisation costs at acquisitions, and social complexity (Seppänen et al., 2007). However, it is important to highlight as well that individual relationships within ROIs are vulnerable to labour turnover or interpersonal difficulties, thus it requires constant management (Dodgson, 1993).

5. Managing cultural differences in collaboration efforts

Alongside inter-organizational trust, another area which has a high influence on the dynamics and performance of IOR efforts - and thus requires constant management - is the cultural differences between partners. The definition of culture is relatively consistent among academics and it is defined as "the pattern of thoughts, feelings, behaviours, symbols and so forth that give meaning to actions and behaviours, and provide interpretations of situations for people" (Knoben & Oerlemans, 2006). Culture is publicly shared and accepted by a given group at a time, which identity binds the members together whether it is between a nation, family or organization (Burns & Stalker, 1961; Knoben & Oerlemans, 2006). To successfully manage cultural differences and mitigate risks in multicultural alliances, organizations must be able to identify the critical role of boundary spanners. Boundary spanners facilitate transactions and the flow of information between groups that are hindered by some gap or barrier such as authority, gender or culture. Regarding cultural boundary spanners, Barner-Rasmussen et al. (2014) identified that an individual's cultural skills and language skills are crucial for performing the most demanding functions such as intervening or exchanging. Furthermore, several scholars emphasise leadership style as an important tool to bridge groups of people with different perspectives, values and cultures (Ernst & Yip, 2009).

IV. Market characteristics

To fully understand the innovative processes as well as the implications of developing a new industry, understanding the various market mechanisms and their characteristics is necessary. Innovations indeed often rely on their market specificities to determine the strategy they should proceed with (Mowery & Rosenberg, 1979).

1. Market Demand

Understanding the market demand in coordination with its supply defines the way innovators should approach their market development (Mowery & Rosenberg, 1979). Companies should approach the market and understand its current needs and wants to be able to answer them properly. In the case of Hydrogen, this would mean that innovators would study the current energetical needs of their respective markets as well as the feasibility of the implementation of their solution.

However, understanding the current demand is not sufficient. The regulatory system also must be set in a way to facilitate the industry actors' decisions and provide sufficient structural answers so that the demand can be fulfilled properly (Strbac, 2008). Market demand can also become limited depending on the existing economic barriers of a country's market (Rahman et al., 2017), if a country's economic situation cannot support the innovative environment, exporting to another market with better economical standing might be the most efficient way for companies to answer demand (Rahman et al., 2017).

2. Market Size

The economic barriers of a market can often be linked to the intrinsic market's size. Indeed, a small market will rarely be able to support a large supply. For these reasons, market size studies should be conducted when determining a supply strategy of a firm's particular product or service (Mowery & Rosenberg, 1979). Market size not only determines demand but is also a key consideration to have to understand a market's existing competition (Melitz & Ottaviano, 2008). Indeed, bigger markets tend to have more numerous competitors to be able to meet the existing large demand while smaller markets can be less competitive or be limited to a dominant player (Melitz & Ottaviano, 2008).

The market size mechanisms also work when operating with a partnered country. In cases where the partner country has a bigger market, more opportunities will arise in addition to fiercer competition (Melitz & Ottaviano, 2008). The various opportunities and the competition should be equal considerations when researching a market to the demand, supply and market infrastructure for companies to have a proper idea of their rolling out processes (Mowery & Rosenberg, 1979).

3. Market Infrastructure

Infrastructure and infrastructure development also play a crucial role in the understanding of a specific market (Mapila et al., 2017). A market will always be limited by the existing infrastructure and will only be able to expand if the infrastructure supporting mechanisms allow it, particularly in developing and new markets (Stewart & Yermo, 2012).

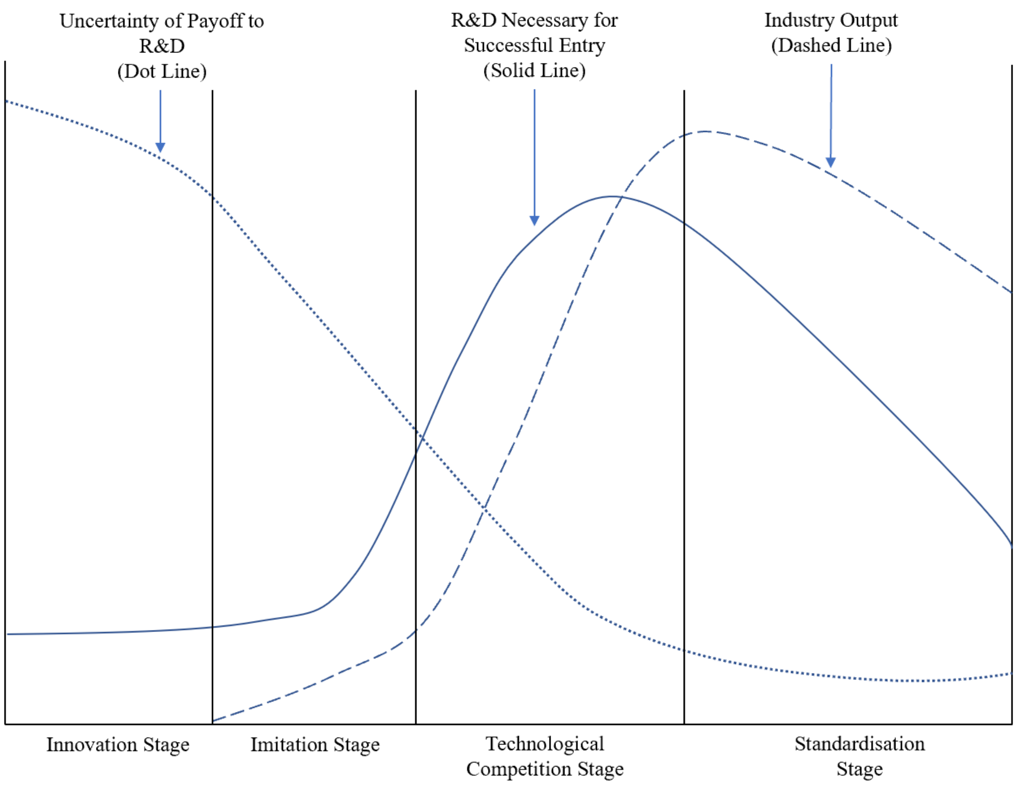
The infrastructure should also support exploitation and exploration for companies to be able to answer the market's needs efficiently. In the energy sector, this support is particularly needed as challenges such as transportation, efficient exploitation and efficient utilization of energy are key for the industry to function properly (Klass & Meinhardt, 2014).

Another important point that the infrastructure needs to support is the information aspect of the market. The various industry actors have to be aware of the current proceedings and supporting mechanism to be able to operate but also the demand has to know what it lacks so it can formulate its actual needs and wants. Lack of said information is one of the biggest issues encountered for markets' infrastructures (Strbac, 2008).

4. Market Entry Barriers

As discussed before, one of the major challenges for a market is the existing economic barriers it might face. These economic barriers surpass even the social and cultural barriers (Rahman et al., 2017) as they represent the first entry point of a specific market.

Nonetheless, economic barriers will often be paired with other market barriers which might make it difficult for a company to enter a specific market. If you follow the technological development cycle, depending on the industry, you might observe different economic barriers depending on the current stage of the development cycle.



Entry and the technological development cycle

Figure 1: Entry and the technological development cycle (Mueller & Tilton, 1969)

The first major deterrent for a company to enter a new market, especially in its innovation stage is uncertainty (Mueller & Tilton, 1969). The high R&D cost required to enter the market will not always be offset by the demand which might not be existing yet. The high cost fades when you enter the imitation stage of the development cycle, this often becomes the “easiest” point of entry for companies as you are still ahead of the competition that will move in the later stages. In the technological competition stage and standardization stage, the entry barrier shifts: uncertainty is gone but competition becomes a bigger challenge (Mueller & Tilton, 1969).

The technological development cycle means that timing is also a very important factor for a company to consider especially if it wants to mitigate economic barriers in some ways.

For smaller markets and smaller actors, considering their inherent condensed technological development cycle, a way to mitigate these costs further is to leverage the economies of scale principle and create a niche for themselves (Mueller & Tilton, 1969).

V. Hydrogen as an energy carrier

1. The role of hydrogen in the global energy transition

Due to the growing global awareness of climate change, the general public, policy and business interest has also increased in sustainable energy consumption and production (Hielscher, Seyfang & Smith, 2011). To achieve the EU’s commitment to carbon neutrality by 2050 and the global effort to implement the Paris Agreement, turning to alternative methods and sustainable innovation is necessary (European Commission, 2020).

Hydrogen is an energy carrier that has several applications of use and also a significant potential to reduce local, national, and global emissions, as well as to create economic value for Norwegian businesses (Norwegian Ministry of Petroleum and Energy ‘MPE’ and Norwegian Ministry of Climate and Environment ‘MCE’, 2021). Hydrogen energy conversion systems are expected to become a choice for the future as it is possible to produce hydrogen from renewable and sustainable sources instead of natural gas (Acar & Dincer, 2018). Another advantage of hydrogen energy conversion systems is the fact that supply comes from various energy sources such as wind or solar thus nobody is expected to have the power to regulate the supply and distribution of hydrogen (Acar & Dincer, 2018).

2. International cooperation in the implementation of the hydrogen economy

The strategy of the European Commission is to deploy clean hydrogen on a large scale around 2030 (Espegren, 2021). According to Espegren et al., Norway cannot afford to be left out of this global movement. Indeed, hydrogen will certainly play a central role in the decarbonization of Norwegian society. Firstly, because bio-resources are limited and not sufficient to cover sectors such as transportation or industry, but also because hydrogen is a potential source of sustainable income from the natural gas that Norway has in abundance (Espegren, 2021). For these projects to be successful, it seems necessary that European coordination be put in place. The country seems to be aware of this and the major projects underway in the country are often the result of collaboration with European actors. For example, the Danish-Norwegian project, Europa Seaways, which aims to create a hydrogen ferry (Morgan, 2020), or the European project "Flagship" which finances the development of maritime hydrogen in France and Norway (Norled).

3. Challenges in pursuit of a green hydrogen economy

While the electrolyzers and the PEM technologies are seriously developed or researched, the storage technology of hydrogen is quite problematic (Hoecke et al., 2021). While different possibilities arise such as liquid hydrogen or different storing technologies, each of them has strengths and weaknesses which leads to no solution being the obvious one to roll out (Hoecke et al., 2021). The immaturity of these complementary technologies might be one of the seemingly hardest obstacles to solve yet, depending on the advancement of the technologies (Suurs et al., 2009).

METHODOLOGY

I. Research Methodology and Design

In this section, we want to go deeper into the research framework of our thesis and give an overview of the research design, methods and limitations.

We believe in the case of the hydrogen industry and its obstacles, utilising a conceptual framework presents the answer to our question as an overview of the existing considerations as the main literature contribution (Jaakkola, 2020). Indeed, with the hydrogen industry still being in its early stages, providing a presentation of the various obstacles to consider when entering the industry will facilitate researchers and industry players' work to gather the relevant information necessary for their tasks.

The goal of the paper is to bridge the gaps between the different information presented as well as provide an answer to a research question (Van de Ven, 1989). To create an adequate conceptual paper it needs to answer various questions to make sure it integrates with the existing literature (Whetten, 1989). The question "what is new?" is of utmost importance. However, unlike a classic theory paper, a new theory does not need to be presented at the construct level (Cropanzano, 2009) but rather the newness should be sought through the creation of the various bridges that help the understanding of the problem (Gilson & Goldberg, 2015).

II. Data collection and analyses

In this section, we discuss our data collection and analysis processes. The partnership with BI Innovation allowed us to secure more sources for our data and to ensure its relevance for industry players. The goal was to provide an overview of the hydrogen industry's obstacles.

All of the data presented in this paper is secondary data. Indeed, conceptual papers are not expected to present new empirical data (Gilson & Goldberg, 2015) as the main goal is to bridge the different existing constructs already present in the field. When building a conceptual paper and trying to understand an industry's performance, secondary data provides an already proven source of data. In some cases, it even brings insights and industry knowledge which could not be attainable through other means (Venkatraman & Ramanujam, 1986).

The types of secondary data sources that are presented include presentations from industry players during conferences, existing datasets that emphasise a point of the overview, industry reports and forecasts, policy reports and government roadmaps.

Due to the decision we made about the design and the framework of the paper, we thought that separating the overview into four focal points presenting the key obstacles to the hydrogen industry in Norway would fit into the idea of presenting an overview of the issue and the concepts. The four analyzed and discussed points have different approaches to the problem yet they bridge to the same conclusions about the development of the hydrogen industry. These focal points are:

1. The market context
2. The capital limitations
3. The collaboration limitations
4. The entrepreneurial context - a comparison with China and Israel

III. Limitations

The limitations of the conceptual research paper design and the utilisation of secondary research methods should be carefully considered when attempting to answer our research question.

- Lack of relevance: Answering the “what is new?” question (Whetten, 1989) can be quite difficult if the data answered a different question than the research question. Understanding the secondary data’s initial scope of research as well as considering the context of the initial research when performing the secondary analysis is a crucial aspect to consider.

- Lack of accuracy: Secondary data and constructs might not have equivalent quality and research design properties to each other. The data could then show inconsistencies between the different studies presented or even not fit within the secondary analysis. Accounting for the original authors’ limitations as well as their bias when creating conclusions is important for our study.

- Inability to validate the operationalization: This limitation is particularly relevant for industry players that would utilise this research paper for their business decisions (Venkatraman & Ramanujam, 1986). Indeed, the data presented here does not provide an absolute answer to solutions and reasons for the hydrogen industry's struggles.

- Data availability: By utilising secondary data only in a research paper you limit it to the currently available data, this means that certain aspects might not be considered if the data presenting said aspects are not available.

IV. Ethical Considerations

Conceptual research design is ethical by nature as you do not impose variables on the incumbents addressed in your dataset. In addition, the high internal and external validity solidifies the ethical nature of the design. Nonetheless, we have to be wary of the retrospective studying of the process and self-validation mechanisms which might invalidate the fairness of the research. Furthermore, we also have to consider the initial ethical considerations of the data we utilise as well as the intellectual property considerations of each dataset we present. The data we utilise also does not allow any re-identification or cause harm to the actors involved as we relied on industry-level data (Paola Tubaro, 2015).

Additionally, we follow the general ethical considerations of the Norwegian National Research Ethics Committees (The Norwegian National Research Ethics Committee, 2019a). We abide by the 16 principles suggested as general ethical guidelines, including respect, fairness, integrity, quality, confidentiality, laws and regulations etc.

ANALYSES

The Global and Norwegian context of the energy transition

Norway's oil fund or Government Pension Fund Global is based on the income from the oil that was discovered in the North Sea in 1969 (Ditlev-Simonsen, 2022). The oil fund served as a backbone for the Norwegian economic upturn during the past decades as it allowed the government to manage oil assets and revenues sustainably, while also creating wealth for future generations (*The Government Pension Fund Global (GPFG) in Norway*, 2022). However, current global trends and challenges such as climate change, circular economy or digitalisation and also the recent geopolitical events demand a thorough reform in economic development to address and tackle these issues. Consequently, Norway's future as an energy producer, exporter and investor should be considered in a wider context of the global energy transition (Froggatt et al., 2020).

A transformation of energy systems is already underway in an increasing number of countries around the world, turning to alternative, renewable energy sources such as wind, solar or green hydrogen. However, the speed and depth of this transition are characterised by high uncertainty and controversy (Froggatt et al., 2020). Furthermore, it is important to note that the speed and depth of the energy transition heavily vary between regions due to several factors such as the difference in governmental regulations, incentives, natural resources and the development of infrastructure. Regarding the global demand and production of renewables, most sector specialists agree that forecasting agencies continuously underestimate the growth rate of the industry.

Figure 2 shows the International Energy Agency (IEA)'s demand forecast for oil and non-hydro power renewables - primarily till 2030 with the continual revisions of their scenarios between the period 2006 and 2019. While the 2006 World Energy Outlook forecast predicted 296 (Mtoe) for 2030, the 2019 WEO forecasted 681 (Mtoe) for the same year making it a 230% increase. On the other hand, the forecast for oil demand is 7.2 per cent less in 2019 than the equivalent in 2006. However, it is important to point out that alongside renewables, the global demand for fossil fuels is continuing to rise as well. There are countless discussions about whether sustainable conditions - such as the use of carbon capture storage (CCS) - exist for the continued use of fossil fuels, however, exploring this area more thoroughly is beyond the scope of our paper.

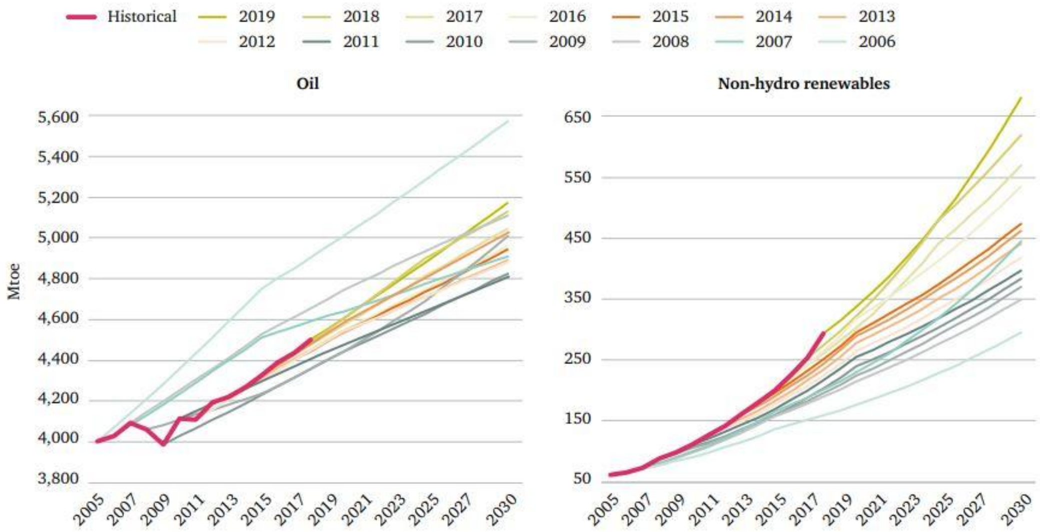


Figure 2: Comparison of IEA scenarios of global oil and non-hydro power renewable production until 2030 (Froggatt et al., 2020)

Regarding the energy transition in Norway, while oil and gas exports are set for continuous decline after 2025 - resulting in significant losses of export revenues - growing green, export-oriented industries are not accelerating at a necessary rate (*Energy Transition Norway 2021*, 2021). As a result, most industry reports argue that Norway is not likely to meet its 2030 climate targets on CO2 emission reduction (Bakken et al., 2022; *Energy Transition Norway 2021*, 2021). Not fulfilling climate targets is a great challenge for the environment but it also offers opportunities for Norway to find and develop new alternative solutions and technologies to fill the gap (Bakken et al., 2022). At the 2022 Green Growth Conference in Oslo, among other industry experts, provost Hilde Bjørnland also argued that as the downturn in oil exports is approaching, Norway is in a pivotal position to find and develop new sectors - such as battery factories, ammonia and blue or green hydrogen production - that would make the country unique and offset the losses in export revenues.

Overview of Norwegian energy infrastructure in the pursuit of hydrogen

Regarding hydrogen production, Norway is in a great techno-economic and R&D position to accelerate the development of the sector and be an important player in driving the global energy transition (Evensen et al., 2022). The country has a high level of natural resources including natural gas, hydropower and wind or solar energy which are necessary sources for hydrogen production. Furthermore, Norway has the knowledge, capabilities and high technical competence to develop new technologies (Bjørnland et al., 2022). Unlike most oil-producing countries, Norway is also in the process of diversifying its economy and is no longer as oil-dependent as other producers due to the country's sovereign wealth fund (Froggatt et al., 2020). Consequently, Norway is in the position to offer significant governmental support in terms of creating certainty and providing more direct support through subsidies (Bakken et al., 2022). This would ensure to overcome initial core issues such as the high-risk nature of this novel technology and market, thus attracting more private investments.

Opportunities for Norway in the global hydrogen market

Being an energy and technology nation, hydrogen presents several opportunities both for the Norwegian domestic market and for the export market. Due to the increased global focus, the Norwegian government has proposed the country's hydrogen strategy (2020) for the upcoming decades, which assesses the various areas of the market where Norway can play a crucial role involving production, storage (CCS) or in the transport sector. Regarding the production of hydrogen, two alternative methods that contribute to sustainable economic development. First is low-emission hydrogen production, which is achieved through steam reforming processes involving natural gas or other fossil fuels combined with CCS (Ministry of Climate and Environment, 2020). To accelerate low-emission production, the Norwegian government has already developed initiatives such as the Northern Lights project involving key investors of Equinor, Shell and Total. The first phase of the project is set to be completed by mid-2024 with a capacity to transport and store up to 1.5 tonnes of CO2 annually (*Northern Lights*, 2022). The second production method for hydrogen is achieved through the electrolysis of water using renewable energy resulting in zero-emission (Ministry of Climate and Environment, 2020). While this method is more costly than its low-emission alternative, the decrease in national dependence on fossil fuels will require developing new solutions to increase efficiency and lower costs of production (Nikolaidis & Poullikkas, 2017).

Regarding the transport sector in Norway, it accounts for 29 per cent of the country's overall CO_2 emissions (Simonet, 2019) The Norwegian government has also identified this sector as a vital area in the pursuit of a decarbonized society and has the ambition to halve emission levels by 2030 compared to its 2005 levels (*National Transport Plan 2022–2033*, 2021). Hydrogen and other hydrogen-based systems have a great potential to reduce emissions in this segment, especially in heavy goods transportation and in the maritime sector (Ministry of Climate and Environment, 2020). Therefore, it is important to introduce and further develop new zero-emission technologies as several Norwegian shipping companies have already done so. At the same time, we must emphasise that it is still difficult to decide where exactly will hydrogen gain a competitive advantage compared to other, related technologies as there is a rapid pace of development in all areas (Ministry of Climate and Environment, 2020).

Lack of pace in the Norwegian hydrogen market

However, at DNV's 2022 seminar on 'The Impact of Hydrogen in The Industry Value Chain', there was a strong consensus amongst industry experts that Norway lacks the pace of other European countries to scale the hydrogen market even with all of the already provided infrastructure and opportunities listed previously. Regarding the production of hydrogen, currently, Norway produces 225,000 tonnes of hydrogen from natural gas for industrial purposes (Bakken et al., 2022). Its current method, however, doesn't involve carbon capture solutions thus it is labelled as 'grey hydrogen'.

The slow pace of development is tangible in other segments of the Norwegian hydrogen market as well. Figure 3 below represents the average annual state funding that is available for hydrogen-related projects per country as of 2021 (*Geopolitics of the Energy Transformation*, 2022).

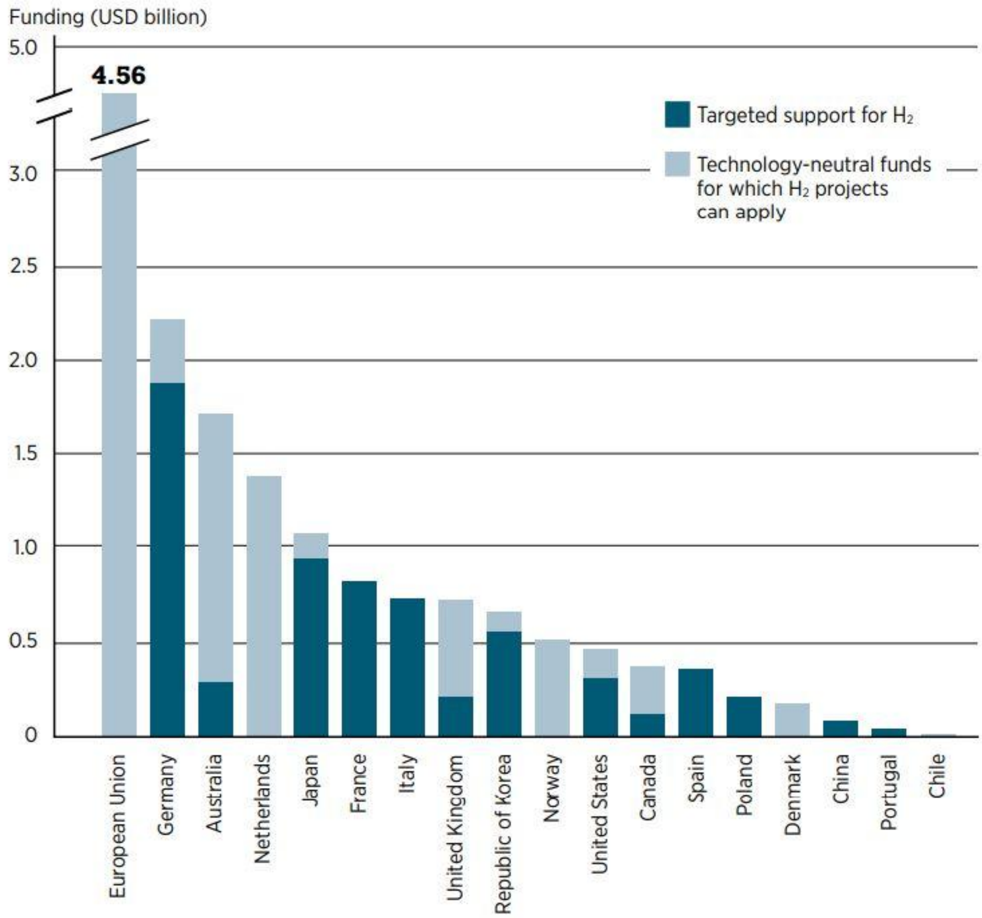


Figure 3: Average annual funding potentially available for hydrogen projects between 2021-230 (Van de Graaf et al., 2022)

It is well illustrated that Norway is not part of the industry leaders while Japan, Australia and other European nations such as Germany and the Netherlands are making the most significant commitments. As briefly discussed in a previous paragraph, governmental funding is crucial in the early stages of new technologies to fast-track projects to the stage with lower risks and where projects are fit to attract private investments (Bakken et al., 2022). Einar Evensen, a renewable energy industry specialist at DNB, also highlights (2022) that currently, no green hydrogen project in Norway has an offtake contract which is largely due to the insufficient level of funding from the government. As DNB and most other investors are risk-averse, setting up a market and infrastructure are crucial prerequisites for them to contribute.

Focal points that serve as the basis of analyses

In the following part of this paper, we provide a thorough overview of the Norwegian hydrogen economy and its current main barriers that hinder further development. The analysis focuses on four focal points including (1.) market characteristics (2.) capital characteristics and limitations, (3.) collaboration limitations and (4.) Norway's cultural context compared to other countries. These areas have been carefully identified and chosen based on our research on the topic which involves a series of industry reports and conferences.

I. The Market for Hydrogen

As the first focal point, discussing the current market for hydrogen is important to be able to understand the following discussion points.

1. Supply

When considering the global hydrogen supply, it is important to note that a lot of countries can produce hydrogen as it does not come from a limited resource from specific geographical locations such as fossil fuel energies. A range of countries in both the northern and southern hemispheres are envisioning themselves as hydrogen (and its derivatives) exporters either as blue (from a coal or natural gas source) or green (from solar, hydro and wind) (KPMG, 2021). This means that by participating in the worldwide hydrogen supply chain, you would be competing with various countries that could produce various types of hydrogen (see appendix A) and export it just as well.

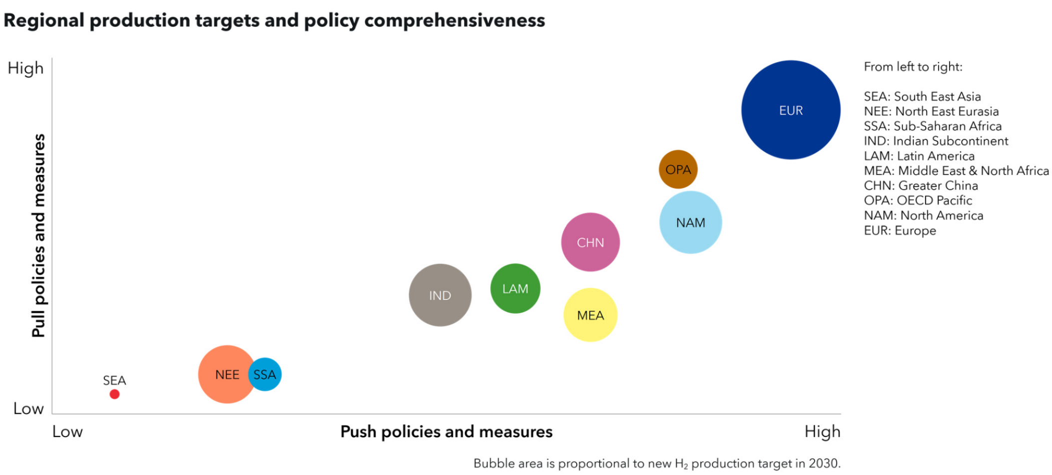


Figure 4: Regional production targets and policy comprehensiveness (Bakken et al., 2022)

Because of this issue, regional production targets need to be set high to compete on the highest scale. In addition, as observed in figure 4, a push for policies and measures supporting the development of hydrogen and its understanding will be very important which is why Europe places itself as one of the future leaders in the hydrogen industry.

In the more specific case of Norway, when “supplying” hydrogen, various options are possible: producing hydrogen on-site (Blue and Green Hydrogen) then exporting the finished product, exporting the natural resources to produce hydrogen (Mainly natural gas), exporting the energy to produce it etc. (Stiller et al., 2008). Considering the current infrastructure in Norway and other energies utilizing the same method for export, we believe the Norwegian system favours the development of diversified exporting solutions. Additionally, in some cases, retrofitting the current installations for natural gas to be able to support hydrogen is also possible (Bakken et al., 2022), which makes Norway’s position even stronger as it already is one of the main exporters of natural gas (NorskPetroleum, 2021).

Moreover, Norway already produces 99.998% of its electricity from renewable energies and keeps investing further in renewables (Energi Norge, 2022). This makes the production of green hydrogen (the most sought hydrogen as it is nearly carbon-free, see appendix A) evident for the Norwegian grid. Norway thus has to keep investing and leveraging its infrastructure assets to place itself as one of the main suppliers of hydrogen.

2. Demand

When considering the global hydrogen demand, it is important to note that the demand for hydrogen will also be limited by the country’s infrastructure and its overall investment to take part in the hydrogen market. As observed in Figure 5, in the North Sea, the demand for hydrogen already exists. Due to the high R&D investments by various Western and Northern Europe countries (IEA, 2022), the demand in the region will also continue to increase in the years to come.

Furthermore, existing country relationships regarding energy production and natural gas export will also influence the hydrogen market (Stiller et al., 2008).

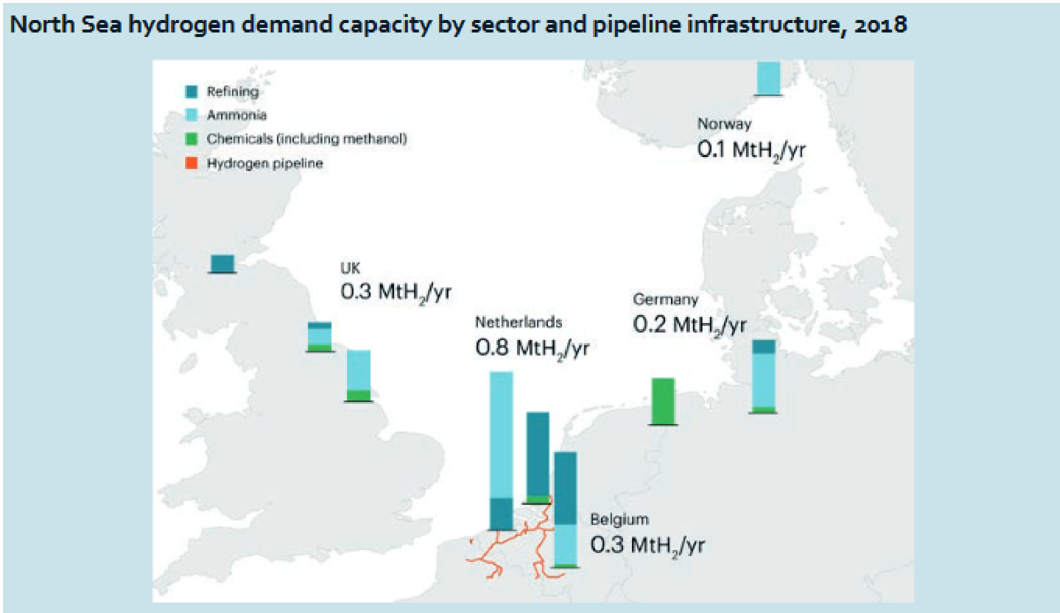


Figure 5: North Sea hydrogen demand capacity by sector and pipeline infrastructure (IEA, 2019)

Existing exchange and export relationships such as the one with Germany will be particularly beneficial to Norway. Leveraging the high demand for (better) energy supply of the German industry, Norway can present itself as one of the main suppliers of the high hydrogen demand the German market will have (Stiller et al., 2008). Furthermore, the global hydrogen demand will increase as various sectors move away from fossil fuels as observed in figure 6, which presents an additional opportunity for suppliers to position themselves early for the transition to come.

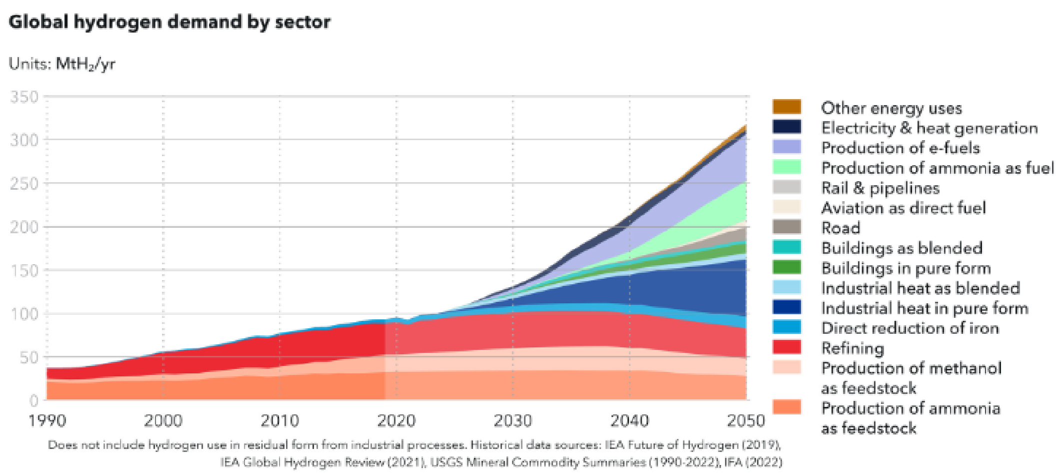


Figure 6: Global Hydrogen demand by sector (Bakken et al., 2022)

According to a SINTEF report, Norway would be able to position itself as a strong player in the hydrogen market. Based on benchmark years (2007 and 2020), SINTEF built predictions about the production scenarios for Norwegian hydrogen to meet the global demand. In 2036 it was estimated that Norway will be able to produce 150 billion NOK of hydrogen. In 2050, that number rises to 680 billion NOK (Damman et al., 2020). For both of these predictions, most of the value produced would go towards exports, the remaining hydrogen being utilised for transportation solutions within Norway. In comparison, the Oil and Gas exports represented 83 billion euros for exports in 2020 (NorskPetroleum, 2021). For all of these reasons, Norway will most likely position itself as one of the world's hydrogen suppliers, especially considering the need to replace the expiring revenues of the Oil and Gas industries.

As for the local demand, transportation will be the main sector for demand in the Nordics, particularly in the maritime sector (Hoecke et al., 2021). Projects such as the flagship EU-sponsored HyShip (Hyship, 2022) and pushed by numerous industry actors are already positioning themselves for maritime hydrogen solutions. Projects such as these will be particularly key for maritime-focused countries such as Norway. Indeed, in 2020, the maritime sector represented 8.6% of Norwegian carbon emissions and contributed to 8% of value creation in Norway and 17% of exports (Ministry of Climate and Environment & Ministry of Petroleum and Energy, 2020).

3. Controversies

Last but not least for the Hydrogen market, there are controversies surrounding hydrogen production held by the general public as well as some of the industry experts.

The first controversy is the overall safety of the production and utilisation of hydrogen. Indeed, similarly to other gases and fuels, hydrogen is highly flammable and thus has to be handled carefully (NFPA, 2022). The public perception of hydrogen is mixed because the properties of hydrogen and its utilizations remain relatively unknown to the public eye (Leachman, 2017).

Accidents such as the 2019 Kjørbo explosion in a Nel and Gexcon electrolyzers (Nel, 2019) are incidents which could hamper the overall development of hydrogen if it is perceived as dangerous in its industry infancy. Even if industry experts and researchers (Leachman, 2017; Nel, 2019) ensure the safety of hydrogen production and utilisation, incidents during the development of the industry could permanently damage its image in the public eye.

The second controversy is the actual environmental impact of hydrogen. According to some researchers, the overall ecological impact of hydrogen might not be as positive as we believe it to be (Tabuchi, 2021). If those accusations were to be proven, this would drastically hamper the development of hydrogen, particularly blue and green hydrogen, as they were presented as long-term solutions to fight climate change (see appendix A).

The third controversy is the cost of production of hydrogen. Indeed, it was determined that hydrogen remains quite costly to produce and investments in wind energy could be as much as twice as effective as hydrogen investments (Hydrogen Council, 2020). However, the high cost of production of hydrogen is linked to the currently high investment cost necessary to develop the industry further. Costs will eventually go down when the industry begins to scale up as per the economies of scale principle (Hydrogen Council, 2020). Moreover, countries need to diversify their energy sources to guarantee energy security and a constant supply (European Commission, 2022).

II. Norwegian Hydrogen Industry and Capital

To better understand the state of the Norwegian industry and why some of the key industry players struggle to push the effort further, it is important to consider the ambiguous relationship Norway has with public and private capital (Evensen et al., 2022).

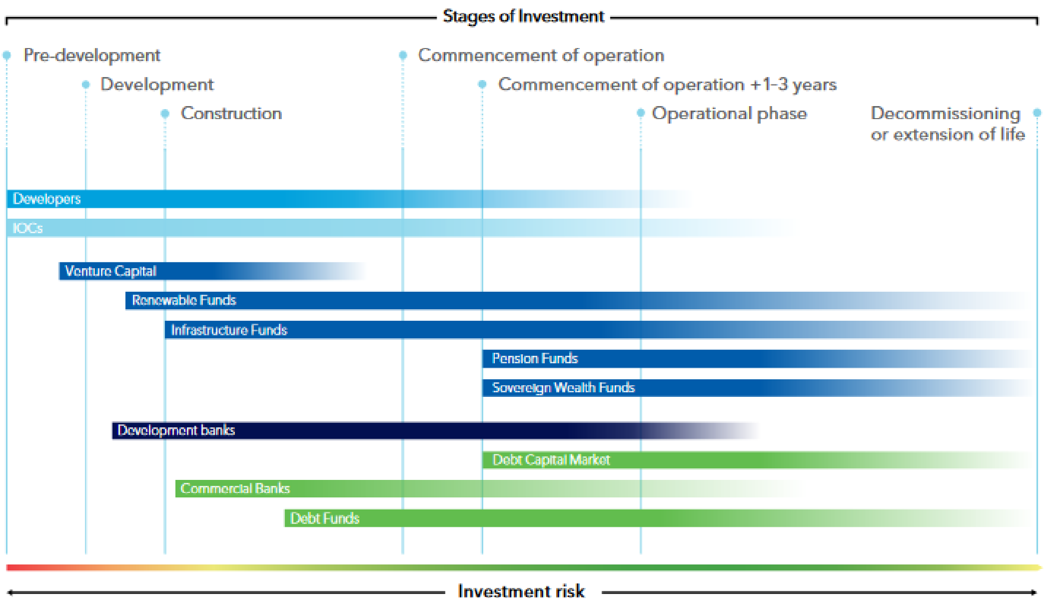


Figure 7: Stages of investment and Investor Appetite (DNV, 2021)

1. The Norwegian Sovereign Fund

As mentioned in the literature review: Barriers and incentives to innovate: the public sector, the public sector can often push industries forward as it remains one of the major investors to fuel innovation. It is important to note though that while the public sector might fuel innovation and incentivize the development of the hydrogen industry, it tends to be quite risk-averse when it comes to investment (See Figure 7). Financial instruments such as the Norwegian Sovereign Wealth tend to remain quite risk-averse and diversify themselves without committing too strongly to specific industries or sectors (Norges Bank, 2017).

The Norwegian Sovereign fund is a particularly interesting investor to consider when considering new energy investments. Indeed, it places itself as the world's biggest fund, owning between 1.3% of all listed companies with a total market value of 11 734 billion NOK (Norges Bank, 2017). The fund also pledges to reduce the world's global emissions and invest in sustainable projects that it believes in.

However, when you observe the portfolio of the fund and its investments and the fund's overall strategy, none of the investments are direct actors of the hydrogen industry (Norges Bank, 2021, 2022). More importantly, investments are never made in Norway and only 0.1% of the overall fund capital is used in renewable energy infrastructure projects, for the wind sector (Norges Bank, 2022). This means that the Norwegian biggest and most influential investor does not push for national investment but more importantly, does not appear to believe, yet, in the hydrogen industry as a viable investment opportunity. While the risk of such an investment is undeniable and investing locally would go against the investment charter of the Norwegian Sovereign Wealth Fund, the absence of a position for the hydrogen industry makes it quite detrimental to the overall investment trends.

Indeed, according to the OECD Venture Capital Review of Norway, the public investment stance on specific sectors will determine where lead investors will decide to invest their money (Baygan, 2003). The overall over-reliance of the Norwegians on their government and public investors' actions to make financial decisions becomes detrimental for new industries such as the hydrogen sector.

2. **The struggle of private capital**

Firstly, the Norwegian investment market is characterised by asymmetric information. Because the government is involved in most industries and makes most of the country's business decisions, an initiative from private individuals is often risky as they do not possess the same knowledge as the government. Secondly, the small and medium enterprises (SMEs) do not have access to a marketplace for risk capital instruments. This widens the information asymmetry gap and reduces the money supply in the secondary market, leading to the misallocation of capital in a socio-economic setting (Ministry of Trade and Industry, 2002).

In a survey of 269 SMEs, most of the respondents found that capital investment in Norway mostly arrives at a later stage. A lack of commitment during the businesses' early stages is often observed (Widding & Sørheim, 2006). When industry actors were asked why the Norwegian investment landscape behaved as such, respondents indicated that there was a lack of competent capital in Norway for early-stage projects (Widding & Sørheim, 2006). According to the OECD, Norway ranked 17th in terms of Venture Capital investment out of the 38 members (OECD, 2021).

The issue arose because of the union culture Norway has. Most investors and actors in the financial industry will follow the public investment decisions as their lead investors. However, the Norwegian government rarely invests in early-stage industries. (Menon Economics, 2009). Another cultural difference which influenced Norwegian investing trends is the tendency to "follow on", the general loyalty the typical Norwegian investor has (Menon Economics, 2011). Indeed, if an early-stage investment was successful, investors will tend to commit to the investee without investing in new prospects again. This overall limits the opportunities within new sectors.

The problem of early-stage investment is also exacerbated by the economical instabilities, which change the investors' profile to a more risk-averse, thus investing at later stages of the company (Menon Economics, 2011). Figure 8 shows the typical investment groups observed in the Norwegian setting in regards to the risk and return of the investment. On one hand, group 1 and group 2 constitute most if not all of the investment trends in Norway due to the risk aversion of both the private and public investors (Menon Economics, 2011). On the other hand, group 3, considered too risky, might be the one showing the most profitable social welfare outcome. In our case, the reduction of global emissions thanks to the development of the hydrogen industry would most likely locate itself around group 3, which means that incentivizing investment in group 3 or reducing the risk with governmental action is a necessary tradeoff for the investment trend to change.

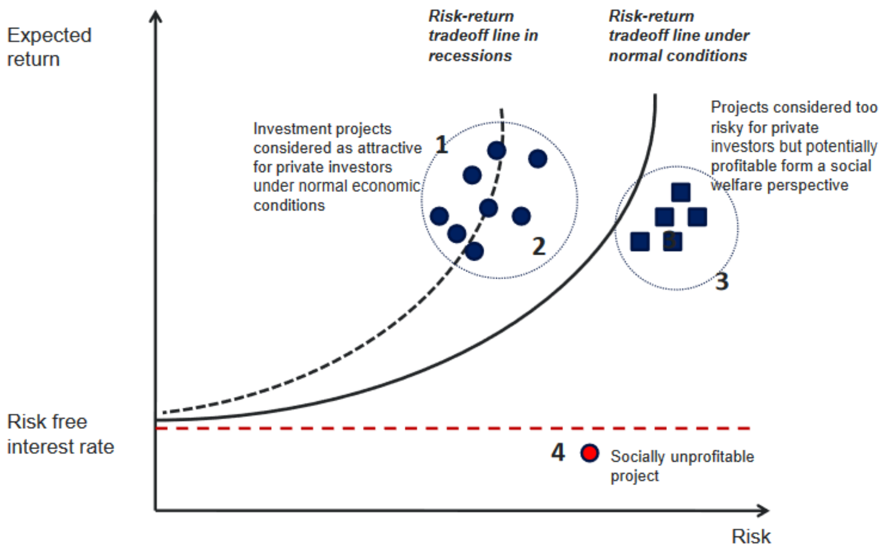


Figure 8: Illustration of the risk-return tradeoff and the role of government capital support (Menon Economics, 2011)

Fundamentally, if Norway wants to improve its overall capital expenditure in new industries, which is particularly relevant in a nascent industry such as the hydrogen one, there is a necessity for private-public partnership in terms of investment (Menon Economics, 2011) and for the Norwegian public investors to lead the way.

3. R&D spending trends

According to the Norwegian Government's Hydrogen Strategy, Research and Development (R&D) authorities, investment in hydrogen in Norway amounted to 550 million NOK between 2009 and 2019 (Ministry of Climate and Environment & Ministry of Petroleum and Energy, 2020). Even though the governments have since changed since the publication of the strategy, Norway continued its work for the Hydrogen industry. According to the International Energy Agency, Norway ranked 13th for government R&D spending in 2020 with a total investment of 60 million NOK (IEA, 2022). However, that number was multiplied 22 times the following year, most likely due to the publication of the Hydrogen Roadmap as well as the worldwide increasing considerations for hydrogen.

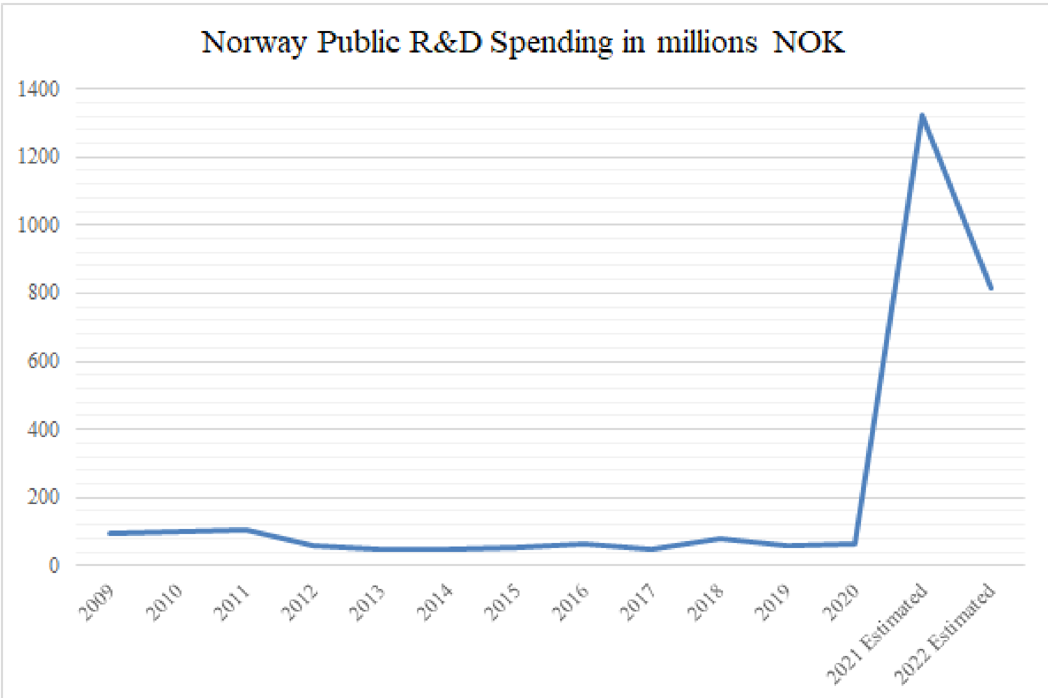


Figure 9: Norway Public R&D Spending in millions NOK (IEA, 2022)

Note: Both 2021 and 2022 numbers are estimates and the 2022 number might severely increase as we are currently in mid-2022.

The R&D spending numbers look promising and we should be hopeful about the potential of Norway in the hydrogen industry thanks to these considerable investments. It is impossible so far to deduct if that strong increase in public investment will strongly affect the development of the hydrogen industry in Norway, particularly for private actors and private investors. Yet, as previously discussed, such strong commitments from the government, particularly if they reveal a long-term trend, will have to be of utmost importance for the viability of the hydrogen sector in Norway.

III. Collaboration in the global hydrogen market and Norway's limitations

1. Current Norwegian hydrogen strategy, benefits of collaboration

According to the Norwegian government's hydrogen strategy (2020), international collaboration will play a crucial role in establishing a functioning market since most of the technology development and future demand for hydrogen solutions will come outside of Norway. As previously discussed in the literature review part of this paper, collaboration on joint initiatives drives value-creating innovation through the exchange and combination of knowledge, resources and best practices (Maznevski & Dhanaraj, 2017; Mitsuhashi & Greve, 2008). Furthermore, collaborative networks facilitate the discovery of new market opportunities and improve the performance of existing technologies (Jialu et al., 2021). Regarding hydrogen, many industry actors in Norway highlight that strengthening international collaboration is also important to address regulatory gaps in some areas such as the maritime sector and to develop large-scale projects that connect key players in the different steps of the value chain (Damman & Gjerløw, 2019).

2. EU Initiatives for regional collaboration

In recent years, the European Union has identified hydrogen as a key priority and aspires to become a leader in the global market as part of the new industrial strategy to achieve a climate-neutral economy by 2050. The European Hydrogen Strategy (2020) aims to scale up the renewable energy supply and demand with a strong focus on infrastructure (Virone & Tovar, 2021) To achieve such ambitious goals, facilitating a high level of international collaboration between European players is an important necessity. Consequently, the European Clean Hydrogen Alliance was launched alongside the EU's new strategic direction in 2020. The main goal of the alliance is to support the large-scale development of clean hydrogen technologies by 2030 by bringing together renewable and low-carbon hydrogen production, demand in the industry, local and national authorities and other sectors (European Commission, 2022a). To integrate the hydrogen value chain across Europe it is crucial to establish an investment agenda and build up a robust pipeline of projects through the European Clean Hydrogen Alliance (Weinberger, 2020).

Due to the increased efforts and its offered benefits, the alliance currently (2022) has over 1000 members from all corners of the industry. Regarding Norway, members include leading companies and research organizations such as Equinor, Sinteff, Yara, NTNU and Nordic Energy Research. However, among the members, we see a lack of public authorities and financial institutions from Norway which would be crucial when Norwegian companies take part in developing large-scale hydrogen projects. In 2021 the European Clean Hydrogen Alliance announced a pipeline of projects which is a testimony of the EU's ambition to become a leader in the domain. The pipeline features over 750 projects that range from clean hydrogen production to its use in the industry such as buildings, mobility and energy (European Commission, 2022b).

3. A boom in large-scale hydrogen projects worldwide

As a result of the national and regional hydrogen strategies, investments in clean hydrogen have exploded in recent years on a global level (Van de Graaf et al., 2022). As of mid-2021, 359 large-scale hydrogen projects have been announced globally where Europe is leading with a total investment of $130 billion, however other regions are catching up quickly (Hydrogen Council, 2021). Around half of the global investments are planned for green/clean hydrogen production using renewable energy sources and electrolysis (Van de Graaf et al., 2022).

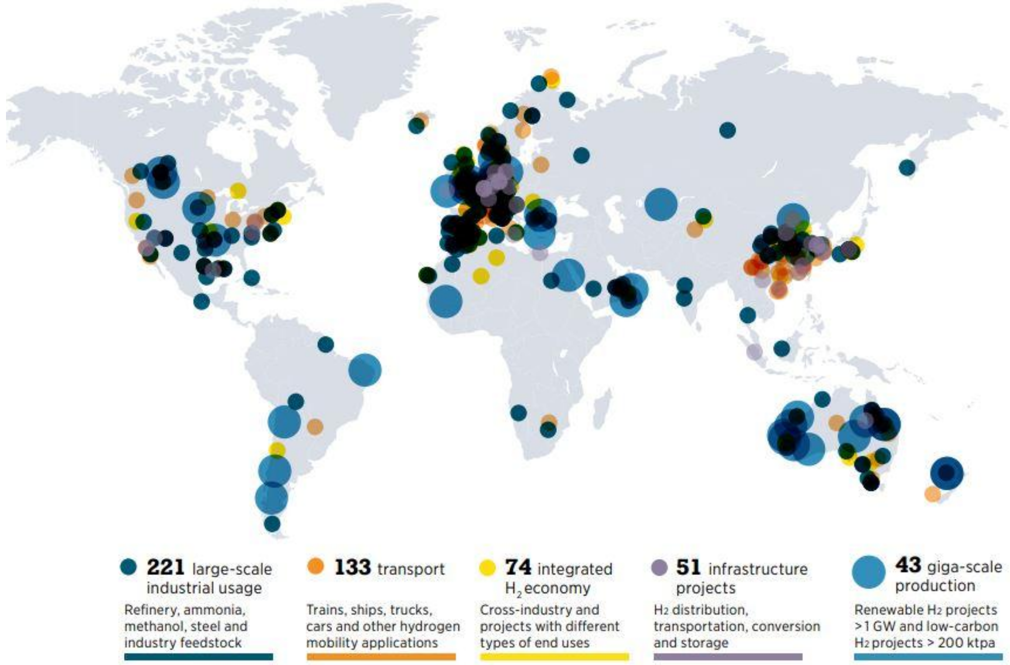


Figure 10: Announced large-scale clean hydrogen projects and investments as of November 2021 (Van de Graaf et al., 2022)

Source: Natural Earth, International Renewable Energy Agency (IRENA)

Figure 10 above showcases the global distribution of these projects while describing their magnitude and area of focus such as production, infrastructure, transportation application and industrial usage. It is well illustrated that around half of the world's announced large-scale projects are located in Europe. The region is followed by Asia with 23% and North America with 13% of the announced projects (Van de Graaf et al., 2022). Alongside the European Union, China has increased its efforts to become a leading player in the developing hydrogen market, thus it is a factor which shall not be overlooked. Currently, China is the largest hydrogen producer, however, it is mostly made from fossil fuels (Nakano, 2022). The country also holds the world's third-largest fuel cell vehicle (FCV) market with a growing rate of governmental and commercial investments in the area (Nakano, 2022).

4. Large-scale hydrogen projects in Norway

In the middle of the growing hydrogen momentum, Norwegian organizations were also active in developing international collaborative relationships with several important actors, mostly from Western Europe and the Nordics. Currently, there are around half a dozen announced large-scale hydrogen projects in Norway with different progress levels and scopes. Due to the country's rich natural resources and high level of infrastructure - as described previously - projects range from green hydrogen production, maritime and fuel cell applications, transportation and storage via CCSs. One of the projects with high potential is located in Porsgrunn where Yara and Linde, the world's largest industrial gas company, has announced the construction of a green hydrogen demonstration plant (*Yara and Linde Engineering*, 2022). The plant aims to deliver the first supply of green hydrogen and ammonia, offering the market fossil-free fertilisers and shipping fuel. The project is a good example of a mutually beneficial international collaboration that also heavily involves the local authorities as the project is supported by a NOK 283 million grant from Enova (*Yara and Linde Engineering*, 2022). However, several industry actors in Norwegian highlight the need to develop a larger showcase to demonstrate the economic, environmental and social sustainability of a full hydrogen value chain both regionally and nationally in Norway (Damman et al., 2020). The showcase would be a project that combines production, and several uses of hydrogen on a larger scale (Damman et al., 2020).

While we see a growing number of large-scale hydrogen projects in Norway that focus on a specific step of the value chain, it is important to point out that Norway lacks the pace to organise projects at a large scale compared to other countries. This is especially interesting given the country's natural resources, infrastructure and other opportunities. A report by the International Renewable Energy Agency (2021) describes that none of the world's 20 largest hydrogen projects (giga-scale projects) happen in Norway as of 2021, while several European countries such as Germany and the Netherlands were able to develop giga-scale projects through international collaboration. We argue that identifying a specific stage in the hydrogen value chain - e.g. green hydrogen production - would increase the likelihood of developing larger-scale projects and better position Norway as resources would not be scattered among several areas. Furthermore, by targeting a specific step in the value creation process Norway would better position itself within the integrated European market. In the following section, we further assess the main limitations that are behind Norway's inability to attract more international companies to develop hydrogen-related technologies and scale up local production.

5. Limitations and opportunities for international collaboration in Norway

To fulfil the country's ambition and become a leading actor in the global hydrogen market, the Norwegian authorities need to better prompt and guide the development through supportive incentives, institutions and capital (Damman & Gjerløw, 2019). While the industry and relevant authorities are working jointly to address the challenges of the developing market, a more active role is called for by the Norwegian government when it comes to bilateral cooperation (Meldahl, 2021). This is especially the case in the maritime industry where a large part is controlled through international conventions which take a long time to change (Damman & Gjerløw, 2019).

When it comes to developing large-scale projects locally, it is argued that the Nordic region - including Norway - lacks the general organising mechanisms (Ma et al., 2016). The Norwegian government's moderate activity level is tangible in other areas as well such as financing. As showcased previously, figure 10 visualises that several European countries - such as Germany, the Netherlands, Ireland and France - are ahead of Norway when it comes to the available annual funding amount for hydrogen-related projects. Thus it is without surprise that the listed countries could develop giga-scale hydrogen projects with a high level of international collaboration (Van de Graaf et al., 2022).

Regarding clean hydrogen production, a global challenge when attracting international companies is the recent increase in electricity prices as it is the main cost driver for green hydrogen (Berge, 2022). Due to the increase in natural gas prices and the recent geopolitical conflicts electricity prices skyrocketed in most countries, however in Norway the wholesale electricity price (€107 per megawatt-hour) is significantly lower than in most other European countries that are ahead of Norway in developing hydrogen technologies (Alves, 2022).

IV. Norway's context - A comparison

Alongside natural resources and infrastructure, other important factors influence the successful development of a new market. These include a country's entrepreneurial activity and its output, talent acquisition ability and available capital (Mainela et al., 2018). In this part of the paper, we compare Norway to Israel and China based on the previously listed factors.

1. Israel as a leading start-up nation

While Israel is not a leading player in the global hydrogen market, the country is known for its ability to launch new ventures and identify global technology trends before the new fields become crowded (Aharon et al., 2018). We consider Israel an appropriate research site, as similar to Norway the country has an export-dependent economy with a small domestic market (Mainela et al., 2018). Furthermore, both countries are considered to be innovative nations with Israel ranking 13th and Norway 20th globally according to WIPO's 2021 Global Innovation Index. However, while Israel has been seen as a start-up nation with a strong historic entrepreneurial performance, Norway hasn't performed that well in creating wide-ranging entrepreneurial success (Mainela et al., 2018; Tellis, 2016). Despite having one of the best business enabling environments globally, Norway cannot develop high-performing enterprises on a large scale (Global Entrepreneurship Monitor, 2022; Tellis, 2016). We believe by this comparative analysis we can identify important areas and approaches that could foster entrepreneurial activity in Norway.

2. The entrepreneurial ecosystem in Israel and Norway, differences in approach

Regarding the entrepreneurial ecosystem in Norway, the main stakeholder is the government through several supportive programs, funding policies, education and R&D transfer (Tuft, 2009). On the other hand, in Israel, the government has created policies since the late 80's to unleash the potential of the private sector which greatly contributed to kick-starting innovative industries (Yin, 2017). By creating different governmental programs and policies, Israel was able to encourage companies and foreign investors to take risks and explore new technologies in the country (Yin, 2017). Due to this approach, Israeli companies were provided with necessary early-stage funding and the country has become a leading high-tech ecosystem in the world. Currently, there are over 320 active funds in Israel and since 2015 there was an average of 25 VCs established annually (Cardumen Capital, 2020). Consequently, in 2019 Israel was ranked 1st globally in venture capital investments per capita with over $410 raised (Cardumen Capital, 2020).

On the other hand, entrepreneurial activity and the level of private investments have been moderate or even slightly low in Norway. According to The World Bank (2020), total early-stage (TEA) entrepreneurial activity is below the world median in Norway with essentially experiencing no increase between the period 2001-2020. Furthermore, when it comes to the total amount of VC investments per capita Norway raised $24 in 2018, while most Nordic countries such as Sweden, Denmark and Finland have been in the front row (Statista Research Department, 2022).

3. Norway's venture capital momentum

Most experts argue that one of the most important reasons behind this phenomenon is Norway's petroleum-heavy economy which has locked top-tier talents and capital over the past decades (Norselab, 2021). While Israel and most Nordic countries have fostered a high-performing entrepreneurial ecosystem, Norway has built its wealth upon the country's natural resources which approach has created different market dynamics from most countries (Norselab, 2021). However, due to the approaching oil downturn, Norway is showing more activity in the entrepreneurial landscape as for the first time, in 2021 Norway's venture capital firms invested a total of $1.3 billion which is a 150% increase from 2020 (Hodgson, 2022).

4. China and Norway: Similarities and differences

To further the understanding of the hydrogen market as a whole and how Norway fares compared to other players, we present data about the Chinese involvement in Hydrogen. Indeed, China is one of the leaders in Hydrogen, surpassing Europe in terms of demand and supply (Bakken et al., 2022).

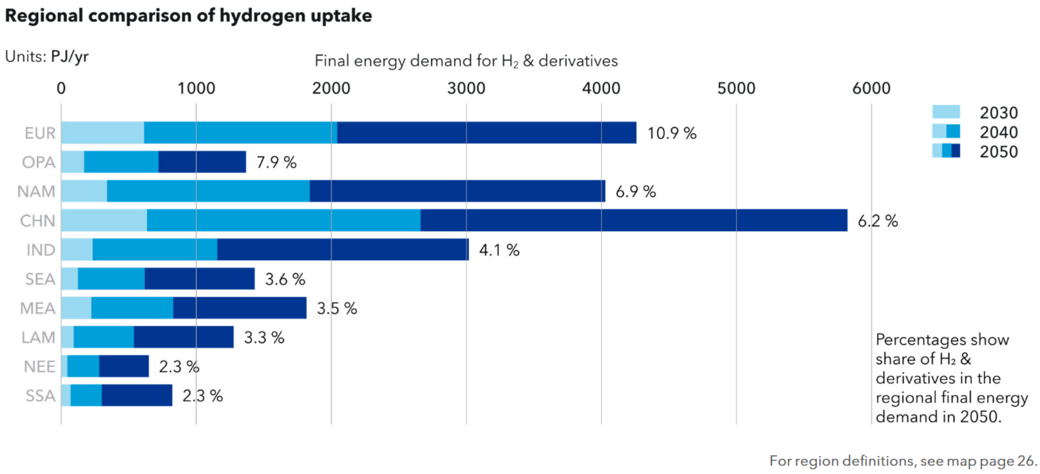


Figure 11: Regional comparison of Hydrogen uptake (Bakken et al., 2022)

Comparing China to Norway in terms of capital investment in new ventures is interesting, particularly the amount of venture capital deals (see analysis part II), China and Norway are quite similar standing at 0.10 deals per billion dollars of gross domestic product based on purchasing power parity (The World Bank, 2022b). The markets are obviously not comparable in terms of size, however, quantifying based on GDP and the overall manoeuvrability of capital, China could be considered to be performing to its fullest in the hydrogen industry.

The overperformance can also be observed when you consider the overall entrepreneurial output of China compared to a country like Norway. According to the world bank, the entrepreneurial activity of China and Norway is comparable with 8% of their population being nascent entrepreneurs or business owners (The World Bank, 2022a).

However, when you compare Norway to China on factors such as the Global Talent Competitiveness Index, Norway can be seen as one of the best performers, surpassing China in talent growth, attracting talent and retaining talent (INSEAD, 2021). Nonetheless, China remains quite attractive, placing 12 cities in the top 100 most attractive cities to operate businesses, while Norway only places its capital, Oslo, in that ranking.

As previously said, it would be unfair to draw conclusions solely based on the previously mentioned factors as the markets are uncomparable in size. However, we can also wonder, what, besides market size, does China have compared to Norway? The answer is supporting public institutions.

The overall industrial capacity of China is supported by the Chinese Five-Year-Plans (FYP) which details all the aspects the Chinese economy should act upon, across all sectors and industries. In their 14th FYP, China identifies hydrogen as one of their main levers of action to achieve carbon neutrality by 2060 and begin reducing their global emissions beforehand (*Issue Brief - China's 14th Five-Year Plan | United Nations Development Programme*, 2021). The long-term oriented market plans, as well as the government providing support to the hydrogen industry by setting ambitious targets (such as multiplying by 5 the number of electrolyzers between 2030 and 2050, making it 40% of the worldwide electrolyzers), provide China with a very strong competitive advantage to make it one of the bigger players on the hydrogen market.

Electrolyser capacity by region

Units: GW

		2030	2040	2050
NAM	North America	10	120	305
LAM	Latin America	4	27	83
EUR	Europe	111	351	574
SSA	Sub-Saharan Africa	4	16	66
MEA	Middle East & North Africa	8	35	147
NEE	North East Eurasia	3	13	22
CHN	Greater China	258	899	1248
IND	Indian Subcontinent	18	80	263
SEA	South East Asia	3	27	123
OPA	OECD Pacific	45	180	244
World		**465**	**1748**	**3075**

Figure 12: Electrolyser capacity by region target (Bakken et al., 2022)

Ultimately, Norway has a lot of potential and a big role to play in the hydrogen sector in the European market. But, if Norway wants to remain competitive and perform as one of the industry's major players, it needs to make sure the supporting infrastructure is present to help the Norwegian hydrogen industry move forward in the European Market.

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DISCUSSION AND CONCLUSION

Our research aimed to highlight the current situation for hydrogen development, particularly the points where the hydrogen industry struggles in Norway. By analysing various data sources and reports, this thesis presented key points of analysis that can further the understanding of the hydrogen industry in Norway for industrial actors, institutions and research organizations.

As the world slowly moves away from Oil and Gas, new solutions and opportunities have to arise and reach the broader market to become viable alternatives to the current polluting energy sources. In this ecological transition period, hydrogen plays a key role. Considering the current early stage of the hydrogen industry, we can also deduct its current position on the technological life cycle or S-Curve. Indeed, the hydrogen industry will soon witness an uptake and progression on the curve as it expands on various markets and exploits new opportunities. Nonetheless, it will only be possible if the industry manages to cross the chasm, as described by Moore (1991) and reach the early majority of the market.

The crossing of the chasm will mark a definite shift in investing philosophy in Norway, in particular regarding its general positions on new industry investment. As discussed in the Israeli comparison and the capital structure sections, Norway can be considered a laggard in riskier investment and new venture financing opportunities. If Norway wants to remain involved in the hydrogen sector and secure its position as one of the key players, there needs to be a substantial increase in investments and a reduction of the risk-aversion of investors in the country. The effort will have to be led by the government as the Norwegian culture emphasises trust and loyalty, particularly in its public institutions.

Acknowledging the market characteristics, its limits and opportunities is another key element to pushing the industry past the gap between early and mainstream markets, locally and internationally. The Norwegian market remains limited in size, nonetheless, if Norway leverages its existing infrastructures and processes used for fossil fuels as well as fostering relationships with the European market, the potential is immense. The ability to retrofit the existing infrastructure and processes gives Norway a competitive advantage in the development of its hydrogen industry which can be maintained if R&D investments and infrastructure commitments continuously improve in the years to come.

The competitive advantage Norway possesses is especially useful when you consider the universality of hydrogen production. Acting as an earlier mover for the industry and even focusing on a niche or segment of the value chain could be invaluable for Norway's positioning in the world's hydrogen market, placing it as one of its leaders.

As the Norwegian government's hydrogen strategy (2020) highlights, international collaboration will play a crucial role in establishing a functional domestic market since future demand for hydrogen and related technologies is expected to come from outside of the country. However, our research underscores the deficiency in several related areas. To attract more international companies and develop large showcase projects that demonstrate the economic, environmental and social advantages of hydrogen Norway must increase its efforts in bilateral cooperation. Creating investment opportunities, supportive frameworks and policies are key tools, especially in the maritime industry where a large part is controlled through international conventions.

What is the potential of the Norwegian Hydrogen market?

Hydrogen ultimately has the potential to replace Oil and Gas as the main revenue source for Norway as it transitions away from fossil fuels.

To conclude, our master thesis illustrates the potential of Norway in the hydrogen industry but it also raises the question of whether Norway will achieve its full potential or not. The conceptual approach of the paper allowed us to cover most of the factors which should be discussed for the development of the hydrogen industry as well as bridging the considerations that actors should have for the industry. Based on the points presented, industry actors, and particularly the Norwegian government, should increase their financial and infrastructure involvement to place Norway as the hydrogen leader of tomorrow.

APPENDIX

Appendix A:

The colours of hydrogen and resulting GHG emissions

	Colour of hydrogen	Feedstock	Production technology	Direct GHG emissions[a] kg CO_2e/kg H_2	Indirect GHG emissions[b] kg CO_2e/kg H_2
Produced using electricity	Green	Renewable electricity, water and/or steam by thermolysis	Electrolysis	-	>0[c]
	Yellow	Grid electricity, water		-	<1 - 30 *Depends on the carbon intensity of the grid mix*
	Pink	Nuclear electricity, water		-	>0[c]
Produced using fossil fuels	Grey	Natural gas	Methane reforming	9 - 11	0.5 - 4
	Brown	Lignite	Gasification	18 - 20	1 - 7
	Black	Black coal	Gasification	18 - 20	1 - 7
	Blue	Natural gas or coal	Methane reforming with CCS Gasification with CCS	0.5 - 4	0.5 - 7
	Turquoise	Natural gas	Pyrolysis	Solid carbon (by-product)	0.5 - 5
	Green	Biogas or biomass	Reforming with or without CCS Gasification with or without CCS	Possibility of negative emissions with CCS	1 - 3
Other	Red	Nuclear heat, water	Thermolysis	-	>0[c]
	Purple	Nuclear electricity and heat, water	Thermolysis and electrolysis	-	>0[c]
	Orange	Solar irradiance, water	Photolysis	-	>0[c]
	Green	Waste wood, plastic, municipal solid waste	Thermochemical	Possibility of negative emissions with CCS	Not assessed as variabilities in the value chains are too great to accurately represent the GHG equivalent emissions

[a] Direct emissions account for the hydrogen production process emissions.
[b] Indirect emissions account for the feedstock supply-chain emissions as well as the energy generation supply-chain emissions. Other indirect emissions, such as capex-related emissions, are also important but are not included here.
[c] Comparable to renewable power production infrastructure (1-20 gCO_2/kWh). The emissions related to the hydrogen infrastructure and hydrogen leakage will also contribute to indirect GHG emissions, where the exact quantities have to be identified.

The table is inspired by: Global Energy Infrastructure (GEI), 2021.

The colours hydrogen and resulting emissions (Bakken et al., 2022)

Appendix B:

Characteristics of Norway that enable the development of new technologies (Bjørnland et al., 2022)

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