MSc Thesis

Forming a guideline for the design and maintenance of resilience in an international green hydrogen supply chain

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Executive Summary

International efforts have been made to reduce carbon emissions and increase the use of renewable energy sources like solar and wind power since the adoption of the Paris Agreement at the United Nations Framework Convention on Climate Change in 2015. Due to the asymmetry in (green) energy production, consumption between nations as well as limits of renewable energy generation caused by seasonal and temporal intermittency and geographic variances, there is a demand for efficient energy transporters. Considering this, hydrogen is seen as one of the promising carriers, due to its high stored energy density and the fact that it only creates water after burning. Some (inter)national governments have already declared their roadmaps, such as the REPowerEU package in line with the EU Green Deal in Europe. On the other side of the world, the "Basic H2 strategy" was formulated by Japan. Two countries that are thus regarded as substantial importers of hydrogen, are Japan and The Netherlands. But while plans for international green hydrogen supply chains (IGHSC) are being made, so does the need grow for shaping resilient characteristics for the supply chains, so that these future supply chains are robust, reliable and resistant towards the numerous unexpected disruptions they are subject to. The objective of this thesis is therefore to develop a guideline on how to establish a resilience design methodology for an IGHSC, choosing supply chains involving Japan and The Netherlands as importers as examples for a thorough understanding of the functioning and configuration of an IGHSC. Therefore, the main research question central in this thesis is: What guideline can be established to design and maintain resilience in an IGHSC, using the role of The Netherlands and Japan as large future importers as exploratory examples? This thesis was executed through a blend of literature research and analysis, and interviews, all orchestrated within a qualitative exploratory interdisciplinary approach. Most of the time, the type of topics that this thesis encompasses use a geo-political-technical perspective and approach. This thesis added to the existing body of research concerning international green hydrogen supply chain by using the resilient lens as the main approach. For this, a theoretical framework was established to unveil interconnections of diverse theories and fields of study. This framework not only aided in identifying previously unnoticed associations but also served to define the disruptions and the mechanisms of resilience intrinsic to an IGHSC. Consequently, this study identified and introduced two novel optional IGHSC configurations, cataloged relevant disruptions along with their respective domains. Through a rigorous evaluation of existing research on disruptions and the improvement of corresponding categorization schemes employed in these studies, this thesis constructed a new structure for cataloging potential disruptions that might occur within an IGHSC. These disruptions were systematically categorized based on the domains from which they could potentially arise, being geo-political, market economics, natural hazards, technical and human resources. Resilience was then defined, categorized into two distinct phases and three scopes, providing a structured framework for designing and maintaining resilience in an IGHSC. This thesis therefore established a novel guideline that contributes to toolkit for the design and maintenance of resilience in an IGHSC. In the initial design phase of our study, this thesis delved into the fundamental concepts that

distinguish it. It became evident that the foundation of configuration resilience is laid during this phase. Drawing parallels with real-world systems, particularly within the LNG and gas market, this thesis identified how the choices made during location selection, partner selection, partner securitization, diversification, and harmonization can reverberate throughout the subsequent post-design phase of the supply chain configuration.

Moving into the post-design phase, this thesis established a comprehensive framework. Our approach began by deconstructing the definition of resilience into four pivotal abilities: anticipation, response, recovery, and improvement. In doing so, this thesis rigorously examined how these abilities interplay and influence each other. This thesis further dissected these four abilities into distinct elements, adhering to the MECE (Mutually Exclusive, Collectively Exhaustive) principle. These elements served as the qualitative metrics for resilience during the post-design phase. Subsequently, this thesis introduced Key Performance Indicators (KPIs) to quantitatively assess these metrics, forming the bedrock of our resilience evaluation. These efforts culminated in the creation of a robust framework encompassing these critical components: the abilities, the elements, and the quantifiable KPIs. This framework serves as a valuable tool for evaluating, maintaining, and enhancing resilience within the post-design phase of the supply chain. A comprehensive overview was established that weaves together the two distinct phases, the design choices made, the resilience abilities, and their implications within the existing landscape and regulatory framework. This holistic perspective illustrates how adopting a resilient lens can and should be an integral consideration for decision-makers seeking to establish a pioneering international green hydrogen supply chain.

The ensuing discussion and recommendations illuminate the versatility of our resilient approach, framework, and overview. They underscore how these insights can transcend the specific context of an international green hydrogen supply chain, extending their utility to address pressing issues, such as the current security of supply challenges facing the European Union. This revelation underscores the wide-reaching applicability of our guideline, which, although rooted in exploratory examples from Japan and the Netherlands as major future importers of green hydrogen, possesses the potential to inform and guide decision-making processes across a multitude of domains.

Contents

List of Abbreviations

CAS Complex Adaptive Systems
CCS Carbon Capture & Storage
CGH2 Compressed Gaseous Hydrogen
GHG Greenhouse Gas
HSC Hydrogen Supply Chain
IGHSC International Green Hydrogen Supply Chain
KPI Key Performance Indicators
LH2 Liquid Hydrogen
LOHC Liquid Organic Hydrogen Carrier
MCH Methylcyclohexane
NH3 Ammonia
SCRES Supply Chain Resilience

1 Introduction

In the 6th century, Heraclitus said the words “The only constant is change”. This sentence may now be truer than ever. For a very long period, fossil fuels were the primary source of energy. However, there has recently been a shift in focus toward environmentally friendly energy production due to the environmental issues associated with carbon-containing greenhouse gases (GHG) that are emitted when carbon, the primary component of fossil fuels, is burned (Cho et al., 2012). International efforts have been made to reduce carbon emissions and increase the use of renewable energy sources like solar and wind power since the adoption of the Paris Agreement at the United Nations Framework Convention on Climate Change in 2015 (UN, 2015). Due to the asymmetry in (green) energy production and consumption between nations as well as limits of renewable energy generation caused by seasonal and temporal intermittency and geographic variances (Abdin et al., 2020), there is a demand for efficient energy transporters. As a result, the storage and transportation of energy over great distances and abroad is necessary (Abdin et al., 2020). Considering this, hydrogen is seen as one of the promising carriers, and some (inter)national governments have already declared their roadmaps, including the EU Green Deal in Europe (Fetting, 2020) and the "Basic H2 strategy" in Japan (Japanese Basic Hydrogen Strategy, 2017). Due to its high stored energy density and the fact that it only creates water after burning, hydrogen is viewed as a potential energy transporter that is also environmentally friendly (Fetting, 2020).
Two countries that are regarded as substantial importers of energy carriers such as hydrogen, are Japan and The Netherlands (Chen et al., 2023). While Japan has already demonstrated two international hydrogen supply chains (HSC), The Netherlands has not. Nonetheless, as outlined in (RN2, 2020a), there are numerous possible supply chains involving The Netherlands as importing end. On top of that, European annual budgets for H2 support are becoming real and this will support the development of global routes even further. The H2 routes involving The Netherlands and European support budgets as found in the BNEF report are given in 3

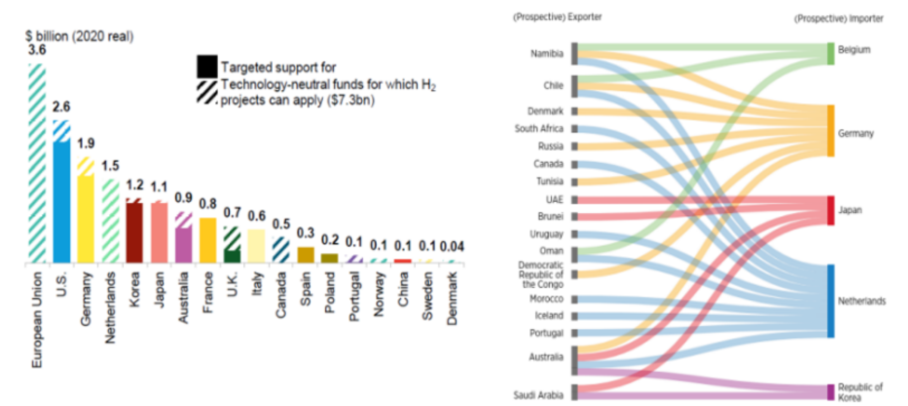

Figure 1: Average annual budgets for H2 and expected global H2 routes to be formed, BNEF (2022)

1.1 The importance of resilient hydrogen supply chains

International HSCs must be built since hydrogen is expected to play a significant part in the global decarbonization, as well as for the Dutch and Japanese energy systems. As with natural gas, hydrogen can be compressed or liquefied to be transported. For some countries, such as Japan as an island country, this is the only option to purchase significant quantities of this emission-free energy carrier. Although it appears to be the perfect fuel source on paper, there have been substantial technical difficulties to overcome in its primary production, storage, delivery, and consumption (Nature Publishing Group, 2023). Despite numerous countries' and continents' apparent plans for their role in the hydrogen economy, researchers have observed that potential hydrogen streams face substantial obstacles because of a lack of infrastructure and distribution networks (Pudukudy et al., 2014). Moreover, throughout the whole H2 supply chain, disruptions may occur; unexpected events that may be the result of natural disasters or human activity (Fazli-Khalaf et al., 2020). It implies that due to the nature of the disruptions, supply chain managers are unable to foresee their occurrence. Correct management of the green hydrogen value chain is crucial for both economic competitiveness and energy security (Pudukudy et al., 2014). HSC's must therefore expand efficient techniques for controlling their negative consequences on reliability. Additionally, due to the technological aspects of the hydrogen value chain and global geopolitical volatility, robustness issues may arise in these international supply networks. As a result, HSC's may benefit greatly from assessing and developing resilient characteristics as part of their supply chain design of these to be formed HSC's. Past demonstrations, research, and current expertise on every aspect of the HSC configuration and the growth of a global hydrogen economy may all teach us valuable lessons about resilience. Up to this point, no research has attempted to define resilience in an IGHSC and form indicators that can assess resilience performance throughout the whole value chain. This is when a problem arises: while the need for a reliant international energy carrier supply chain increases, guidance in designing resilient characteristics in order for these international supply chains to overcome the turbulent environment full of disruptions is lacking. More specifically, countries such as The Netherlands and Japan are increasingly interested in green hydrogen, in order to meet decarbonization ambitions, yet lack the knowledge of building a resilient green hydrogen supply chain.

1.2 Literature Review

With the starting point of the big ambitions of Japan and The Netherlands and the future role hydrogen will play in their energy systems and the sensitivity to possible substantial obstacles or disruptions affecting the reliability of an IGHSC, literature concerning the prospect of hydrogen utility in The Netherlands and Japan is analyzed and literature containing technical research on IGHSC involving these countries was reviewed to establish a more detailed research gap.

1.2.1 The Role of Hydrogen in Japan and its Status

In Japan, where the land area is relatively modest compared to the level of economic activity and the population, renewable energy generation frequently comes with several technological and sociological limitations. For instance, among the 10 most developed nations, Japan has the lowest economic potential for solar electricity generation in homes and businesses (14.5%), largely because of the amount of building space per person that is accessible (IEA, 2011). Additionally, Japan's energy demand is quite big compared to the small economic possibilities of wind power (Dai et al., 2016). Furthermore, given that the majority of (renewable) resources are concentrated in northern regions of Hokkaido and Tohoku, and that the Japanese electricity grid is segmented into 10 regional power supply firms, the geographic asymmetry between regions of electricity consumption and production may also be a barrier to the widespread use of wind power (Dai et al., 2016). Even though Japan has an abundance of geothermal resources, there are non-technical constraints because new projects are frequently located inside national parks (IPCC, 2011). Nuclear energy can also be viewed as a domestic low-carbon resource, however, most of Japan's nuclear plants have been shut down after the Fukushima Dai-ichi nuclear power plant accident in Japan in 2011 (IEA & NEA, 2015). As a result of these restrictions on nuclear power and renewable energy sources, energy and climate policy must bear the hard task of both fulfilling the needs of decarbonization and maintaining energy security.

Because of all the above reasons, for Japan to structurally address the energy and climate issues, hydrogen can play a vital role when incorporated into the country's future energy system. To reach Japan's climate ambitions, developing- and investing in the entire hydrogen value chain is required (Lacey et al., 2020). As with natural gas, hydrogen can be compressed or turned into liquid form for transportation. This method becomes crucial for certain nations like Japan, which is an island country, as it becomes their sole choice to acquire substantial amounts of this clean energy carrier. Additionally, surplus renewable energy can be harnessed to generate hydrogen for the purpose of storing energy (Thema et al., 2019). The capability of hydrogen to circulate through pipelines approximately three times quicker than methane adds to the cost-effectiveness of nationwide transportation of hydrogen (Tashie-Lewis and Nnabuife, 2021).

Because of the important opportunities hydrogen could offer Japan and to overcome these technical difficulties, two demonstration projects have already been concluded. To create MCH from hydrogen and Toluene in December 2019, Brunei used natural gas for hydrogen production (Song and Wang, 2021). Five ISO tanks filled with MCH were sent to Kawasaki City, Japan, where it was utilized to generate electricity for the power plant's hydrogen fuel gas turbines after being dehydrogenated in an oil refinery (Song and Wang, 2021). This occasion heralds the start of the MCH hydrogen storage and IGHSC's commercialization. Because of the similarity to the current LNG industrial chain, the IGHSC could learn from or even directly implement existing experience(Zhang et al., 2022). Secondly, preserving trade links and reusing infrastructure, given the embedded nature of Japan's coal and LNG imports from Australia, strategies have been studied for using Australian resources to create hydrogen that would then be transported to Japan for use (Chapman et al., 2017).

This project adopted the name HySTRA and demonstrated large-scale international hydrogen shipping in the form of liquid hydrogen (LH2) as well as hydrogen synthesis from brown coal (Jensterle et al., 2019). The project involves liquefying hydrogen from brown coal, refining hydrogen, exporting LH2, and successfully receiving and utilizing the LH2 in Japan.

1.2.2 Literature about International Hydrogen Supply Chains Involving Japan

Apart from the demonstration projects that are already conducted for Japanese HSC, research has been done on possible future IGHSC's with Japan as importing country. In (Ishimoto et al., 2020),energy efficiency, CO2 footprint, and cost of liquefied hydrogen (LH2) and ammonia (NH3) as H2-based energy carriers are examined and compared for a supply chain between renewable energy plentiful Norway and predicted importer Japan and Europe (Rotterdam). It has been demonstrated that the LH2 chain is more energy efficient and has a lower CO2 footprint. In (Heuser et al., 2019), a spatially well-resolved wind energy potential study and a rigorous investigation of the supply chain elements between Patagonia and Japan were used to reexamine the idea of a HSC. It is noteworthy to mention that this study describes the same elements as HyChain (2023) and (IEA, 2019)for their analysis of the potential H2 supply chain, but in more specific terms, namely wind energy conversion, water electrolysis, a domestic pipeline transmission system, hydrogen liquefaction and storage facilities, and specific carriers for oversea delivery of liquefied hydrogen (Heuser et al., 2019). (Chapman et al., 2017) present an approach for comparing the technological, economic, and social costs and feasibility of various HSC pathways between Australia and Japan. They propose three case studies. First, a case study of Australian brown coal that utilizes carbon capture and sequestration (CCS) technology is studied. The second and third comparative case studies employ renewable energy and electrolysis near port facilities, the first with solar power serving as the sole renewable energy source and the second using a combination of onshore wind and solar-based electricity generation. In (Kamiya et al., 2015), the technical and economic viability of a CO2-free hydrogen energy supply chain model containing LH2 from Australia to Japan is described, as well as its transportation and storage. As stated before, this was later demonstrated in real life by Kawasaki Heavy Industries (Jensterle et al., 2019). In (Gallardo et al., 2021), the entire solar HSC has been examined from a techno-economic angle. Based on Japan's declared 2025 H2 demand, various distribution, storage, and transportation systems are examined, comparing LH2 and ammonia (NH3) being transported from Chile to Japan.

1.2.3 The Role of Hydrogen in The Netherlands and its Status

The Netherlands is also globally regarded as one of the future's biggest importers, with a target of 4 gigawatts of power from green hydrogen production by 2030 set by the Dutch Climate Agreement in 2019, which was later increased to 8 gigawatts (of Economic Affairs, 2019), due to rising energy costs, the closure of the Groningen gas fields, and a desire to stop importing Russian gas. The Netherlands, according to VVD and D66, is ideally suited for a switch to green hydrogen due to its extensive potential for producing wind energy in the North Sea and its existing gas infrastructure (Gallardo et al., 2021). The growth of demand is another indicator of the importance of hydrogen development. In the course of the Climate Agreement process, the prospective hydrogen consumption was identified. This demonstrated that by 2030, there will be a sizable potential demand for hydrogen for industrial applications on the coast alone (between 125 and 213 PJ)(of Economic Affairs, 2019). Additionally, there might be an increase in demand for hydrogen for producing energy along the shore (of Economic Affairs, 2019). The Netherlands may serve as the point of entrance for enormous quantities of hydrogen (and other hydrogen carriers) for Europe, as European demand will most likely see a very steep increase in demand in the coming decade as well (Partnership, 2023). The Port of Rotterdam also disclosed that it is collaborating with several partners to build a substantial hydrogen network throughout the port complex. This will enable Rotterdam to serve as a global hub for hydrogen production, import, application, and transportation to other nations in Northwest Europe. This will support The Netherlands' ability to continue serving as a key energy hub for Northwest Europe (of Rotterdam, 2021). In summary, The Netherlands is actively engaged in developing domestic green hydrogen initiatives, which notably involve offshore wind energy projects in the North Sea and have garnered substantial interest. Nevertheless, the projected volume of green energy from these domestic sources is inadequate to meet the anticipated future demand for hydrogen as delineated in the Green Deal for green hydrogen (Noussan et al., 2021). Consequently, it is a reasonable conclusion that the Netherlands must import low-carbon hydrogen from regions abroad that possess surplus renewable energy to fulfill its outlined objectives.

1.2.4 Literature about International Hydrogen Supply Chains Involving The Netherlands

(Ishimoto et al., 2020) adopt a techno-economic methodology to assess the feasibility of shipping hydrogen imports from Norway to the Netherlands. Their findings reveal that the cost and CO2 emissions associated with importing liquefied hydrogen stand lower compared to importing ammonia. On a separate note, Konda et al. (2011) delve into the realm of domestic HSC transition paths within the Dutch transportation sector. This inquiry emphasizes the domestic hydrogen infrastructure's structure, encompassing both quantitative and qualitative evaluations of three potential hydrogen production methods. The assessment also extends to a qualitative exploration of the Carbon Capture and Storage (CCS) potential within the Dutch context. It's important to underline that the existing body of scientific literature concerning a comprehensive global Dutch HSC is notably scarce.

1.2.5 Existing Body of Technical Research on Hydrogen Supply Chains

There is established that research on supply chains for hydrogen (carriers) involving Japan has certainly been done to some degree. The body of research on potential Dutch HSC's, however, is not extensive. It is important to investigate what research has been done on establishing new HSC's and, equally important, what aspects and criteria these studies focused on. A lot of the studied literature is focused on techno-economic aspects; in (Neumann et al., 2023), case studies of potential trade routes between the potential energy exporters Morocco, Saudi Arabia, and Australia and the potential energy importers Germany and Japan are examined, evaluating the energy (thermodynamic efficiency), economic (levelized cost of electricity - LCOE), and environmental (CO2 emissions) aspects. In addition, (Kim et al., 2021) looked into the economics of the HSC, from the international supply to domestic consumption in South Korea, while taking several viability scenarios into account. The least expensive option, according to their research, is to import H2 using LH2, as this avoids the need for energy-intensive conversion procedures like hydrogenation or cracking. (Erdoğan et al., 2023) wrote a paper about the design of a HSC network that will reduce costs, carbon emissions, and security risks for Turkey. In (Noh et al., 2023), a life cycle analysis (LCA) for offshore HSCs connected to offshore wind farms is carried out, along with an energy efficiency analysis. Also from a techno-economic perspective, assessing the economic viability of solar hydrogen delivered to a hydrogen pipeline in Stuttgart, Germany, (Eckl et al., 2022) conducts a case study using a HSC originating in Portugal (Okunlola et al., 2022a). evaluate the delivered cost of exporting gaseous hydrogen from Canada, a nation with a wealth of fossil fuels, to the Asia-Pacific, Europe, and inland North American destinations. They discovered a knowledge gap on the viability of transcontinental hydrogen export from an energy-producing region to an energy-consuming region. Once more, techno-economics was utilized to estimate the cost of hydrogen transported to these locations. In (Hong et al., 2021), four solutions for transporting hydrogen between export and import terminals - MCH, LH2, compressed hydrogen, and liquid ammonia - are thoroughly studied in terms of their infrastructure and energy needs, once more from a techno-economic and environmental standpoint. In (Fazli-Khalaf et al., 2020), a new and intriguing perspective is put out to enhance a HSC's reliability, social responsibility, as well as its economic and environmental elements. A new objective function that maximizes the reliability of product distribution is expanded to assure the network's responsiveness. Additionally, a cutting-edge reliability strategy is created to protect the network from interruptions. Social concerns are taken into account in the design of the HSC as a new sustainability indicator.

A large body of work that was investigated focuses on techno-economic and environmental aspects. As future hydrogen supply and distribution chains are subject to address multiple objectives for robustness, it is also important to investigate research that is conducted into reliability, risk, and resilience assessments for HSCs (Markert et al., 2017). (Markert et al., 2017) discuss the "Functional Modeling" methodology as it is established that techniques are required to evaluate the supply chain. It demonstrates how various decision support techniques for thorough risk and sustainability evaluations could be built on the foundation of functional modeling. In a complicated hydrogen supply and distribution network, where there are significant links and interferences between power storage for the supply of electricity and supplying hydrogen for transportation, it demonstrates a framework for explaining how functions are coupled. Along with a few other decision-support tools like Geographic Information Systems (GIS) and Life Cycle Assessment (LCA), the method of "Functional modeling" is described. But ultimately, the goal is to identify the

best options for regional or national, not global, infrastructure development. Other research that addresses the reliability of the HSC is found in (Nunes et al., 2015). It proposes a methodology for developing a HSC while taking into account the inherent uncertainty of the demand for this fuel in the future. An optimization model based on two-stage stochastic mixed-integer programming is suggested to characterize the issue and assess investment options for the logistic infrastructure.
Ren et al. (2013) contain additional pertinent research for creating a HSC. To increase the sustainability of the HSC, the article offers a strategy for ranking the important components in order of importance, identifying the major driving factors that affect the sustainability of the HSC, and mapping the cause-and-effect interactions. For improving the sustainability of the HSC, 37 criteria in four categories-economic, technological, environmental, and societal—have been considered (Ren et al., 2013). A decision-making trial and evaluation laboratory has been utilized to examine the connections between these criteria.

1.3 Research gap

The literature review reviewed all research surrounding the role hydrogen will play for Japan and The Netherlands and the existing body of research about HSCs involving these countries. Additionally, the existing body of technical research on HSCs was investigated, with a focus on resilience design.

All considered, the research gaps that will be central to this thesis project will be the following:

1. It was found that indeed a lot of research was done on establishing new (parts of) hydrogen supply chains. However, the literature almost always focuses on one optimization criterion, e.g. techno-economic, sustainability, energy efficiency, etc., and on a specific route between two new locations. As future hydrogen supply and distribution chains are subject to address multiple objectives for robustness, it is also important to investigate a way for ensuring resilience in the new supply chain. Passed research focused a lot on reliability, risk, and assessments of supply chains subject to specific uncertainty, but no literature was found focused on maintaining or designing a resilient HSC's or even defining resilience for a HSC. On the identification of disruptions and the evaluation of the resilience of HSC's, there is little to no information available, and the literature is more leaned towards risk assessment and mitigation. This highlights the need to develop a guideline for a resilience design methodology to guarantee the HSC's responsiveness to disruptions. Choosing which disruption anticipation measures need to be implemented for global hydrogen supply networks to maintain reliability, security, and resilience is particularly challenging without these essential disruption identifications and resilience assessments. This significant gap has been disregarded in earlier studies in this area.

2. It was found that for Japan and The Netherlands, two countries regarded as large future importers of hydrogen and therefore involved in multiple supply

chains, very little literature was available about HSCs. Moreover, when literature was available, it again was about techno-economic, sustainability, energy efficiency, and country-specific optimization studies. Including these two countries in an assessment study where disruptions affecting supply chain resilience are identified is highly relevant.

The cases of Japan and The Netherlands and the lack of research on IGHSC's resilience demonstrate the need for a guideline for an IGHSC design methodology that bridges the gap between disruption identification, defining resilience for a hydrogen supply chain, and combining the two to establish a method for the design and maintenance of resilience for a future IGHSC.

1.4 Research objective

The main objective of this study is to develop a guideline on how to establish a resilience design methodology for an IGHSC, choosing supply chains involving Japan and The Netherlands as importers as exploratory examples for a thorough understanding of the functioning and configuration of an IGHSC.

The following sub-objectives are established to achieve the main objective of this study:

1. To identify the different pathways and supply chain elements that can be established for an IGHSC, using the exploratory examples of Japan and The Netherlands as large future importers, to gain a thorough understanding of a green international hydrogen supply chain configuration.

2. To identify the disruptions present in a hydrogen supply chain system throughout the entirety of the supply chain and to show how these need to be considered using the exploratory examples of Japan and The Netherlands as large future importers.

3. To define resilience for an international hydrogen supply chain and come up with an adequate overview of the abilities that are required to build and maintain resilience, throughout the design and operations.

4. To establish an overview that captures international hydrogen supply chain resilience throughout its design and maintenance, and how it is connected in the socio-eco-techno-political environment.

5. To identify a resilience assessment methodology and evaluate its suitability to international hydrogen supply chains.

1.5 Research questions

To achieve the research objective, the research question is formulated as follows:

What guideline can be established to design and maintain resilience in an international green hydrogen supply chain, using the cases of The Netherlands and Japan as large future importers as exploratory examples?

The following sub-research questions are formed, together aimed to answer the main research question:

1. How can we define resilience and disruptions for an international hydrogen supply chain?

2. How can we describe international green hydrogen supply chain configurations involving Japan and The Netherlands as importers?

3. What are the disruptions that can be identified affecting an international green hydrogen supply chain's performance and how do these disruptions need to be considered, using the configurations of Japan and The Netherlands as examples?

4. What are the design choices, abilities and KPI's that are required to build and maintain resilience for an international green hydrogen supply chain and how can this be captured in a framework?

Now that we established the RQ's that this thesis is going to answer, it is imperative to form a theoretical framework. This will provide this thesis with the fundamentals that are required to form a solid methodology, and aids in the establishment of key concepts central in this thesis.

2 Theoretical framework

To lay a firm groundwork for this thesis, a theoretical foundation will be constructed. This foundation outlines vital concepts and theories and explains how this thesis contributes to the current literature. Supply chain resilience (SCRES) will be defined and conceptualized within this chapter. Moreover, various theories will be explored, their relevance to the study, and how they can aid in answering the main research question. Before resilience can be defined for this thesis, it is important to have a clearly defined definition of the green hydrogen pathway, know where the system boundaries are, what the system elements are, and how they are connected. Next, as resilience is related to unexpected disruptions, it is important that we define and set clear criteria on the definition for disruptions that affect SCRES and are incorporated in this thesis.

2.1 Green Hydrogen Supply Chain

In this section, the concept of green hydrogen and the basic configuration of an IGHSC will be provided. It is important to have a grasp of the criteria for the green hydrogen pathway and the basic system configuration of an IGHSC, before moving on to the establishment of the definitions of resilience and the disruptions.

2.1.1 Defining Green Hydrogen

First, it is important to define what will be called "green hydrogen" throughout this thesis. Hydrogen is the most plentiful and basic element, consisting of a proton and an electron but rarely obtainable as a pure gas (Howarth and Jacobson, 2021). A scheme based on distinct colors is increasingly being used to codify hydrogen-producing technology (Newborough and Cooley, 2020). The following are the primary hues under consideration, as found in Ivanenko (2020);

1. Grey (or brown/black) hydrogen, which is produced by fossil fuels and therefore causes emissions of CO2 in the process.

2. Blue hydrogen, which is produced by combining grey hydrogen and carbon capture and storage (CCS) technologies, to avoid most of the GHG emissions of the process.

3. Turquoise hydrogen, which is produced through the pyrolysis of fossil fuel, produces the by-product of solid carbon.

4. Green hydrogen, which is produced by electrolyzation of which the energy is supplied by renewable electricity (and sometimes through bioenergy, such as biomethane reforming or solid biomass gasification)

5. Yellow (or purple) hydrogen, which is produced by electrolyzing of which the energy is supplied by electricity from nuclear power plants.

In this thesis, we will solely focus on green hydrogen, as it is ultimately the goal for a worldwide hydrogen economy to use green hydrogen over other colors of hydrogen (Noussan et al., 2021). The renewable sources for the green hydrogen pathway that will be considered are solar power and wind power. Although each technological path to produce hydrogen has advantages and disadvantages, it is important to keep in mind that selecting a particular solution is frequently influenced by other factors, such as geopolitical decisions based on national strategies motivated by the availability of resources, energy security concerns, or the support for industrial sectors (Scita et al., 2020). However in this thesis, international hydrogen trade is regarded as having the potential to transform energy geopolitics due to the necessity for a very strong decarbonization of energy systems in the next decades, and for this goal, green hydrogen would have the biggest impact on the long term (Van de Graaf et al., 2020). Moreover, it is expected that in the long term, green hydrogen will be the cheapest form of hydrogen and therefore its share will be increasing over time (RN2, 2020a).
This means that the green hydrogen pathway will be considered solely in this thesis. The definition for the green pathway that will be used in this thesis will thus be the combination of renewable energy generation with water electrolysis. This also entails specific resilience and technical implications, that will be discussed further throughout this thesis.

2.1.2 Defining a Green International Hydrogen Supply Chain Configuration

Now that we have defined the green hydrogen pathway requirements, it is important to describe the elements of the green hydrogen pathway system and its global supply chain. In Chapter 4, the elements that make up the system will be specified based on for the examples of Japan and The Netherlands. By definition, a chain is a collection of elements connected in a line, with each link connecting no more than two additional elements (Reyes Levalle and Nof, 2017). Due to how successfully this idea of sequential links served as a conceptual framework for actual industrial activities including the conversion of raw materials into completed items, the concept of a supply chain was initially proposed (Reyes Levalle and Nof, 2017). Even though the number of actors and their relationships have led to an increase in supply chain complexity, the notion of a supply chain as a sequence of stages is still widely held. The HSC will be viewed in this thesis as a collection of interconnected elements that interact through flow exchanges and communications to accomplish either their own particular goals or a set of mutually exclusive goals(Reyes Levalle and Nof, 2017). According to the (IEA, 2019), HSCs are separated into the following elements, that will also be used in this thesis: production, conversion, transport, reconversion, storage, and utilization. Hydrogen produced and processed in another nation and then transferred to the Netherlands or Japan is referred to as an IGHSC. For this thesis, a green hydrogen pathway with onshore production, overseas shipping, and onshore utilization will be considered. For an international HSC to be labeled as a green hydrogen supply chain, the element of production will have to meet the beforementioned requirements for a green pathway. This means that the electricity production must be provided by renewable sources and the hydrogen production is performed with electrolization.

2.2 Defining Supply Chain Resilience

Supply chain management is a relatively new field, and the idea of SCRES is even more recent. It is reasonable to expect that theory building will be crucial at this stage of defining resilience for this thesis after evaluating all the many viewpoints on resilience and talking about the need for a comprehensive conceptual framework for SCRES. Therefore, to better understand the interdisciplinary meaning of resilience, some conceptual ideas from related disciplines can be taken and modified for the IGHSC environment. To begin with, this section will conduct a thorough literature review to investigate the different meanings and applications of resilience in supply chains. Following this, the succeeding section will identify and elucidate the concept of SCRES as relevant to this research, taking cues from previous studies and finally establishing the definition of SCRES that will be used in this thesis.

2.2.1 From Resilience to Supply Chain Resilience

To form a guideline for the design and maintenance of resilience of the IGHSC, it is important to determine which concept of resilience will be utilized. Supply networks are complex adaptive systems in which a subset of agents generate flow and must deliver it to sink agents at the other end of the network(Reyes Levalle and Nof, 2017). Flow delivery under predefined service conditions necessitates a resilient design and operating methods (Reyes Levalle and Nof, 2017). Without resilience, a problem at one element of a supply chain could lead to interruptions or decreased capacity throughout the entire supply chain (Craighead et al., 2007), (Wakolbinger and Cruz, 2011). A striking example of this phenomenon can be observed in the aftermath of the 2011 tsunami and earthquake in Japan's Tohoku region. In addition to Japan, this catastrophe resulted in supply chain delays in Thailand, Taiwan, Canada, Australia, the United Kingdom, and the United States (of Australia, 2011). The repercussions of these disruptions were felt on a global scale, affecting the entirety of the manufacturing supply chain worldwide (Brennan, 2011).

SCRES has been a topic of discussion in academia since the beginning of the millennium, as highlighted by (Bevilacqua et al., 2019). Researchers have been increasingly interested in the application to energy supply chains of this concept due to the emergence of global energy supply chains and developments in energy markets. Furthermore, critical economic and industrial events have prompted the scientific community to delve deeper into this subject (Bevilacqua et al., 2018). As human development demands more efficient and cost-effective systems, optimizing normal operating conditions weakens systems' resilience to disruptions, reducing their ability to predict, respond to, and recover from these unfavorable events (Reyes Levalle and Nof, 2017). Furthermore, current supply networks' increased dynamicity and complexity render static supply network designs and techniques inapplicable (Reyes Levalle and Nof, 2017). Traditional views on national resilience continue to coexist with modern perspectives that consider environmental and geopolitical factors (Bevilacqua et al., 2018).

One must have an operational definition of the resilience phenomena and a grasp of the essential components and capabilities that define it to defend the need for resilient supply chains. The work of (Holling, 1973) on the resilience of ecosystems is regarded by many authors as the foundational work on system resilience. According to (Holling, 1973), resilience is a characteristic of ecological systems that is responsible for the persistence of interactions within the ecosystem in the face of changes to system variables or parameters. This definition is based on the observed behavior and evolution of diverse ecological systems. Research on system resilience spanned a variety of fields over the following 40 years, from supply network management to psychology (Bhamra et al., 2011). The concept of SCRES has surfaced in scholarly literature, integrating diverse perspectives on resilience from various relevant fields. Across these fields and amid different definitions scattered throughout the literature, scholars have consistently recognized the multidimensional and interdisciplinary nature of resilience (e.g., (Bhamra et al., 2011); (Ponomarov and Holcomb, 2009); (Spiegler and Wikner, 2012)). This multidisciplinary view will also be adhered to in this thesis. Since, some definitions of supply chain resilience have been proposed in the literature, with (Christopher and Peck, 2004) providing the most tractable one, defining resilience as:

- "The ability of a system to return to its original state or move to a new, more desirable state after being disturbed" ((Christopher and Peck, 2004), p. 2).

On the other hand, it is defined by Ponomarov and Holcomb as

- "The adaptation capability to prepare for unexpected events, respond to interruptions, and recover from them to maintain continuity of operations at the desired level of connection and control over the structure and function" ((Ponomarov and Holcomb, 2009), p. 131).

There are some interesting differences and similarities between these two widely accepted definitions. The first similarity, which is at the core of both definitions, is the system response and subsequent recovery back to the desired state. In the definition by (Christopher and Peck, 2004), it is stated as the "ability to return to the desired state after disturbance", while in the definition by (Ponomarov and Holcomb, 2009), it is stated as the "response to interruptions and recovery from them". In both definitions, there is a desired state, an (unexpected) disturbance, and a degree of ability or capability to respond. In the definition by (Ponomarov and Holcomb, 2009), however, an extra element is added; the ability to prepare for unexpected events. This is relevant, as it implies that some of the disturbances can be prepared before they occur. An even more extensive definition of SCRES is given by my (Ponis and Koronis, 2012), which is

- "The ability to proactively plan and design the supply chain network for anticipating unexpected disruptive (negative events), respond adaptively to disruptions while maintaining control over structure and function and transcending to a post robust state of operations, if possible, a more favorable one than that before the event, thus gaining a competitive advantage" ((Ponis and Koronis, 2012), p. 925).

This definition is similar to the definition by (Ponomarov and Holcomb, 2009), however, it implies that favorably, a more desired state is reached after the response to the disturbance. This element, of increasing the desired state after the disturbance is overcome, can also be found in the definition of (Christopher and Peck, 2004).

Thus, there seems to be a lacking consensus about the definition of SCRES. In a study by (Tukamuhabwa et al., 2015a), a definition is established, based on an extensive literature review of 91 articles, by combining the most occurring elements of all definitions. The definition for SCRES this study derives is:

- "The adaptive capability of a supply chain to prepare for and/or respond to disruptions, to make a timely and cost-effective recovery, and therefore progress to a post-disruption state of operations – ideally, a better state than before the disruption" ((Tukamuhabwa et al., 2015a), p. 8).

This suggests that instead of choosing from a pre-existing set of responses, the elements of the IGHSC could be adapted so that they can provide an effective response to a disruption. The characteristics of disruptions, which may be unpredictable, ingrained in the supply chain, or coevolving with the supply chain's responses, are reflected in these adaptive capabilities. The supply chain may eventually gain knowledge from or be trained for disruptive events and the resulting responses, as well as new capabilities that will make it more resistant to threats of the same nature in the future.

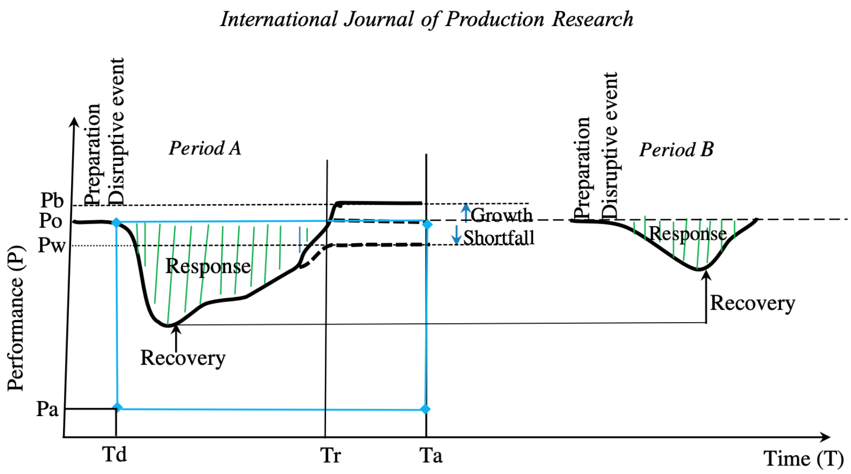

Figure 2: a schematic overview of the concept of resilience as given by (Tukamuhabwa et al., 2015a)

2 portrays the fundamental constituents of the definition of SCRES in a concise manner. Within this depiction, resilience manifests as a process wherein a supply chain confronts a sequence of disruptions, necessitating a well-designed response and recovery. The graphical representation designates Period A as the instance of the first disruption, leading to performance loss, while Period B pertains to the second disruption, resulting in a diminished loss owing to the assimilated knowledge and

skills derived from the initial disruption. To evaluate the resilience, an examination of the shaded region above the performance curve highlighted during Period A is needed. This evaluation provides a static metric of resilience, enabling the assessment of the performance decrease following a disruption, coupled with the temporal duration required to respond and recover to the desired level of performance. While defining a cutoff point is important, broadening the scope of analysis to encompass the established learning could be contemplated. A complementary dynamic metric can be derived by contrasting the two 'triangles' denoted as A and B, thereby discerning whether the supply chain's resilience improves progressively. This is a metric that will be discussed in Chapter 6.3. Within this framework, P0 signifies the custom performance level precluding any disruption, whereas Pa signifies the minimum acceptable performance level, below which operational cessation is assumed. Additionally, Pb and Pw denote the optimal and adverse potential outcomes upon recovery. Td signifies the onset of a disruption, Tr represents the factual recovery duration, and Ta embodies the utmost permissible recovery period. (Tukamuhabwa et al., 2015a).

2.2.2 Resilience through a Complex Adaptive Systems Lens

While we now established the definitions of resilience that are regarded as most suitable for the IGHSC, a lack of theoretical application could result in a constrained understanding of resilience, its related variables, and the connections among them. Also, system theory has to be incorporated for giving arguments for choosing the definitive definition of resilience. When no theory application is suggested, it is also challenging to generalize research findings from one environment to another. It is crucial to approach the phenomenon via a theoretical lens to better understand it. (Blackhurst et al., 2011) have applied systems theory to elucidate resilience as an inherent attribute of a system comprising flexibility, agility, adaptive capacity, and robustness. According to their framework, a supply chain is viewed as an open system susceptible to disruption stemming from environmental events, and the impact of such disruptions is contingent on the resilience level of the system (Blackhurst et al., 2011). From this systems theory perspective, (Blackhurst et al., 2011) posited that various factors, such as stringent security measures, custom regulations, product complexity, or insufficient supplier capacity, can diminish SCRES. More recently, (Day, 2014) drew upon Complex Adaptive Systems (CAS) theory to expound on the emergence of resilience in disaster relief supply networks, recognizing the distinctiveness of these networks compared to commercial supply chains. However, it's worth noting that contemporary supply chains transcend traditional systems; they embody complexity, with components continuously engaging in adaptive interactions among themselves and with their environment (Day, 2014). Their resilience is achieved through these adaptive and coevolving processes. Therefore, an alternative theoretical lens that takes these features into account is required to make further progress in understanding and building SCRES. This study suggests that CAS theory provides such a lens.
A CAS is recognized as a specific type of complex system due to the ability to adapt (Nilsson,), and it may coexist in situations that are unstable but not wholly chaotic

(Innes and Booher, 1999). In a CAS, adaptation denotes that the system's agents or components respond quickly, flexibly, and proactively to input from other agents or components that have an impact on the system (Nilsson,). Coevolution may cause new changes in the CAS and its surroundings during the adaptation process (Choi et al., 2001). As a result, learning is required to make the necessary changes to the supply chain structure and elements to improve fitness (Day, 2014). This is important to acknowledge as it implies the ability to learn is important for achieving resilience through adaptive and coevolving processes. However, a CAS also affects and changes its surroundings, and entities in the surroundings pick up knowledge from the system's answers (Day, 2014). It is important to note that from the CAS perspective, the process of improvement of performance after disruption is part of the nature of CAS. Since this thesis uses the CAS lens for the IGHSC, this feature will also be regarded for the resilience definition. A supply chain naturally resembles a CAS because it shares the key characteristics of a CAS. Furthermore, such a CAS has the intrinsic quality of resilience. Thus, the theoretical perspective of CAS and the investigation of SCRES seem to make sense together. Therefore, we will use CAS lens to define our definition of resilience. In Chapter 6, the CAS lens will be used once more to gain a level of nuance for establishing the IGHSC guideline. Below, the characteristics of CAS and the way they correlate to supply chains and resilience are given ((Choi et al., 2001); (Day, 2014); (Hearnshaw and Wilson, 2013)).

1. **Adaption and coevolution:** the supply chain evolves because of environmental dynamism to adapt. The supply chain environment may also be influenced by the actions of certain elements or disruptions of the IGHSC. According to (Ponomarov and Holcomb, 2009), and (Hearnshaw and Wilson, 2013), SCRES is an adaptive phenomenon. Elements adjust to supply chain challenges, but this could lead to additional environmental changes.

2. **Multi-scale/heterogeneous agents:** The individual companies may act as actors in a supply chain. Each of these operates an element of the configuration at a different level with distinct guidelines, purposes, and goals, such as production facility, conversion company, shipment company, and port. The interactions of various elements throughout the supply chain as they employ strategies and rules to improve fitness/survival result in and contribute to a supply chain's resilience (Day, 2014).

3. **Environment, dynamism, and rugged landscape:** changes occur in a supply chain environment, such as in the supply base, regulatory rules, etc. Environmental change generates disruptive threats. SCRES entails adapting to threats from both the inside and the outside.

4. **Ability to learn:** There is organizational learning among supply chain actors. SCRES is improved via organizational learning ((Ponis and Koronis, 2012); (Ponomarov and Holcomb, 2009)). Learning facilitates the adjustment of resilience methods, which aids in adaptation.

5. **Network connectivity/ interaction:** the physical connections between the elements and their actors in a supply network enable the movement of information, resources, and materials. Telephone lines and the internet are examples of such connections. Information flow-enabled supply network clustering and connection promote collaboration, curb opportunistic behavior, and boost resilience (Hearnshaw and Wilson, 2013). Interdependence among actors in a supply chain and the existence of a shared common framework are essential for the resilience (ability to adapt and survive) of the entire supply chain (Schneider and Somers, 2006).

Now that the common perception of the criteria for SCRES are identified, and the IGHSC is identified as a CAS, the last important factor is determining the characteristics of the disruptions that the IGHSC is subject to, to form the most adequate definition of SCRES for an IGHSC possible.

2.3 Defining Disruptions

To form an adequate definition of resilience, it is important to have a thorough grasp of the nature of the disruptions the IGHSC is subject to. The IGHSC is a complex system in and of itself. Furthermore, it is part of a broader system. As a result, it is affected not just by the interactions of its internal elements, but also by external disruptions originating from the wider system in which it is embedded (Guckenheimer and Ottino, 2008). The occurrence of disruptions to routine operations due to unwanted (but not always unplanned) circumstances is also connected to resilience. According to the majority of definitions we looked at, resilience is what motivates the reaction to unfavorable events that affect flow and/or communications, such as stress, disruptions, interruptions, turbulent change/periods, failures, and attacks. Undesired events could be either random, as implied by words such as failure or disturbance, and/or reference to the probability of occurrence ((Falasca et al., 2008); (Hearnshaw and Wilson, 2013)), or targeted, implied by words such as attack ((Baroud et al., 2014); Smith & Vidal, 2011). Additionally, internal (systemic) and external disruption can be either unexpected ((Ponomarov and Holcomb, 2009); (Spiegler and Wikner, 2012)) or predictable (Madni and Jackson, 2009) , as implied by the possibility of being better positioned for (Sheffi, 2005), or defending against (Smith & Vidal, 2011), such events. According to CAS theory, the nature of the environment that produces the disruptions is non-linear, dynamic, and unpredictable. In this thesis, the predictability of disruptions will therefore not be regarded as an option. This would mean it is a risk, which is defined as a disturbance with certain statistical predictability of occurrence, meaning it can be mitigated and as (Sheffi, 2005) and Smith and Vidal (2011) describe, being better positioned for or defending against does not necessarily mean the disruption is predictable and can be planned for (Sheffi, 2005); (Smith & Vidal, 2011). It only means that the system is better equipped to handle the disruption, which means, according to the definition by Ponomarov and Holcomb that the system would be resilient (Ponomarov and Holcomb, 2009). Therefore, the inherent qualification of the disruptions used for this thesis will be the following:

- Unexpected and unpredictable, meaning the disruptions are not predictable.

- Targeted or random, meaning the disruption can either be a random occurrence or a targeted disruption.

- Non-linear, meaning the disruption can be anything between very severe in a short amount of time, and less severe during a longer period.

- Dynamic, meaning the disruptions are ever-changing.

In addition to the disruptions' nature, it's critical to recognize the various domains in which their causes may manifest. One possible classification of disruptions provided by (Vakharia and Yenipazarli, 2009) is to divide them into those brought on by humans, such as political instability, terrorism, and quality issues or natural causes (for example, flooding, earthquakes, and storms). The root cause of disruptions would be revealed by such a classification. To deal with disruptions that are less frequent and more unpredictable (low mean/high variation), evolutionary and tailored mechanisms would need to be created. (Christopher and Peck, 2004) demonstrate supply chain vulnerability by separating the system into four layers: value stream and product, assets and infrastructural dependencies, organizations and inter-organizational networks, and the environment. Given the inter-organizational nature of supply chains and the presence of numerous uncontrollable factors, (Christopher and Peck, 2004) contends that we must accept complexity and limited managerial control. In addition, they argue that supply chain vulnerability is an organizational issue unrelated to supply chain management functions. As stated by (Azadnia et al., 2023a), who analyzed all components that can cause risk factors in green a supply chain, there are more detailed categories to divide disruption causes. When integrating these categories with the two main categories we distinguished, we obtain the following classification of disruption causes:

- Human-caused
    - Economic
    - Supply chain processes & governance
    - Technological & Infrastructure
    - Market & Social
    - Policy and regulation

- Natural caused
    - Environmental
    - Supply chain processes & governance

Note that supply chain processes and governance disruptions can have both human- and natural causes. Additionally, while the human-caused category may have more sub-categories, the number of disruptions caused by environmental causes is more abundant than most of the human-caused categories (Azadnia et al., 2023a). After carefully evaluating the proposed combined list of (Azadnia et al., 2023a) and (Vakharia and Yenipazarli, 2009), this thesis argues that an even better and more robust classification can be made. The following domains are thus provided.

1. Geo-political
2. Market Economics
3. Technical
4. Natural Disasters
5. Human Resources

In Chapter 4, after the entire IGHSC's for Japan and The Netherlands are provided, the inherent qualifications stated before will be used together with the domains of causes of disruptions to identify every possible disruption for the IGHSC that affects performance. Now that the nature of the disruptions the IGHSC is subject to is also identified, the definition for SCRES suitable for this thesis can be established.

2.4 Defining Resilience for International Green Hydrogen Supply Chain

By drawing on our system for the IGHSC and its purpose, passed literature about SCRES, adapting a CAS theory lens, and finally analyzing the nature of the disruptions, the definition of resilience for the IGHSC can be established. This is visualized in 4 below. According to CAS theory and literature about disruptions present in IGHSC's, the environment that produces the disruptions is non-linear, dynamic, and unpredictable nature of the environment. In this thesis, the predictability of disruptions will therefore not be regarded as an option and any notion of predictability will therefore be discarded in the definition. Also, it is important to conclude the ability to learn, adaption, and coevolution and the dynamic environment characteristic of the IGHSC provided by the CAS theory in the definition. This means also that the process of improvement of performance after disruption is part of the nature of resilience in a CAS such as an IGHSC. It also means that emphasis should be put on designing an adaptive response and recovery, while not putting emphasis on mitigation of disruptions, due to the inherent CAS nature of the supply chain and its disruptions. Therefore, the definition that will be adopted will be the following:

The adaptive capability of the international hydrogen supply chain to anticipate and respond to unexpected disruptions, to make a timely recovery to the desired level of connection and control over the structure and function, and thereafter improve to a post-disruption state of performance that is ideally a better state than before the disruption.

An important conclusion of the Theoretical Framework that needs extra attention is the distinguishment of reliability and resilience. Building a resilient supply chain demands more than simply creating and maintaining reliable supply chain procedures. As established in this Chapter, reliability primarily concerns the consistent execution of established processes and procedures. In a supply chain, a reliable system ensures that goods are delivered on time and according to plan, like a well-oiled machine that operates smoothly under normal conditions, following predefined pathways. Resilience, on top of that, considers the dynamic and unpredictable nature of the supply chain environment. It's not just about adhering to predetermined processes but about the ability to adapt and respond effectively when faced with unexpected disruptions, shocks, or uncertainties. A resilient supply chain can absorb, recover from, and even thrive in the face of challenges, whether they stem from natural disasters, economic fluctuations, geopolitical tensions, or other unforeseen events. This is put forward by the definition that was established above. To elaborate, the management of supply chains is undeniably complex and challenging. Factors like weather, political shifts, economic fluctuations, and even global health crises can disrupt the entire supply chain, totally unexpected. Reliability seeks to ensure that, under normal circumstances, the supply chain functions predictably and efficiently. It focuses on optimizing processes, reducing errors, and meeting established performance metrics. While reliability is crucial for day-to-day operations and customer satisfaction, it may not be sufficient when faced with unexpected disruptions.

This Chapter established an important foundation that this will draw upon. The green pathway and the basic structure of the IGHSC was defined. Afterwards, the demarcation from the concept of resilience to SCRES was conducted and it was found that the CAS lens lends itself particularly well for analyzing an IGHSC. Subsequently, the definition of disruptions as suitable for an IGHSC was formed, using the CAS lens. Last, all the foundations were combined to form the definition that this thesis will use and holds central, to describe resilience for an IGHSC. Now that the objective of the research is established, and the theoretical foundation is formed, it is time to find a suitable methodology for writing this thesis. For this, the CAS lens will also be used. An overview that aims to visualize the framework to show the relationships between the main concepts and their logical sequence in the framework is provided below in Fig. 3

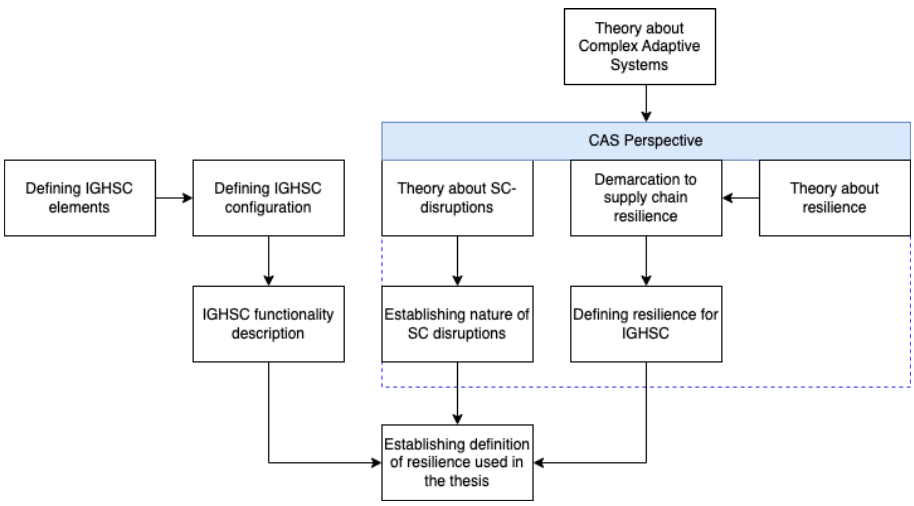

Figure 3: Framework showcasing relationships between the main concepts and their logical sequence in the framework

3 Methodology

Within this chapter, first it will be outlined wat the research approach is used within this thesis. Subsequently, we will delve into the research strategy for each sub-question. Building upon this, we will provide a comprehensive discussion of the methods employed and the data collection process.

3.1 research approach

The decision to adopt a qualitative research approach is based on careful consideration of both the research's objectives and the specific system under investigation. The primary aim of this study is to develop a comprehensive guideline for designing and maintaining resilience within an IGHSC. To achieve this, we will employ exploratory examples from the Netherlands and Japan, two major prospective importers, to gain a nuanced perspective on the subject. The main conclusion of the theoretical framework is that building a resilient network requires considerably more than just creating and maintaining reliable supply chain procedures. Management of supply chains is difficult and constrained because supply chains are inter-organizational networks immersed in an environment with many unpredictable influences. Furthermore, compared to integrated supply chain management, business continuity planning, commercial corporate risk management, or a combination of all these disciplines, supply chain vulnerability due to disruptions and subsequent resilience have a broader scope of applications. With this in mind, CAS theory proposes that supply networks face continuous adaptive pressures, resulting in coevolution and evolution. Resilience, being an inherently adaptive and ongoing process, proves challenging to predict or objectively assess. On top of that, an IGHSC is not yet operational in a real-world setting, causing a lack of historical data. Therefore, it indicates that non-objective, constructionist approaches like qualitative methods are the most suitable for investigating SCRES for an IGHSC. Consequently, these qualitative methods will form the foundational basis for establishing the methodology of this thesis.
The complex multi-elementary and adaptive system under investigation is therefore thought to lend itself particularly well to the qualitative approach. On top of that, a quantitative approach would not have been appropriate as that would entail the measuring of resilience objectively. However, since there is currently no IGHSC, no historic data is available and thus this approach would be too hypothetical. This thesis considers potential IGHSCs, with Japan and The Netherlands serving as significant potential importers in the future to answer: what guideline can be established to design and maintain resilience in an IGHSC, using the role of The Netherlands and Japan as large future importers as exploratory examples?
The research approach is exploratory in nature, seeking to describe and comprehend disruptions and metrics related to establishing resilience within an IGHSC. This dynamically adaptive system is very important as these disruptions and resilience indicators coevolve in a dynamic environment characteristic of the IGHSC provided by the CAS theory in the definition.
This thesis also adopts an interdisciplinary approach, driven by the increasing com-

plexity of the diverse actors, components, and disruptions within the subject matter. Markets, companies, and governments are all significant stakeholders in the trading of commodities like green hydrogen, and they are all vulnerable to disruptions from various domains.
Additionally, this thesis is exploratory because it examines a system that has not yet developed in a real-world environment. The use of historical data on the creation of a global (green hydrogen) supply chain is therefore not possible. Exploratory research is often carried out to identify previously unrecognized connections between various theories and fields of study. In this study, a novel theoretical framework is created, and it contains the qualitative metrics for resilience in a global supply chain for green hydrogen.

3.2 Research strategy per sub-question

The first research question was established as a foundation for the other three, and is answered in the Theoretical Framework. Because it was important to first find a concept for resilience based on a fitting system lens and the definition of a disruption and a thorough literature review of articles discussing resilience towards the supply chain domain. As the first research question is already answered in the Theoretical framework, this section will only outline the last three questions. This thesis is about the IGHSC. The second research sub-question is therefore meant to thoroughly map what an IGHSC configuration would look like. This is important since the functioning of all the linked elements that make up the supply chain system needs to be fully grasped, for the last two research questions to be answered. The examples of Japan and The Netherlands as large future importers were then chosen, as these two contexts are in completely different parts of the world, subject to completely different disruptions, giving an even better understanding of what an IGHSC could entail. In the third research question, the disruptions relevant for an IGHSC are identified, and to give the reader a better grasp of how these should be considered, the examples of Japan and The Netherlands are used to show what the identified disruptions could mean for IGHSC's involving these countries. It must be noted that the main goal does not contain a thorough analysis for shaping resilience for IGHSC's for these two examples. The examples serve the purpose of gaining a sufficient level of understanding and nuance for both the writer as the reader, about IGHSC's. In the last research-sub question, the concept of resilience is coupled with the analysis and outcome of the first three research questions. Resilience will be accurately defined for the IGHSC, and it will be broken down how resilience can be designed and maintained. A sequential path of conceptual, qualitative and quantitative resilience metrics will be given, and an overview will be constructed that captures the essence of the resilient lens for a decision maker that chose resilience as a design criteria for an IGHSC. The strategy per research sub-question to ensure the described sequence of the thesis is given below:

2. How can we describe international green hydrogen supply chain configurations involving Japan and The Netherlands as importers

To address the initial sub-question, a comprehensive desk study involving academic papers on IGHSCs will be undertaken. This study will focus on understanding how this supply chain is likely to be established for Japan and The Netherlands, drawing insights from existing literature. Interviews are to be carried out to collect additional and more insight data about these two supply chains, and to validate the established configurations. Moreover, it will be decided what the utilities are in the region of origin and destination of the supply chain so that the systems can be generalized. The outcome of this research question is a thorough and extensive understanding for both the reader and the writer of the functioning and structure of the configuration of an IGHSC, important for the depth of analysis for the last two research sub-questions.

3. What are the disruptions that can be identified affecting a global green H2 supply chain's performance and how do these disruptions need to be considered using the configurations of Japan and The Netherlands as examples?

For the establishing an extensive overview of all possible disruptions for an IGHSC, this thesis will use the first two steps of the disruption identification and analysis step of the resilience assessment framework proposed by (Chen et al., 2023). This entails:

1) **Data collection.** The primary purposes of this step are to analyze possible natural disasters based on the geographical location of the system, human caused disruptions and to collect information on disruption events that have occurred in analogous systems.

2) **Disruption identification and classification.** This step can determine and classify the potential disruption based on relevant information, literature, and expert knowledge provided by the interviews carried out for this thesis.
Literature is analyzed for identifying major human-activated and natural hazard disruptions, generally unexpected and significant, affecting the IGHSC's, and interviews are to be carried out to collect additional and more insight data about disruptions present in the two supply chains specifically for Japan and The Netherlands. An overview of the data collection process can be found in Appendix C.

4. What are the design choices, abilities and KPI's that are required to build and maintain resilience and how can this be captured in a framework?

By considering all knowledge gathered in the first three research questions, a new literature review is conducted to established how resilience can be built and maintained. For this, resilience is split up in the design phase and post design phase, and a list of design choices, abilities to maintain resilience, their elements and the subsequent KPI's are provided. Afterwards, interviews are to be carried out to collect additional nuance and insight about resilience and the established design choices and abilities. There will be established what resilience means for IGHSC's and how it can be built and maintained, when resilience is a design criterium for establishing new IGHSC's.
An overview of the sequence and workflow of the thesis can be found in the research flow diagram in Appendix B, which breaks down how the RSQ's relate to the Chapters and how the thesis is built up.

3.3 Expert interviews

The interviews serve the purpose of capturing diverse viewpoints from stakeholders within the IGHSC domain, specifically focusing on aspects like disruptions, resilience, and the logical configuration for the IGHSC's. A key objective is to establish a comparison between the interview data and the insights gleaned from the literature examined in Research Sub Questions 2, 3 and 4. This comparison serves as a means to validate the configurations proposed for IGHSC's and to validate the identified disruptions. In the context of exploratory research, interviews frequently act as a means to gather empirical data or verify research findings (Adams, 2015). Additionally, this thesis tries to grasp the current perceptions of resilience in Japan and The Netherlands. To ensure an open and receptive environment for dialogue, semi-structured interviews were adopted. This approach encourages participants to respond on their own terms, using an open discussion after each question (Myers and Newman, 2007). Such interviews steer conversations toward issues rather than strictly adhering to a set of predetermined questions. The choice of conducting individual in-person interviews in Japan and individual online interviews in The Netherlands allows for a diverse additional nuance to findings in the thesis. Yet, it is important to acknowledge that a drawback of semi-structured individual interviews lies in their susceptibility to the interview design and the interviewer's influence on responses (Adams, 2015). The interviewer's role transcends neutrality, potentially influencing how respondents react (Myers and Newman, 2007). While the processing time for semi-structured interviews tends to be longer than structured interviews due to the open-ended nature of questions, this is mitigated in the current study due to the limited number of diverse stakeholders being interviewed, eliminating concerns related to large-scale data processing (Myers and Newman, 2007). This approach is informed by the interview strategy developed by(Myers and Newman, 2007), which involves a series of steps to guide the interview process:

1. Preparation phase
   (a) Define the objective of the interview.
   (b) Formulate the question of the interview.
   (c) Find relevant interviewees for the interview.
2. Execution phase
   (a) Conduct the interview.
3. Data extraction phase
   (a) Transcribe the answers to data.
   (b) Summarize the data.
   (c) Follow up on interviewees with summary for approval.

The initial phase of preparation initiates by delineating the aim of the interview, which in this instance pertains to capturing interviewees' perspectives on disruptions and the coherent structure for green hydrogen (H2) supply chains within their respective national contexts. Selection of companies is predicated on their engagement in specific components of the hydrogen supply chain, identified based on the constituents of a green global hydrogen supply chain as deduced from the literature analysis. Identification of interviewees was facilitated through the connections established by the Innovation Department of the Embassy of The Kingdom of The Netherlands in Japan. Execution of interviews transpires within the implementation phase. All interviews adhere to the framework outlined by (Myers and Newman, 2007), characterized by a structured sequence: initiating with setting a common context encompassing the topic, objectives, methodological approach, and critical definitions and assumptions. After this, the questions are tailored to the interviewee's professional background and knowledge, aiming to find nuanced insights not readily accessible within existing literature. Employing an open-ended structure, the questions lack a predetermined sequence. The complete set of interview questions and corresponding answers is accessible in Appendices H-K.

The list of interviewees, their title and lastly their function within this thesis is listed in 3

#	Title(s)	Company	Function in Thesis
1	Manager & Head of Business Development, Carbon Solution Business Unit	IHI Corporation	Validation of green ammonia supply chain, information about standardization strategies
2	General Manager & Business Development Group Leader, Hydrogen Business Department	Chiyoda Corporation	Validation of MCH supply chain and information about role division of responsibility of disruptions throughout IGHSC
3	Business Development Director	Koole Terminals	Validation MCH supply chain and information about diversification practices
4	Business Advisor Hydrogen Import-Export	Shell	Validation of overview in Appendix G and discussion about real world application

The complete set of interview questions and corresponding answers is accessible in Appendices H-K. The most important quotes, that will be used throughout the thesis, are also given. Every used quote will have a corresponding number that matches the footnote in the text where it is used.

3.4 System analysis

For establishing the configurations of the IGHSC's in Chapter 4, selection criteria are used to reduce the list of optional parts for the IGHSC's involving Japan and the Netherlands. These consist of (1) every technology selected for use in every component of the supply chain must comply with the green pathway as specified in the Theoretical Framework, and (2) technologies must be demonstrable or commercially accessible and must be described in scientific literature as having a relatively high maturity. These are taken into consideration since it is believed that these technologies will then be feasible to use in 2030. The supply chain configuration based on (IEA, 2019) provided in the Theoretical Framework is used, to structure formation of IGHSC configurations. The technologies are merged into technically feasible IGHSC's once they have been recognized for each component. Utilizing a defined order of components to configure IGHSC's has the advantage of improving comparability and reducing the range of potential supply chain configurations. The final three components-reconversion, storage, and utility-are established using specific characteristics and requirements of Japan and The Netherlands. Based on their political drivers, current and planned utility for hydrogen and by choosing a country of origin that potential export-import relationships due to signed MoU's with The Netherlands or Japan. Based on the characteristics of the countries selected as producers, the first three elements of energy production, hydrogen production, and conversion are established. The transport element is again based on existing carrier options and routes, that have been proven to have potential.

Additionally, the CAS perspective, as presented in the Theoretical Framework is also applied to the system analysis. The consequences of using this lens for Chapter 4 are the following: according to the CAS perspective, it is important to view the supply chain holistically rather than separating its elements and actions from the whole to ensure SCRES. The IGHSC configuration may help with this by providing a clear perspective of the entire pertinent network or supply chain. Without it, supply chain-level systemic resilience capabilities are likely to be lost because individual elements with resilient goals and specialized schemas are likely to feel the need to adapt acutely without regarding the network to for example geopolitical or economic disruptions, which will be discussed in more detail in Chapter 5. Therefore, even if they meet the selection criteria, it should be avoided to include certain technological choices in the network whose orientations are incompatible with a homogeneous and common response to disruptions. This pertains to the CAS property of visibility, which assumes that the agents managing the various elements of the global hydrogen supply chain at various levels share the same worries or common schemas, as stated in the Theoretical Framework. Due to their shared experiences, they engage in behaviors that result in resilient patterns at the network level.

The methodology for this thesis is now formed, following an interdisciplinary approach, due to the various types of actors, elements, and disruptions involved. Additionally, this thesis is exploratory because it examines a system that has not yet developed in a real-world environment. The use of historical data on the creation of an IGHSC is therefore not possible. In this study, a novel guideline will be created, containing the steps for a stakeholder that wants to design and maintain resilience for an IGHSC. As part of this, a list of design choices and a framework with qualitative metrics and measurable KPI's will also be formed.

In order for both the writer as the reader, the next Chapter will use two possible real-world examples as exploratory cases to form a thorough understanding of the considerations for the formation of an IGHSC configurations.

4 International green hydrogen supply chain configurations

In the context of this thesis research focused on IGHSC configurations, identifying, and dissecting two possible real-life examples holds significance. The goal for identifying these two examples is attaining a comprehensive idea of the dynamics that shape hydrogen supply chains and the significance of resilience within this context. By analyzing and unraveling the complexities of possible real-world cases, this thesis will take an extra step from theoretical descriptions and delve into in the practical implications of hydrogen supply chains. Furthermore, the significance of resilience within international hydrogen supply chains becomes more apparent when we delve into these examples. Through studying these examples, we can discern how supply chains must learn to adapt to natural disasters, geopolitical shifts, infrastructure failures, and other disruptions while still maintaining the desired performance and gain a holistic understanding of the configurations.
Therefore, two supply chain configurations with The Netherlands and Japan as importing countries must be defined to assess the resilience of an IGHSC. To do so, this Chapter will be divided into three parts. In Chapter 4.1, the first three elements of the IGHSC will be thoroughly analyzed, meaning that all technical options that pass the criteria to fulfill these elements will be reviewed. The first three elements of the supply chain are not yet country-specific and do not need data from Japan and The Netherlands yet. The last three elements require research in what is the most probable green hydrogen configuration for Japan and The Netherlands. After the last three elements are established, the most fitting hydrogen carrier will also be determined. Nonetheless, it is important to first give an overview of these different carriers in Chapter 4.2. In Chapters 4.3 and 4.4, the most likely configurations of the supply chains for respectively Japan and The Netherlands will be derived. Mainly the last three elements of the supply chain, storage, reconversion, and utility, are characterized by the countries' policies, hydrogen strategies, and utilities. The expert interviews will be used to validate the derived most logical future IGHSC's.

4.1 International Green Hydrogen Supply Chain Configurations

As stated in the theoretical framework, the IGHSC has six consecutive elements: production, conversion, transport, reconversion, storage, and utilization (IEA, 2019). This chapter will therefore also be divided accordingly.

4.1.1 Production

As hydrogen cannot be produced without energy, the production of the energy itself will also be a production step in this thesis. Also, this step is one of the most important elements for labeling the supply chain green, as the energy source is the most prevalent individual factor when determining the GHG intensity of the global hydrogen supply chain, as compared to hydrogen produced by any technique based on fossil fuels without CCS, green hydrogen resulting from electrolysis using renewable power has substantially lower lifespan GHG emissions (Jensterle et al., 2019). Without CCS, the most popular energy source for hydrogen production today, hydrogen from natural gas, has about half the GHG intensity of hydrogen produced from coal through gasification while with CCS, hydrogen produced from fossil fuels has a GHG intensity that is comparable to coal hydrogen (Jensterle et al., 2019). CCS can dramatically lower the GHG intensity of hydrogen produced from fossil fuels. However, depending on the specific supply chains, green hydrogen produced by electrolysis from renewable sources still lands at about 40% to 75% less GHG intensive than blue hydrogen (IEA, 2019).

On the one hand, green hydrogen can be produced using electrolysis with renewable sources. Additionally, biomass can be converted into hydrogen through biochemical (using microorganisms) or thermochemical processes (gasification or pyrolysis of solid or liquid biomass, reforming, and partial oxidation of biogas, biomethane, or bioethanol) (Buffi et al., 2022). However, although it has the future potential to fill the gap of the non-continuous production of green hydrogen coming from intermittent sources, the amount of hydrogen produced from biomass at this time is so minimal that it is a drop of water on a boiling plate, and the biochemical processes have not yet become commercially viable and have a low technological readiness level (Buffi et al., 2022). Therefore, in this thesis, the argument is made for hydrogen to come from only the combination of renewable electricity and electrolysis.

Now that we have determined the option of proceeding with green hydrogen produced by electrolysis from renewable sources, the sources of renewable energy must be established. Although just 2% of the hydrogen produced worldwide is produced by electrolysis, there is tremendous room for electrolysis to produce additional green hydrogen (IEA, 2019).

A substitute for using grid electricity for hydrogen production is dedicated renewable energy generation (Ren et al., 2013). Even after considering the transmission and distribution costs of delivering hydrogen from (often remote) renewable locations to the end users, installing electrolyzes in areas with exceptional renewable resource conditions might evolve into a low-cost hydrogen supply option (Ren et al., 2013). Argentina, New Zealand, Northern Africa, the Middle East, Chile Australia, and parts of China and the US are among the countries with excellent opportunities (Okunlola et al., 2022b). Initiatives to create hydrogen from specialized solar and wind power in different parts of the world are either being planned or have already been disclosed. Additionally, according to research by (IEA, 2019) combining solar PV and onshore wind in a hybrid plant has the potential to further reduce costs in locations where both resources are outstanding. Surplus electricity might be inexpensively available in electricity mixes with rising ratios of variable renewable energy sources. Therefore, one approach to utilize this surplus electricity would be to electrolyze water to produce hydrogen, which could then be stored for later use (IEA, 2019). However, if this electricity is only occasionally accessible, it is unlikely to be cost-effective to rely only on it (IEA, 2019). It may be less expensive to run the electrolyzer at high full load hours and pay for the extra electricity than to only rely on excess electricity at low full load hours (Hosseini et al., 2019). Because of the huge potential and high maturity of solar PV and wind power, these two sources

will be included in this thesis as the electricity generation sources for hydrogen production.
Now that the source of renewable power is determined, hydrogen is produced with electrolyzers. Hydrogen and oxygen output flows are produced by providing an electrolyzer with electricity and pure water. Water electrolysis can be accomplished using a variety of technologies. Alkaline electrolyzers are the most advanced, and proton exchange membrane (PEM) technologies are in the demonstration stage, while solid oxide electrolyzers are still in the research and development pipeline (Bhandari et al., 2014a). Annual capacity additions for worldwide electrolyzers reached 25 MW in 2019, but stated projects are rapidly ramping up, and they will reach 1.5 GW of new capacity in 2023 (RN2, 2020a). According to the size, type, and demanded output size of the electrolyzers employed, industrial solutions currently display a wide range of electricity consumption. The average electrolysis efficiency is 65%-70% (Thomas, 2018), defined as the ratio of hydrogen energy content to electrolysis power consumption. Water usage is another issue associated with electrolysis. The use of pure water is typically in the range of 10-15 L per kilogram of hydrogen output (Al-Qahtani et al., 2021) and the input water must be deionized. In the lack of freshwater sources, saltwater desalination or wastewater recovery are options. Different technologies for seawater desalination are now commercially available, and they might be used with electrolysis with a very small increase in energy usage (Santiago et al., 2021). Nonetheless, for choosing the technology used for the production element in the supply chain, the technologies must be demonstrable or commercially accessible. The technology for alkaline electrolyzers is well-developed and widely used. Since the 1920s, it has been employed, particularly for the synthesis of hydrogen in the fertilizer and chlorine industries (Bhandari et al., 2014b). Following the CAS lens, the property of scalability assumes that the actors managing the various elements of the global hydrogen supply chain at various levels share the same schemas. Due to their shared experiences, they engage in behaviors that result in resilient patterns at the network level. Therefore, it only makes sense to choose the mature and well-known technology of alkaline electrolyzers for the hydrogen production element.

4.1.2 Conversion

Hydrogen has low energy density, which makes it more challenging to store and transport than fossil fuels. There are two forms for transporting hydrogen in physical form without converting it, which are LH2 and compressed gaseous hydrogen (Noh et al., 2023). However, it can be converted into hydrogen-based carriers, with the most common being ammonia and Liquid Organic Hydrogen Carriers (LOHC) (Noh et al., 2023). These can make use of existing infrastructure for their transport, storage, and distribution. This can reduce the costs and complexity of reaching final users. Ammonia is already used today as a feedstock in the chemical industry and could be a hydrogen carrier for the long-distance transport of hydrogen in the future, or itself be used as fuel in the shipping sector (Noh et al., 2023). There are certainly potential benefits and opportunities of these hydrogen-based carriers. This must be weighed, however, against the costs of converting hydrogen into these

products. Many of the technological pathways to produce these fuels and feedstocks are at an early demonstration stage, resulting in high costs. Producing ammonia requires the separation of nitrogen from the air, while the production of LOHC requires binding the hydrogen to Toluene and afterwards separating it again (Noh et al., 2023).
Below is an overview of the current four most prevalent hydrogen carriers and their (dis)advantages:

- **Compressed gaseous hydrogen (CGH2)** is pressurized hydrogen that is stored in a storage vessel at 250 - 700 bar in high-pressure cylinders , which requires a substantial amount of energy and a container capable of dealing with high pressure (Zheng et al., 2012). Even when pressurized, CGH2 has a low density, resulting in large storage volumes and limited transport efficiency. In addition, CGH2 is extremely explosive and hazardous to transport and store (Zheng et al., 2012). As a form of physical storage, it has the advantage of maintaining a high level of hydrogen purity.

- **Liquid hydrogen (LH2)** has the characteristic that at a very low boiling point of -253 degrees Celsius, LH2 can be liquefied with high purity (Züttel, 2004). Due to its high cryogenicity, liquefaction requires a great deal of energy. To preserve cryogenic LH2, a vessel with exceptional thermal insulation is necessary and boil-off gas, which is hydrogen escaping from an insulated tank, is inevitable, making it challenging to transport it over large distances (Züttel, 2004). LH2 has a density of 70,6 kg/m3, which makes LH2 800 times denser than hydrogen at standard temperature and pressure, with a density of 0.084 kg/m3, and 1.3 times denser than CGH2 at 700 bar. LH2 is comparatively less explosive than CGH2 and is therefore deemed less dangerous (Usman, 2022). Additionally, LH2 is easier and less expensive to transport and store than CGH2 due to its higher density (Usman, 2022).

- **Liquid Organic Hydrogen Carriers (LOHC)** are organic substances with an unsaturated double bond that store hydrogen liquid phase at ambient temperatures (Teichmann et al., 2012). As their properties are very comparable to those of diesel, LOHC can utilize existing infrastructure and be governed by existing laws, which is very favorable (Hosseini et al., 2019). It has advantages for long-term storage and transport over great distances. LOHC is also considered cost-effective because it can repeatedly store hydrogen through cycles of hydrogenation and dehydrogenation. Hydrogenation is a catalytic reaction that LOHC- into a hydrogen-rich molecule (LOHC+) that can store hydrogen. The LOHC+ can release hydrogen in a reversible manner via dehydrogenation. High energy utilization during dehydrogenation, which requires high temperatures (250-450 degrees Celsius), is the bottleneck of this technology (Teichmann et al., 2012). MCH is the most prevalent LOHC at present, and it is actively researched by Japanese research organizations and businesses, both in Japan and with projects in Rotterdam due to its low cost and economic viability (Port of Rotterdam, 2022). As MCH's potential for large-scale commercialization has been reported ((Sekine and Higo, 2021); (Teichmann et al., 2012)), this study compared MCH to other hydrogen carriers as a LOHC.

- **Ammonia (NH3)** Hydrogen can be generated with the Haber-Bosch process or electrochemical methods by combining hydrogen (H) with nitrogen (Wang et al., 2022). NH3 is liquid under atmospheric pressure at 33 degrees Celsius (Wang et al., 2022). Alternatively, it can be preserved as a liquid at room temperature and high pressure (Demirhan et al., 2019). Liquid NH3 can about 1.7 times more hydrogen per unit volume than LH2 (Sekine and Higo, 2021). Due to these properties, NH3 can be transported with relative ease and converted back into high-purity hydrogen at the destination country by NH3 cracking (Lucentini et al., 2021). NH3 transport is a commercially available technology whose reliability has been demonstrated. Nevertheless, NH3 splitting occurs at high temperatures and pressure, necessitating the addition of a great deal of heat (Lucentini et al., 2021). Moreover, the toxicity and pungent odor of NH3 are cited as disadvantages (IEA, 2019).

To clarify the reconversion element, the carrier-specific steps that comprise the reconversion element are enumerated below:

- CGH2: following electrolysis, the hydrogen must be compressed, and the CGH2 must then be stored pending cargo handling.
- LH2: following electrolysis, the LH2 must be liquefied and then stored in pending cargo handling.
- MCH: Since we select MCH as the LOHC carrier form due to its relative maturity (ref of paper itself), the hydrogen is dehydrogenized and bound to Toluene after electrolysis, and the MCH is then stored pending cargo handling.
- Ammonia: following electrolysis, hydrogen is synthesized into ammonia using the Haber Bosch method, which was selected for this thesis due to its technological maturity (zelfde paper ref), and then stored pending cargo handling. It is essential to note that using this carrier necessitates the presence of a N2-generation plant for ammonia synthesis.This step will be described in greater detail in Chapters 4.2 and 4.3 for the selected carriers for the Netherlands and Japan.

4.1.3 Transport

The supply chain element of transport is largely dependent on the hydrogen carrier that will be used in the green hydrogen supply chain. In this sub-section, an overview of different transport combinations will be given, together with the hydrogen carrier that fits these modes.

Transport configurations

It is presumed that hydrogen carriers are transported on container ships fueled by marine diesel oil (MDO), with a small 400 twenty-foot equivalent unit (TEU) container carrier. There are already numerous studies on the use of hydrogen as a marine fuel ((Madsen et al., 2020); (Saito,)). In the future, ships and port facilities are anticipated to switch from conventional oil to eco-friendly fuels such as hydrogen and ammonia. However, the immaturity of the current technology is also mentioned in these studies, indicating that it cannot be included in this thesis due to low technological maturity.

- **CGH2:** Utilizing pressurized containers, hydrogen is stored and transported by ships equipped with pressurized containers from the production location to the utility site. Through the cargo handling system, compressed hydrogen is discharged into onshore storage pressure vessels. Hydrogen is pressurized or liquefied for distribution to end consumers at the point of utility. When a consumption site requires liquefied hydrogen, 700 bar of hydrogen is expanded to the appropriate pressure for liquefaction before being liquefied to 1.2 bar at -253 degrees Celsius. The liquefied hydrogen would be stored in a cryogenic vessel and distributed as liquefied hydrogen following liquefaction. The hydrogen transported to land is transformed into pressurized gas or liquid before being distributed to consumption sites (Zheng et al., 2012).

- **LH2:** The produced hydrogen is liquefied and then carried to onshore utility sites by liquefied hydrogen carriers. The utility sites are supplied with the liquefied hydrogen. Hydrogen-produced renewable energy is stored in a buffer storage vessel for processing by a continuously operating liquefaction system. Even though intermittent hydrogen production is a result of the renewable electricity source, the liquefaction system must operate continuously (Usman, 2022) In this chain, a buffer storage vessel is necessary. Hydrogen is liquefied by the liquefaction system, and the liquefied hydrogen is then stored in a cryogenic storage vessel. Heat ingress causes the production of boil-off gas (BOG) when liquefied hydrogen is stored in cryogenic storage vessels (Usman, 2022). A cargo handling system (using pumping) is used to transfer the liquefied hydrogen into a liquefied hydrogen carrier. The hydrogen carrier conveys liquefied hydrogen to an onshore consumption site. When the transported liquefied hydrogen reaches land, it is transferred into cryogenic storage vessels and then either compressed or liquefied depending on the needs of the consumption site. When hydrogen is supplied in compressed form, pumping and vaporization processes are utilized. In contrast, if the hydrogen is in liquid form, only pumping would be required to supply it. An important conclusion is the need for cryogenic storage vessels for liquefied hydrogen transport (Usman, 2022).

- **MCH:** Since LOHC is liquid at atmospheric pressure and temperature, it can be stored in conventional storage containers, which is a significant advantage (Teichmann et al., 2012). A cargo handling system loads the LOHC containing hydrogen (LOHC+) into LOHC carriers. Typical chemical tankers can be used to transport LOHC. Hydrogen is discharged from the transported LOHC through the dehydrogenation process. The LOHC+ is transported by the LOHC carrier and unloaded into storage containers on land (Teichmann et al., 2012).

- **Ammonia:** The ammonia produced is liquefied and moved to ammonia storage containers. The ammonia transporter is designed to transport LPG because their storage conditions are comparable (Wang et al., 2022). Ammonia is then transported to the consumption site by the ammonia carrier. Transported by ammonia carriers, the produced ammonia is subsequently cracked to extract hydrogen. The extracted hydrogen is transformed into pressurized gas or liquid before being distributed to consumers.

Now that the first three elements are distinguished and the most prevalent carriers are established and outlined, it is useful to provide an overview of the important advantages and disadvantages of each carrier. In Chapter 4.3 an IGHSC configuration will be established for Japan and The Netherlands that is in part based on coupling country-specific political drivers and utility with the most fitting hydrogen carrier.

4.2 Overview of Hydrogen Carriers Characteristics

Now that the first three elements of the hydrogen configuration are established, an overview is given of all characteristics of the different carriers, that can be used to choose the carrier for Japan and The Netherlands. Table 1 demonstrates the advantages, disadvantages, and level of maturity of each hydrogen storage technology, including its infrastructure and use. LH2 is preferable for hydrogen consumption requiring extremely high purity, such as fuel cells, which is related to the use of transported hydrogen. Ammonia, on the other hand, is thought to be useful for applications that require less pure hydrogen, such as co-firing during combustion. Ammonia can also be used directly without decomposing when administered properly. When hydrogen is held as a liquid, cryogenic liquefaction requires a very large energy input and has a low energy efficiency. Additionally, the boil-off that occurs during storage causes a number of issues in the storage. Dehydrogenation to release hydrogen before use in the MCH system also causes a sizable decline in overall energy performance. Additionally, because MCH has the lowest hydrogen density of the three, it takes larger or more vessels to deliver the same amount of hydrogen. The toughest hurdle for ammonia is its synthesis, where energy-intensive nitrogen generation is required. Ammonia requires a lot of energy to break down into its constituent parts if decomposition is necessary.

Characteristic	LH2	Ammonia	MCH
Infrastructure	Needs more refinement and building for large-scale	Possibility of using the propane infrastructure that is currently in place	Possibility of using the gasoline infrastructure that is currently in place
Utilization	• Hydrogen combustion • Fuel cells	• Direct combustion • Fuel cell (after dehydrogenation and purification) • Direct fuel cell	• Hydrogen combustion (after dehydrogenation) • Fuel cell (after dehydrogenation and purification)
Advantages	• High purity • does not need to be purified and dehydrogenized	• Direct use • Existing ammonia infrastructure and regulation can be utilized	• Storable in liquid without cooling; ambient temperature • Existing storage infrastructure and regulations can be utilized.
Disadvantages	• Requires very low temperature • High energy requirement for cooling/liquefaction • Liquefaction can consume about 15% of the energy brought by hydrogen – • Difficult for long-term storage • Requires boil-off/risk of leakage	• a lower degree of reactivity than hydrocarbons. • treatment is necessary due to its toxicity and strong odor. • In the case of dehydrogenation purification, very high energy input is required.	• High temperature for dehydrogenation • handling infrastructure tends to be large, Toluene consumes volume in transport
Maturity	• Small scale: application stage	• Demonstration stage	• Demonstration stage
	• Large scale: infrastructure development		

Table 1: Characteristics of the three different carriers ((Abdin et al., 2020); (Jiang et al., 2014); Lan et al., 2012)

4.3 Supply chain configuration involving Japan and The Netherlands

Now that the options for the first three elements of the IGHSC are listed, and the country of production is determined, the green global hydrogen supply chain configuration for Japan and The Netherlands must be established. To do this, three factors that affect the choice of hydrogen carrier are analyzed. First, the political drivers are summarized to get a clear view of the drivers of Japan and The Netherlands. Afterward, the hydrogen utility of Japan and The Netherlands is analyzed, to get a clear image of the way the hydrogen is used and in which sectors. Last, the (geographical) relation with the country of origin is analyzed. Combined, these three factors will lead to a choice of carrier for the green global hydrogen supply chain for Japan and The Netherlands used in this thesis. After the carrier is chosen, the configurations chosen for the IGHSC's are provided in Appendix A.

4.3.1 Political drivers Japan

This study assesses Japan's long-term energy prospects within the framework of the Japanese Basic Hydrogen Strategy (2017), which outlines ambitious climate mitigation targets of an 80% reduction in greenhouse gas (GHG) emissions by 2050 compared to 2010 levels. It's worth noting that scenarios projecting a 95% reduction in GHG emissions indicate a substantially increased demand for hydrogen and hydrogen-based synthetic fuels compared to scenarios assuming an 80% reduction. This underscores a positive correlation between the level of ambition in GHG emission reductions and the growing importance of hydrogen in Japan's energy landscape (IEA, 2019). Japan's vision for a "hydrogen-based society" was initially introduced in the 4th Strategic Energy Plan of 2014 and further elaborated upon in the Strategic Roadmap for Hydrogen and Fuel Cells of 2016. The groundbreaking Japanese Basic Hydrogen Strategy of 2017 solidified Japan's status as the first country globally to unveil a comprehensive government blueprint for the advancement of hydrogen and fuel cell technologies (Japanese Basic Hydrogen Strategy, 2017). The Institute of Energy Economics Japan (IEEJ), the New Energy and Industrial Technology Development Organization (NEDO), and strategic partnerships with Japanese technology firms actively pursue a well-defined hydrogen strategy delineated by the Ministry of Economy, Trade, and Industry (METI). For Japan, the total hydrogen demand in 2050 scenarios ranges from 600 to 1,800 PJ. In addition, Japan placed its hopes on a small number of items that were widely distributed and stressed a quick transition from research and development to market activation (Japanese Basic Hydrogen Strategy, 2017). This thesis can contribute to Japan's Strategic Roadmap for Hydrogen and Fuel Cells, which envisages the construction of global blue hydrogen supply networks first, followed by the adoption of green hydrogen supply chains after 2040. For Japan, we can therefore incorporate carriers for the green hydrogen supply chain that are as of now still in the demonstration phase, bearing in mind the year 2040 for deployment.

Japan's three main motivations for hydrogen deployment are technological leadership, energy supply diversification, and climate mitigation, and other environmental concerns (of Economy, 2023a) Japan prioritizes importing liquefied hydrogen from

outside that is chemically stored as ammonia or as LOHC, bearing in mind that these two hydrogen carriers are as of now still in the demonstration phase. However, several of the Japanese scenarios refer to domestic production.
In the latest version of the Basic Hydrogen Strategy (of Economy, 2023a), some more important points arise that have an influence on the choice of hydrogen carrier. It is stated that Japan is planning the creation of a support system for the establishment of a large-scale supply chain. The strategy argues that the situation in Ukraine and the global energy crisis have prompted countries to invest heavily in hydrogen. As an energy-advanced country, Japan calls for a transition to low-carbon hydrogen, with the following pillars.

- Promptly develop a pioneering regulatory and support system that is ahead of its Asian counterparts.
- Institutional development for building a large and robust supply chain.
- Establish a system to build a large-scale and robust supply chain.
- Establish a system to take risks and make investments ahead of other businesses, even when the outlook for hydrogen is uncertain.

Furthermore, Japan plans to start supplying low-carbon hydrogen and ammonia by around 2030, taking the risk of investing in hydrogen before other companies do. In this way, the supply chain will be strategically selected from the perspective of S+3E, and the supply of low-carbon hydrogen and ammonia will be promoted. The concept of S+3E stems from the Japanese 6th Strategic Energy Plan (2021) and entails 1) ensuring safety as a major premise, 2) ensuring a stable and resilient energy supply, 3) ensuring environmental suitability from the point of view of climate change and harmony with surroundings and 4) ensuring economic efficiency of energy. For the first movers, Japan will strategically select a supply chain from the viewpoint of S+3E and will pay a standard price for the hydrogen and ammonia supplied by the first mover. This reference price (the price at which the operator is expected to earn a reasonable profit while reasonably recovering the costs required to continue its business) are a way of ensuring off-taker security, which is favorable since hydrogen production involves risks such as the procurement of raw materials and the long payback time required for large capital investments. Additionally, based on the revision of the JOGMEC (Japan Oil, Gas and Metals National Corporation) Act 44, JOGMEC will provide risk money support (capital injection and debt guarantee) for the production and storage of hydrogen and ammonia, as well as support from the Japan Bank for International Cooperation, the Development Bank of Japan, and the Japan Bank for International Cooperation. On top of that, Japan will support the development of supply infrastructure such as tanks and pipelines to realize large-scale demand creation and efficient supply chains that enable a stable and inexpensive supply of hydrogen and ammonia and to promote internationally competitive industrial clustering.

4.3.2 Utility in Japan

As stated in Japan's latest (6th) Strategic Energy Plan, hydrogen is mostly used for power generation, with transportation and industry being mentioned less frequently. The creation of synthetic fuels other than hydrogen is hardly mentioned in Japanese scenarios; instead, hydrogen will be used in end-use industries. The decarbonization of industrial processes, a portion of the transportation industry, and, to a lesser extent, the thermal supply and the power grid, is projected to be significantly aided by hydrogen (Japanese 6th Strategic Energy Plan). Due to its existing reliance on imported coal, oil, and natural gas, Japan is vulnerable to geopolitical shocks affecting the extraction or supply countries. Therefore, a key component in Japan's adoption of hydrogen is the diversification of imported energy carriers, origin nations, and supply routes. Green hydrogen also offers the chance to supplement domestic energy production with a portion of imported fossil energy sources. Another crucial element is Japan's scientific superiority in a subject that could be a cornerstone of the future global energy system; Japan is already acknowledged as a leader in key hydrogen technologies (Chaube et al., 2020). Japan has greater experience with demand-side applications than any other country, especially in the building sector, with over 250 000 CHP units (Narita, 2019). In the interim, Japan has prioritized producing hydrogen from fossil raw materials, notably natural gas through steam methane reforming (SMR) and coal through gasification (Züttel, 2004), in order to fulfill its anticipated future demand (Chaube et al., 2020). The broad implementation of CCS, primarily close to the point of extraction of main energy sources, is called for in future plans. Japan is the world leader in terms of the number of fuel cell deployments (whether they are CHP plants, fuel cell vehicles, or related infrastructure), and it has more expertise with fuel cell applications in the heating and transportation sectors (Chaube et al., 2020). In order to look into the feasibility of large-scale hydrogen imports, Japan is seeking international projects for large-scale hydrogen manufacturing plants. Japan anticipates a high demand for hydrogen in the power generation sector and aims to implement 30%-hydrogen co-firing in gas-fired power generation or hydrogen-fired power generation and 20%-ammonia co-firing in coal-fired power generation. Co-firing/single-fuel discharge demonstrations will be promoted, and the environment for appropriate assessment of non-fossil value will be created. In addition, 1% hydrogen/ammonia will be added to the electricity generation mix by FY2030 (Government, 2021a).

4.3.3 Hydrogen Carrier Choice for Japanese Configuration

After careful consideration, green ammonia is chosen as an energy carrier for Japan. Ammonia will be both used directly and cracked into hydrogen in the IGHSC. For direct use, ammonia will serve for co-firing purposes in coal plants in Japan. This is one of the most prevalent pathways as stated in the 6th Strategic Energy Plan of Japan. Additionally, ammonia, alongside hydrogen, is expected to supply 1% of the Japanese energy mix as of 2030, by means of direct combustion. Apart from being used as ammonia directly, it will also be cracked into hydrogen during the described reconversion process (of Economy, 2023a), and this hydrogen will be used in the power generation sector, expected to serve a large of the hydrogen amount.

Also, the transport sector is expected to take on large demand, the industry sector, with large-scale diversion of manufacturing processes such as hydrogen-reduced ironmaking and hydrogen-fired boilers, and lastly, the building sector.

Apart from the utility purposes of green ammonia, the Japanese Government has stated it will strategically select a supply chain from the viewpoint of S+3E and will pay a standard price for the ammonia supplied by the first mover (of Economy, 2023a). Additionally, "comprehensive resource diplomacy" will be deployed to integrally promote the establishment of ammonia supply chains and secure suitable sites of resource-rich countries in the network Japan has fostered in past diplomacy (of Economy, 2023a). On top of this, there is the possibility of using LPG infrastructure that is currently in place for ammonia handling, and the Japanese government will support any necessary infrastructure as stated in their new Hydrogen Strategy (of Economy, 2023a). In the LPG industry, Japan has already achieved a unique development to protect the environment while strengthening safety measures and maintaining resilience through the joint efforts of the government and the private sectors (JAEPA, 2021). From a resilience perspective, these are all favorable advantages of using green ammonia.

4.3.4 Country of Origin Choice for Japanese Configuration

Australia would be logical choice for Japan in establishing a green ammonia supply chain for several reasons. Firstly, Australia has a significant advantage in terms of its abundant renewable energy resources (Energy, 2023). The country boasts an abundance of solar and wind energy potential, which is essential to produce green ammonia through electrolysis. Secondly, the long-lasting connections between Australia and Japan provide a significant foundation for collaboration. Both nations have maintained strong economic and trade relations for decades, which caused mutual trust. Moreover, The Japan Organization for Metals and Energy Security (JOGMEC) entered into a Memorandum of Understanding with the State of Western Australia (WA State) to enhance collaboration in the realm of energy resources encompassing oil, gas, hydrogen, and ammonia (RN2, 2022). This MOU also encompasses broader cooperation in CCS and CCUS initiatives. This existing rapport can facilitate smoother negotiations, agreements, and the establishment of shared supply chain infrastructure. Second, HySTRA, a demonstrated large-scale international hydrogen shipping project in the form of LH2 as well as hydrogen synthesis from brown coal, was conducted between the two countries (Jensterle et al., 2019). This project serves as evidence of the collaborative potential between the two countries in this domain. In conclusion, Australia's wealth of renewable energy resources, coupled with the enduring relationship between the two nations and the existing demonstration projects, positions it as an excellent partner for Japan to develop and strengthen a green ammonia supply chain.
The international supply chain configuration for Japan used in this thesis is therefore determined as shown in 7a in Appendix A.

4.4 Supply chain configuration for The Netherlands

While the Dutch energy landscape has historically been dominated by fossil fuels, a notable and ongoing transition towards renewable energy sources is in progress. As of 2023, fossil fuels still constituted 65 percent of the Netherlands' energy supply, with renewables accounting for 40 percent of the overall energy mix (OIES, 2019). Presently, the Netherlands hosts one of Europe's most concentrated clusters of oil refineries, marine storage facilities, and LNG (liquefied natural gas) terminals (RN2, 2020b). In light of its current infrastructure and strategic geographic location, the Netherlands plays a critical role as an import hub for energy transit and trade within the European context (RN2, 2020b). The country's proficiency in industrial gases, material handling, and chemical processes is a testament of dedication and robust business activities within the oil and gas sector. By harnessing this accumulated expertise, the Netherlands is strategically poised to assume a prominent role as a key participant in the regional and global development of the hydrogen market (EZK, 2022).

4.4.1 Political Drivers for The Netherlands

The National Climate Agreement of the Netherlands emphasizes the important role of hydrogen in bridging a variety sectors, thereby boosting the adaptability of an imminent low-carbon energy framework. Hydrogen emerges as facilitator in scenarios where certain processes remain incompatible to electrification due to technical, spatial, or financial limitations. Hydrogen offers the capacity to seamlessly integrate intermittent renewable energy sources into the energy matrix, rendering it a potentially important component (of Economic Affairs, 2019). In 2020, the Dutch hydrogen strategy was unveiled, with a primary focus on cultivating renewable hydrogen through electrolysis, driven by green electricity. The strategy also acknowledges the potential of harnessing hydrogen from natural gas, in tandem with CCS, to aid the evolution of the hydrogen system (Stam et al., 2023). This strategic framework provides a foundational pillar for both domestic and international companies, signaling encouragement for the initiation of hydrogen pilot and demonstration projects. An illustrative example is the LHyTS project, which serves as a tangible demonstration of the feasibility of transporting MCH between Scotland and the Netherlands. This thesis, in its interviews, talked with stakeholders from key participating companies within the LHyTS project, namely Koole Terminals and Chiyoda Corporation. While the absence of well-defined hydrogen guidelines and standards poses obstacles to implementation, particularly at a localized or smaller scale, the Dutch National Climate Agreement has introduced legal and regulatory adaptability to foster collaboration with other stakeholders in executing pilot projects (of Economic Affairs, 2019). The comprehensive national hydrogen strategy encompasses legislative and regulatory facets: delineating market regulations and initial responsibilities for network operators, instituting guarantees of origin to cultivate a robust market for carbon-free hydrogen, establishing safety protocols to ascertain risk extent and management for new hydrogen applications, and devising an energy infrastructure program to ensure integration of hydrogen with the electric grid (of Economic Affairs, 2019).

4.4.2 Utility for The Netherlands

Within the Dutch policy transition framework, hydrogen-based transport is a step towards green mobility with potential (Huétink et al., 2010). Establishing hydrogen infrastructure, including refueling networks, is imperative to facilitate hydrogen vehicle adoption and address the "chicken-and-egg problem" (Van de Graaf et al., 2020), wherein consumer reluctance stems from the lack of refueling options. In alignment with this, the Netherlands is poised to make substantial investments in hydrogen-powered transport infrastructure, effectively countering the significant GHG emissions from the transportation sector. This initiative encompasses the proliferation of fuel cell electric vehicles (FCEVs) and hydrogen fueling stations, ensuring emission-free travel while easing pressure on electric vehicle charging infrastructure (Huétink et al., 2010).

The Dutch industry produces an estimated 180 petajoules (PJ) of hydrogen per year(Weeda and Segers, 2020a). The current hydrogen demand is largely met by fossil hydrogen, resulting in significant CO2 emissions (NWP, 2022). Replacing fossil hydrogen with renewable and low-carbon hydrogen is a crucial step in the industry's sustainability efforts. Heavy industries, despite their economic significance, often rely on fossil fuels, contributing substantially to the nation's carbon footprint (Scheepers et al., 2022a). The Netherlands aims to revolutionize its industrial sector by leveraging hydrogen as a clean energy source (Scheepers et al., 2022b). By integrating hydrogen in the production processes of steel, chemicals, and refineries, the nation can significantly reduce emissions while maintaining its industrial competitiveness. Through the greening of the existing hydrogen consumption, there is already an initial demand that can be met through domestic production and imports (NWP, 2022). Soon, climate-neutral hydrogen production and import will also be necessary for emerging applications, including industries, mobility, and electricity generation (carbon-free grid balancing). The demand for renewable hydrogen is expected to significantly increase in the long term; according to a study by CE Delft and (Weeda and Segers, 2020b), the demand for renewable hydrogen from the industry and mobility sectors could be between 60 and 100 petajoules by 2030.

Last, Netherlands acknowledges that achieving a climate-neutral economy requires a hydrogen (gas) transport network to efficiently connect users with providers of low-carbon hydrogen, along with storage facilities because hydrogen transport and storage ensure a continuous alignment between hydrogen supply and demand (EZK, 2022). Pipelines represent the most efficient means of fulfilling domestic hydrogen transport needs, as they are more cost-effective than alternatives. Pipelines also facilitate the emergence of a dynamic market involving various producers and consumers (NWP, 2022). Netherlands also recognizes that hydrogen can be transported using alternative carriers and that storage is necessary to accommodate hydrogen from import streams and to address domestic temporal imbalances between supply and demand (NWP, 2022). Furthermore, storing (potential strategic) reserves enhances the energy security of the Netherlands (NWP, 2022).

4.4.3 Hydrogen Carrier Choice for The Netherlands Configuration

Given this context, this thesis argues that The Netherlands is likely to choose MCH as an import carrier for its international hydrogen supply chain. MCH, a Liquid Organic Hydrogen Carrier (LOHC), offers advantages such as high hydrogen storage capacity, ease of transport, and reversible hydrogen release. These properties ensure efficient and safe cross-border transport and enable the Netherlands to accommodate international hydrogen imports effectively. By leveraging MCH as an import carrier, the Netherlands can first enhance its ability to access and integrate hydrogen from nearby international sources, further contributing to the nation's ambitious goals for a sustainable energy future. By choosing MCH, The Netherlands can repurpose or retrofit portions of its current infrastructure, capitalizing on investments already made and avoiding the need for massive infrastructure overhauls. This approach not only accelerates the deployment of hydrogen within the energy system but also ensures a smoother transition, as existing facilities can be adapted to accommodate the unique properties of MCH without major disruptions. A demonstration project of an international MCH supply chain involving the Port of Rotterdam and Scotland, to study the transport of hydrogen in the form of MCH is already formed (RN3, 2022a). Big partners in this project were also interviewed for this thesis (Appendix H&J). A validated overview of the hydrogen supply chain configuration with The Netherlands as importer is derived and can be seen in **??** in Appendix A.

4.4.4 Country of Origin Choice for The Netherlands Configuration

The Port of Rotterdam, an established energy hub, currently imports 13% of Europe's energy and aims to transform into the Hydrogen Hub of Europe. To realize this goal, the port will leverage its comprehensive import, export, and storage infrastructure, well-developed energy industry supply chain, and pipeline connections to other industrial clusters in Northwest Europe (Koole Terminal, 2022). As MCH is chosen as carrier, it makes sense to choose Scotland as the country of origin for production of energy, hydrogen and MCH, as there is already a global consortium is initiating a research project to transport hydrogen using MCH from Scotland to Rotterdam (Port of Rotterdam, 2022). Currently, the results of the detailed feasibility study are known and will be made public over the course of September 2023 (Koole Terminal, 2022). Scotland is highly suitable for green hydrogen production due to its abundant wind resources and proximity to the nearby continent, which creates a demand. Additionally, the region serves as a central hub for the oil and energy sector, already possessing the expertise, infrastructure, and companies necessary to catalyze the growth of the hydrogen economy (Port of Rotterdam, 2022). In the pursuit of establishing a robust and efficient guideline, delving into a comprehensive understanding of various design options for the configuration of an IGHSC proved to be of paramount significance. This initial phase of the research journey centered on acquiring knowledge and immersing ourselves in the intricate details of potential design setups and considerations. The underlying rationale was clear: to grasp the underlying mechanics, challenges, and potentialities that each configuration could offer. Within this overarching reason, it was important to use two highly relevant examples—Japan and The Netherlands. These two nations operate

in entirely distinct global contexts, both geographically and economically. By comparing these nations, we were able to discern the profound influence of geographical, economic, and policy on the conceptualization an IGHSC.
For the upcoming chapters, this exploring of different configurations will significantly shape the depth of that is possible for analysis. Insights from investigating design options form a strong foundation for subsequent chapters. Without this learning process, the following chapters might lack depth.

5 Disruption Analysis for International Green Hydrogen Supply Chain

Given that the world is for a large part dependent on maritime supply chain systems (Liu et al., 2021), it is crucial to comprehend how these systems are susceptible to disruptions. The prevalence of low-frequency, high-impact scenarios, or events with a low probability but the potential to cause significant damage to the performance of the system, provides the rationale for why not all efforts should be focused on preventing disruptions, but more so on shaping adequate responses, as (Craighead et al., 2007) argues that supply chain disruptions are unavoidable. The severity of such disruptions depends on the number of elements affected (Craighead et al., 2007). If disruptions are inevitable, how can systems be prepared to deal with these occurrences? This is where resilience comes in. The hypothesis of Christopher and Peck (2004) that supply chains are intrinsically susceptible and prone to disruptions, as stated in the Theoretical Framework, is an insight that this thesis shares with her; because disruption and resilience assessments cannot anticipate all disruptions, they must plan for response and recovery of performance after disruptions occur. However, before resilience can be defined for the IGHSC's, it is important that all disruptions are thoroughly identified. When identifying relevant disruptions for a hydrogen supply chain, it's essential to focus on disruptions that can have significant impacts on the availability, reliability, and overall robustness of the hydrogen supply chain (Ambulkar et al., 2015a). As stated in the framework by (Yang et al., 2023a), the first two steps for the disruption analysis process are data collection and disruption identification and classification. The data collection process is given in Appendix C. Many of the disruptions present in maritime supply chains are also relevant for hydrogen supply chains, so the literature review was not focused solely on specifically hydrogen supply chains. In the disruption identification and classification step however, a critical stance was taken by considering the system structure and configuration as given in Chapter 4, and by using the criteria and categorizations for disruptions as given in Chapter 2.4.

5.1 Overview and Categorization of Disruptions

The domains of disruptions are based on the system's characteristics, function, and environment as analyzed in Chapter 4, but is not limited to one of the example supply chains and rather on a generic international hydrogen supply chain. After critically analyzing all found research about disruptions and the corresponding categorization that was utilized in these studies, this thesis established the following structure to list all disruptions that can occur in an IGHSC, categorized based on domain from which the disruption can occur.

1. (Geo-)political

   a. War or political conflict: The most common geopolitical disruptions occur because of a war breaking out in one or more of the regions where the supply chain is embedded. Furthermore, political disagreement between countries can interrupt commodities trade and have a negative impact on supply chain performance. War is known to interrupt supply networks by shutting down entire countries and halting corporate operations.

b. Trade war/company conflict: When supply chain actors engage in an unexpected conflict, such as owing to competition or divergent standards, it creates a significant disruption to the supply chain. This disruption is linked to a lack of collaboration or transparency because of the trade war or company conflict, which leads to distrust and conflict among SC partners. Because of the uncertainty around the desired commodity flow because of the conflict, can have an impact on storage, transportation, and delivery capacity.

c. Political instability: This disruption is less severe than a true conflict, but it can still cause large disruptions owing to uncertainty and unexpected changes in laws, import/export procedures, or other regulations.

d. Terrorism: both targeted and random acts of terrorism can happen disruptively in certain parts of the world. Incidents of piracy as an act of terrorism have occurred in, among others, Southeast Asia, the Niger Delta, and off the coast of Somalia.

2. Market economics

a. Sudden tariffs & taxes incurred: The risk of a sudden increase in taxes and tariffs can have a huge effect on RE production or hydrogen trade. A sudden tariff barrier will entirely alter the situation of the configuration. An exampke can be found in the US-China tariff war (Cohen and Kouvelis, 2021).

b. Sudden recession: an economic crisis poses a risk of disruption to every company handling an element of the supply chain to operate profitably and being forced to halt operations.

c. Sudden inflation/interest rate changes: The risk of an unexpected increase in inflation or interest rates can cause a disruptive shift in international trade which can affect supplier and demand side performance and desired operation.

d. Sudden Currency rate change: the risk of volatile currency exchange rates can affect organizational and international trade and cause a sometimes suddenly disruptive shift between two currencies, which can influence for instance off-taker security.

e. Sudden demand change: This disruption can occur because of a multitude of causes and events. Demand is never constant and frequently fluctuates with little warning. Because of pricing concerns, there is uncertainty about the market for green H2, and variations can be significant. A fluctuation in demand will generate an imbalance and even a bullwhip effect, disrupting the entire supply chain

f. Sudden Price change: Green hydrogen production involves a technique known as electrolysis, which requires electricity from a renewable source so that the unit cost has a direct impact.

g. Sudden loss of key supplier: This disruptive event is often related to the risk of giving a single supplier too much bargaining power. This can occur when one supplier has too large a share of the raw materials or power required for hydrogen production. This can diminish the profitability of H2 manufacturers and lower the attractiveness of the industry.

h. Sudden loss of key off-taker: This disruptive incident is frequently associated with the risk of delegating too much bargaining power to a single off-taker. This can happen when one off-taker controls a disproportionately big portion of the supply chain since it accounts for a considerable portion of total demand and off-take. This may reduce the profitability of H2 manufacturers and reduce the industry's attractiveness.

3. Technical

a. Power outage due to power/smart grid failure: The intermittent nature of renewable energy output can impair the operation of a power grid. This necessitates additional planning actions by grid companies to manage and balance changes in energy generation. Smart Grid failure or scarcity highlights the lack of a 'smart grid' capable of storing and distributing RE regionally.

b. Explosions: The transportation of hydrogen and ammonia is hazardous to the population as it is explosive and corrosive.

c. Leakage: Leakage poses a significant risk to hydrogen supply chain performance due to the highly flammable nature of hydrogen and ammonia, which can lead to safety hazards, environmental concerns, and economic losses. Even small leaks can result in the rapid dispersion of hydrogen and ammonia, potentially igniting if exposed to an ignition source, while also contributing to loss of valuable resources.

d. Malfunctioning infrastructure

i. Battery systems failure: Battery system failure can pose a significant risk to hydrogen supply chain performance by disrupting the availability of renewable energy sources required for hydrogen production through electrolysis, leading to production bottlenecks and decreased reliability.

ii. IT/communication systems failure: IT systems failure can pose a significant risk to hydrogen supply chain performance by disrupting communication and coordination among various components, hindering real-time monitoring, and emergency response, thereby jeopardizing the efficient and reliable functioning of the entire chain.

iii. Storage systems failure: Storage systems failure can pose a significant risk to hydrogen supply chain performance by causing supply imbalances, hindering flexibility, and potentially leading to disruptions in meeting demand.

4. Natural disasters

   a. Natural disaster-producing country: a natural disaster in a country that produces hydrogen can disrupt production facilities, leading to shortages and affecting the availability of hydrogen supply.

   b. Natural disaster during transport: a natural disaster during transport can damage transportation infrastructure, causing delays, interruptions, and potentially hazardous situations for hydrogen shipments.

   c. Natural disaster importing country: a natural disaster in the importing country can disrupt the infrastructure required for receiving, storing, and distributing hydrogen, leading to supply shortages and logistical challenges.

   d. Disease outbreak/pandemic: a disease outbreak or pandemic can impact workforce availability, causing disruptions in hydrogen production, transportation, and distribution activities.

   e. Fluctuating weather conditions: fluctuating weather conditions can affect renewable energy generation used in hydrogen production, leading to supply instability and potential production gaps during unfavorable weather periods.

5 Human resources

   a. Strike: unfair working conditions often lead to labor strikes which will impact operational output in every element of the supply chain.

   b. Labor error: Green H2 supply chain requires a skilled workforce. The lack of skilled human resources poses a risk to everything from the development of RE production to the reconversion of the hydrogen carrier in the country of destination. Human errors can cause very severe disruptions.

   c. Health and safety: workers can get disrupted production involves several risk factors for workers such as exposure to chemicals, loud noise, and hazardous operating equipment which can be detrimental to their health.

The overview that was established for this thesis is one that can be used for any hydrogen supply chain in the world and thus adds to the guideline that is designed in this thesis. All the disruptions presented are adhering to the qualifications for the disruptions that were presented in the Theoretical Framework. The disruptions generally occur with a low frequency but high impact. The argument that is made for all these disruptions is that effort can and should not be made on prevention, which is also not something that should be strived for according to the definition of resilience that was constructed in this thesis. Therefore, even though some disruptions are generally less likely to occur for supply chains involving Japan or The Netherlands, they still should be considered. The consensus that is made in this thesis is that disruptions, by means of their nature, will occur, and will occur unexpectedly. Additionally, the CAS theory provided the notion of coevolution with the supply chain's responses to the characteristics of disruptions ingrained in the supply chain (Choi et al., 2001). This means that certain responses will evolve the list of disruptions that are presented in this thesis and vice versa. Coevolution may cause new changes in the CAS and its surroundings during the adaptation process, which affect both the disruptions that can occur and the responses that should be shaped. Last, due to the established characteristics of un-expectancy and unpredictability, and dynamicity, meaning the disruptions are ever-changing and never expected, it is a mistake to filter out any of the disruptions listed in the overview listed above. Being resilient to the identified disruptions means that emphasis should be put on the adaptive capabilities of the global hydrogen supply chain to anticipate and respond to unexpected disruptions, and not "the most expected" disruptions. The post-disruption state of performance, which is ideally a better state than before the disruption, will then incur coevolution on the disruptions.

It is also important to know that diverse occurrences of disruptive events, characterized by varying degrees of intensity, will lead to distinct influences on the performance of the hydrogen supply chain (Yang et al., 2023a). The disruptions unpredictably vary in type, scale and nature, are intermittent and irregular to be identified, and may have short or long term negative effects (Hosseini et al., 2019). Nonetheless, some disruptions are more characteristic of the countries and environments that the chosen IGHSC's are embedded in. Therefore, it is still relevant to analyze which ones these are for the two supply chains. For all five domains, if present, characteristic disruptions applicable to the specific supply chain will be discussed. To enhance reader comprehension and insight, it is crucial to exemplify the consideration of identified disruptions through the exploratory cases presented in this thesis. However, it's vital to note that this chapter solely aims to demonstrate the approach for considering these disruptions. As such, the analysis provided here is relatively surface-level, as delving deep into these disruptions is not a central focus of this thesis. The intention is to provide a practical understanding of the evaluative process rather than an exhaustive investigation into the disruptions themselves.

5.2 Disruption Consideration for the AU-JP supply chain

There are several disruptions that the IGHSC between Australia and Japan is more prone to. Even though the two countries have a long-lasting trade history together, it is important to see what disruptions can still occur. An overview of these disruptions is given in thus sub-section.

5.2.1 (Geo-)political

Australia is Japan's foremost energy supplier, accounting for more than 34% of Japan's energy imports and 30% of overall energy consumption in 2022 ((RN2, 2023). Over decades, Japanese investment and energy purchases have contributed to Australia's economy. The economic alliance between Australia and Japan underlies a growing people-to-people and political relationship between the two US allies in an economically and geopolitically unpredictable international context. Australia possesses what Japan lacks: vast natural resource. For the past decade, Japan has relied on imports to meet 90% of its energy demands (RN2, 2023). Australia is a stable and safe provider, capable of mining and shipping natural resources with world-class efficiency, thanks to solid institutions, a well-functioning democracy, and a dedication to the international market. But that is in terms of fossil fuels, and the transition to net zero emissions by 2050 is currently happening in both countries. The bilateral economic relationship will require a complete overhaul. The energy connection between Australia and Japan must be thoroughly rethought. Instead of sending raw energy sources to Japan, cheaper and more environmentally friendly intermediate or final goods are produced in Australia, such as green hydrogen or ammonia, and the embedded energy is exported to Japan. Both countries must take the lead on international standards and the creation of regional and global frameworks for commerce in new energy sources. Given the required investment and size, Japan will require more than one supplier for energy security, and the Australian industry will require more than one client, as the disruption of loss of a key supplier or off-taker also tells us. This proposes that Australia and Japan develop a regional agenda.

It's a significant agenda for Australia and Japan, with big strategic challenges that call for increased bilateral stakeholder and policy discussion. The two governments should establish a bi-national agency to map out the energy transition over the medium to long term, help institutionalize and sustain current discussions and co-operation mechanisms, entail considerable experience and information sharing, and focus on mutually beneficial problems.

5.2.2 Market Economics

In this domain of disruptions, not a lot is expected to pose significant harm to the green ammonia supply chain. The economic relationship between Japan and Australia is very strong and efforts to maintain it that way are in place. On January 15, 2015, the Japan-Australia Economic Partnership Agreement (JAEPA) went into effect, by far the most liberalizing trade deal that Japan has ever negotiated and executed is the JAEPA. The Agreement gives Australia's exporters substantial privileged access and will encourage continued growth in two-way investment, making sudden tariffs or taxes incurred not likely (JAEPA, 2021). Australia and Japan are ideal allies since their economies are very complementary. The Agreement will bring these two market economies and society even closer together and serve as the foundation for a strong relationship for many years to come. However, it must be noted that the strongness of this relationship can also harm the resilience of a supply chain between Japan and Australia if they rely too much on each other's demand and supply. Again, for energy security, Japan will require more than one supplier, and the Australian industry will require more than one off-taker.

Because of the country's strong exposure to commodity exports to China and its susceptibility to global growth, the Australian dollar is usually seen as a 'risk-on' currency. The Yen, on the other hand, is seen as a 'safe' currency to which traders rush during times of market instability. The AUD/JPY pair is sometimes regarded as a useful predictor of risk sentiment in financial markets since it rises during periods of optimism and falls during periods of pessimism (Sokhanvar et al., 2023). In March, shortly after the first hints of US banking problems emerged, the combination fell to its lowest level in more than a year. The Yen benefited from the subsequent wave of risk aversion. Longer term, a slowdown in the US Federal Reserve's aggressive tightening drive, as well as the possibility of a US recession later this year, are likely to be factors that halt the current AUD-JPY trend (Sokhanvar et al., 2023). Some major institutions, like UBS and Credit Agricole CIB, believe the Japanese yen will recover by the end of the year, owing to a shrinking interest-rate gap and fears about the US financial industry. A US recession would also harm risk sentiment, favoring the safe-haven JPY over currencies such as the AUD (Mehra, 2023). Since then, the AUD has managed to make up some ground against its Japanese counterpart, but the progress has been gradual.

5.2.3 Technical

The choice for ammonia as a carrier also bears its own added disruptions in the technical domain. Before ammonia can be used on ships, there are a number of safety concerns that must be addressed. Ammonia is toxic to humans, and crewmembers and other people on board can suffer severe health consequences if they are exposed to it in excess of certain levels and durations (Constable et al., 2003). If a disruption occurs that hits the ammonia infrastructure, consequences among others involve navigation scenarios such as grounding or collision resulting in hull breach, cargo operations in the event of equipment or vent mast damage, and leakage or loss of containment during bunkering, and health and safety hazards from ammonia leaks for crew and passengers (Constable et al., 2003). Additionally, the irregular nature of renewable resources has an impact on NH3 generation, using volatile renewable processes such as wind and solar power, can become problematic: while the alkaline electrolyzer can be immediately shut down, started up, and ramped up/down, the HBS process has practical operational constraints (Verleysen et al., 2023). An intermittent power supply could harm the long start-up procedure for this HBS process, which can take several days to reach nominal operation. To avoid a Power to Ammonia plant shutdown, massive hydrogen and nitrogen buffer tanks, as well as a backup system, must be installed, to increase redundancy. The continuing of ammonia output is secured by these buffer tanks, and the shutdown is averted, although at a higher capital cost (Armijo and Philibert, 2020).

5.2.4 Natural Hazards

Japan and Australia are both countries that must cope with severe natural hazards within their country that other countries in the world are less prone to. To start, Japan is a country known for earthquakes, tsunamis, and sudden typhoons. The magnitude 5 earthquakes or higher, which have the potential to damage infrastructure, occur on average 160 times per year in Japan, due to its location along the Ring of Fire, a region where several tectonic plates collide (MacKenzie et al., 2012). In addition, the country's oceanic location makes it susceptible to tsunamis when an earthquake occurs below or near the ocean. Typhoons and earthquakes are the two most likely natural hazards in Japan, with occurrence probabilities of 44.8% and 22.8%, respectively and compared to the other hazards (Sasaki and Yamakawa, 2004). Additionally, Australia is a country known for its risk of floods, bushfires, and typhoons. Also, all-natural disasters are becoming more frequent and more intense, damaging people and infrastructure which severely affect supply chains (Gentle et al., 2001). Climate change is increasing Australia's natural climatic variability, causing changes in average and extreme weather, and increasing climate impacts on our water resources, ecosystems, health, infrastructure, and economy today and in the future (Bureau of Meteorology, 2019). Beyond the 'noise' of Australia's natural climate fluctuation, clear trends have formed in recent decades with warming as a continuing trend; Australia has warmed by about 1.4 degrees Celsius since 1910, with 2019 being Australia's warmest year on record (national science agency, 2019).

5.2.5 Human Resources

Japan's work ethic and pride in a job well done has garnered the country widespread attention. After all, this is the country where even convenience store employees are expected to follow high professional conduct standards and where a single 20-second train delay is grounds for an official apology (Baseel, 2018). Strikes and labor demonstrations are significantly less common in Japan than in many other major economies throughout the world, and when they do occur, they are often orderly and devoid of violence or property damage (Baseel, 2018). Official figures reveal that Australia saw the most days lost to strikes since 2004 in the June quarter, as a tight labor market and rising cost-of-living pressures drove demands for better salaries and working conditions (RN3, 2022b). According to data given by Cornell University's School of Industrial and Labor Relations, the number of workers engaging in strikes in Australia in the first half of 2022, approximately 85,000, was greater than that of the United States, despite the latter's significantly bigger labor force. A wage dispute at Shell cost the energy company an estimated $1 billion in liquefied natural gas shipments between June and August 2022, when prices were at an all-time high (RN3, 2022b). Australia's first Labor administration in nine years is likely to adopt laws granting unions the authority to negotiate wage agreements that cover multiple businesses, allowing for industry-wide strikes, and expanding workers' ability to request flexible working arrangements. This is definitely a condition that needs to be taken seriously as a possible cause of disruption in the Australian part of the supply chain.

5.3 Disruption Consideration for the NL-SC supply chain

In the upcoming section, this thesis will seek to uncover the disruptions that could arise in a hydrogen supply chain connecting The Netherlands and Scotland. By dissecting these domains, we aim to shed light on the multifaceted factors that could impact the reliability and resilience of this cross-border hydrogen journey.

5.3.1 Geo-political

The aftermath of Brexit has led to a renegotiation of trade relationships and shared projects between the UK and the EU member states (Hendry et al., 2019). In the context of a hydrogen supply chain between The Netherlands and Scotland, the allocation of cross-border infrastructure investments could be affected by the shifting dynamics post-Brexit. Previously established funding mechanisms and collaborative agreements within the EU might need to be reconsidered, potentially leading to disputes over how financial resources should be allocated between the two nations (Hendry et al., 2019). Negotiations might revolve around balancing the desire to continue strong bilateral partnerships with the new realities of independent decision-making outside the EU framework. Brexit has also brought forth regulatory divergence between the UK and the EU, including differences in safety standards, protocols, and regulations. As The Netherlands and Scotland seek to align an international hydrogen supply chain, the challenge of harmonizing regulations becomes more complex due to the varying paths of regulatory independence chosen by each nation post-Brexit (Hendry et al., 2019). The complex interplay of post-Brexit trade renegotiations, regulatory divergence, and the need for harmonization introduces uncertainties that could potentially lead to sudden disruptions in a hydrogen supply chain between The Netherlands and Scotland. The potential delays, disputes, and technical obstacles arising from these factors could affect the reliability and continuity of the hydrogen flow, ultimately impacting the performance of the supply chain.

5.3.2 Market Economics

The post-Brexit era could lead to market-economic issues as the two countries aim to optimize their domestic energy resources while also exploring cross-border energy collaborations. The emergence of differing energy strategies, such as the emphasis on renewable energy sources and hydrogen adoption, might create competition for investments, resources, and market positioning, potentially leading to tensions over market access and investment allocation. However, since The Netherlands and Scotland are collectively engaging in the MCH demonstration project (Rotterdam, 2022), this domain for disruptions is not regarded as particularly significant. Another, more universal cause of disruptions is the development of a hydrogen economy, involving uncertainties related to pricing and market integration (Commission, 2019). Market-economic issues could arise if The Netherlands and Scotland experience significant price volatility in hydrogen production, transportation, or usage. Factors such as fluctuations in renewable energy costs, supply-demand imbalances, and varying levels of international hydrogen trade could impact hydrogen prices, influencing market stability and investor confidence.

5.3.3 Natural hazards

While the Netherlands and Scotland are not located in a part of the world prone to natural hazards like the earthquakes and typhoons that are characteristic for Japan, they are both situated along the North Sea coast, making them susceptible to powerful storms and adverse weather conditions (Gaslikova et al., 2012). These natural hazards can disrupt maritime transportation crucial for the hydrogen supply chain between the two countries. Storm surges, high winds, and rough seas could lead to port closures, delayed shipments, or even vessel accidents, causing interruptions in the timely movement of hydrogen, impacting supply chain reliability.

5.3.4 Technical

Shipping MCH has its own risks, but it's generally considered less risky than other options like ammonia, as one major advantage of using MCH is that it's stable under normal conditions, which makes it much safer to transport (IEA, 2019). While shipping MCH is safer than some alternatives, it's still important to be aware of potential risks. These could include things like making sure it's handled and transported properly to avoid any leaks or spills.

5.3.5 Human resources

As the Port of Rotterdam positions itself as a pivotal hydrogen hub, not just for the Netherlands but also for all of Europe, it is proactively working towards diversifying its workforce (Rotterdam, 2022). This strategy aims to bolster the overall work quality, organizational agility, and decision-making processes (Rotterdam, 2022). Given the Port's extensive historical experience in managing diverse commodities, each with its unique demands and considerations, it anticipates minimal human resource-related disruptions within the Dutch context. Across the of the North Sea, the Scottish Government has recognized the pivotal role of a skilled workforce in driving business productivity and economic prosperity (Government, 2022). Their strategic focus revolves around transitioning to a net-zero economy, embracing the digital revolution, and championing lifelong training to ensure a continuous supply of skills for employers. Scotland already stands out in terms of tertiary education levels when compared to the rest of the UK and similar advanced European economies (Government, 2022). Furthermore, the Lloyds Banking Group and Oxford Economics Green Growth Index position Scotland as the leading region in the UK with the greatest potential and opportunities for green growth (Lloyds Bank, 2023). This reflects Scotland's well-established green industrial base, which supports a growing number of green jobs and fosters innovation. It also underscores Scotland's commitment to developing and utilizing renewable energy infrastructure and the successful adoption of relevant skills and training. Consequently, it is anticipated that this sector of disruption will not pose a significant risk from the Scottish perspective.

In this Chapter, analysis was done on the disruptions that an IGHSC could be subject to. By doing a structured literature review that can be found in Appendix C, a critical re-structuring and selection of the disruptions and domains relevant to IGHSC resulted in an exhaustive overview. This overview can be used as part of the guideline that will be established. After the overview was formed, this Chapter showed how these disruption domains should need to be considered in the two exploratory examples. While keeping a surface level of analysis, the goal to show the way the identified disruptions could occur, was reached. This was the last step required before the formation of the guideline that this thesis will establish, in Chapter 6.

6 Guideline for Resilience Design and Maintenance for an International Hydrogen Supply Chain

To establish a guideline for the design and maintenance of resilience, it is important to take a step-by-step approach. First, resilience will be split into the design phase and the post design phase. After this important distinction, the design phase will be shaped by providing the design choices that can help built resilience in the design phase. Afterwards, the post design phase will be divided into three scopes: conceptual, qualitative, and measurable. In the conceptual scope, the four abilities to maintain resilience will be established. Moving on to the qualitative scope, the elements that built the abilities to maintain resilience will be formed. These will form the qualitative metrics. Last, KPI's will be provided to assess the qualitative metrics. These three scopes, the abilities, the qualitative metrics and KPI's will be captured in a framework, that can be found in Appendix G. An overview of the guideline, that captures both the design phase and the post-design phase, as well as the way the concept of SCRES is embedded within the socio-techno-political-economic landscape, will be broken down and can be found in Appendix F.

6.1 Discerning the Design Phase and Post-Design phase.

This chapter delves into an in-depth exploration of the IGHSC's resilience, dissecting its evolution through two consecutive phases: design and post-design. These distinct stages hold profound implications for establishing and maintaining resilience, each characterized with their own considerations and complexities. By acknowledging the difference between system resilience dependent on itself and the influences stemming from analogous systems, this chapter unravels a nuanced perspective on strategies imperative for reinforcing and maintaining the resilience of the international hydrogen supply chain.

The criterium for a building block of system resilience for being included in the design phase is the following: the hydrogen supply chain must not yet be operational, but still needs to be established. The design phase lays the cornerstone for systemic resilience. Herein, the design choices made, resonate across all the elements of the hydrogen supply chain's configuration. By analyzing literature about design choices in the design phase of SCRES, this chapter will underscore a fundamental truth: a system's resilience is intricately linked with the learning from operations displayed by similar systems. Drawing inspiration from analogous supply chains, particularly the international liquefied natural gas (LNG) supply chains and the Dutch gas market, we can learn invaluable insights for the design and conceptualization of the international hydrogen supply chain. This cross-pollination of ideas and strategies enhances our understanding of the key principles that foster resilience in complex, interconnected supply chain networks in co-evolving environments. In Section 6.1, a sequential process is derived of design choices during the design phase that will enhance resilience in the hydrogen supply chain.

Thereafter, the post-design phase begins when the supply chain enters operational mode. The character of SCRES undergoes a transformative shift. It evolves not

solely in adherence to its intrinsic blueprint but in response to the disruptions it confronts. Disruptions, occurring with low frequency but high impact, surface as formative inputs in shaping resilience during this phase. Here, the focus shifts towards cultivating intrinsic resilience mechanisms, based on inputs from the systems learning capabilities after its anticipation, response, recovery, and improvement after a disruption. The supply chain becomes dynamically responsive and adaptive to disruptions and is coevolutionary as agents in the hydrogen supply chain interact with each other as well as their environment (Koza, 1995), like CAS theory has already taught us (Day, 2014). Resilience, in this context, becomes contingent on a system's ability to adapt to and navigate in the co-evolving environment while gaining insights and refining its operations (Day, 2014). Disruptions serve as the crucible wherein a sturdier, more agile framework is forged through learning and improvement capabilities (Day, 2014). This phase underscores an important factor - resilience is not confined to forming a solid, disruption-resistant structure, but encompasses the embrace of change and adaption, interweaving it into the very configuration of the supply chain. The post-design phase, therefore, holds the key to completing and sustaining the resilience of the international hydrogen supply chain as it navigates the co-evolving landscape of global trade, energy distribution and geographical system.
Last, this chapter will provide an overview that presents the guideline, spanning from design phase to post-design phase, for assessing resilience in an IGHSC. Through this exploration, we contribute not only to the comprehension of supply chain dynamics but also to the broader discourse on building and maintaining SCRES. It will be outlined how the design choices made will enhance all the elements of resilience in the hydrogen supply chain's configuration during the post design phase. By capturing the design choices in the design phase, the resilient capabilities of the post-design phase and the disruptions present, this thesis will establish a robust overview to assess and design resilience for an international hydrogen supply chain.

6.2 Design Phase

By analyzing literature about design choices for designing supply chains and by drawing on lessons that can be learned from analogous systems, a sequential process is formed that breaks down all design choices that need to be considered when designing resilient performance in a hydrogen supply chain. This hierarchy, which can be found in Appendix E, will also form the structure of this section. Per design choice, it will be elaborated why significance for SCRES is assumed. The design choices involve leveraging learning effects and gleaning insights from analogous systems, with a notable example being the international Liquefied Natural Gas (LNG) market (IEA, 2019). By studying historical processes and disruptions in the LNG industry, decision makers in the hydrogen supply chain can identify valuable lessons applicable to their own context. These insights aid in understanding potential vulnerabilities, strategies, and dynamic adjustments required to enhance the robustness of the hydrogen supply chain. Learning from analogous systems allows for a more comprehensive understanding of possible future scenarios, equipping decision-makers with the knowledge to adapt to disruptions effectively. This suggests that system resilience for the hydrogen supply chain is not only dependent on itself and its own inputs and environment, but also on similar systems.

6.2.1 Location selection

Strategic location selection is a critical design choice that significantly influences the resilience and efficiency of an international hydrogen supply chain Christopher and (Christopher and Peck, 2004); (Pereira et al., 2014) involving identifying optimal geographic locations for various supply chain nodes, such as production facilities, storage sites, distribution centers, and key markets (Zegordi et al.,). This decision is paramount in shaping the supply chain's responsiveness to disruptions and overall operational success. It must be noted that this part of the supply chain configuration is not always a design choice. If the hydrogen supply chain would be designed under carte-blanche circumstances, meaning that the design team can choose every part of the configuration, it is an important one. For hydrogen supply chains that are already fixed to a certain point-to-point configuration, this section is less relevant. Designing the international hydrogen supply chain, several factors must be considered for strategic location selection, found after analysis and subsequent factor selection in articles by (Cerniauskas et al., 2020); (Matthias et al., 2021); (Roscoe et al., 2020a); (Stöckl et al., 2021); (Zegordi et al.,).

Geographical selection

Opting for locations close to diverse and reliable sources of hydrogen production, such as renewable energy sites or natural gas fields when the green pathway does not form a constraint, minimizes transportation distances. This reduces energy consumption and transportation costs, and it has the capacity to reduce supply chain disruptions by shortening supply chains and thus reducing the complexity of cross-border logistics, enhancing the supply chain's viability which is desirable in case of a disruption ((Matthias et al., 2021,Ramu and Jayaram, 2022,Stöckl et al., 2021)). Decision makers should also choose locations that offer direct access to key consumer markets. Proximity to demand centers reduces transit times, ensuring timely delivery and meeting market needs promptly (Zegordi et al.,). However, in an IGHSC, where proximity to renewable sources is a key consideration, this proximity to demand is not always a choice.
Additionally, it is important to assess the availability and quality of transportation infrastructure, including roads, railways, ports, and pipelines. Favorable transportation networks streamline the movement of hydrogen between production, storage, and distribution points, contributing to operational efficiency (Cerniauskas et al., 2020). Geographical selection should logically also take into account natural hazards, such as earthquakes, hurricanes, floods, and wildfires as presented in Chapter 5, as they can have devastating impacts on infrastructure and operations (Chester et al., 2013). By factoring in natural hazards, supply chain planners can strategically position facilities and routes away from high-risk areas, minimizing exposure to potential disruptions.

Geo-political stability

It is important to also consider geopolitical stability and regulatory environments of potential host countries. A stable political climate fosters long-term investments and reduces the risk of supply chain disruptions due to unforeseen political events (Roscoe et al., 2020a). The interplay of geopolitical stability and regulatory conditions directly influences a supply chain's ability to adapt, respond, and thrive in an increasingly interconnected global market (Bompard et al., 2017). The geopolitical stability and regulatory environments of countries that make up the supply chain configuration significantly impact supply chains by influencing long-term planning and investment decisions (Berle et al., 2014); (Moradlou et al., 2021). When host countries demonstrate stability and provide clear and consistent regulations, businesses are more likely to commit resources to infrastructure, technology, and workforce development. This creates a virtuous cycle, where increased investment leads to improved supply chain capabilities.

6.2.2 Partner selection

Friend-shoring

Since the advent of the shale gas revolution, the United States has transformed into a net energy exporter, a shift that has significantly influenced its foreign policy (Centre, 2023). This transformation has been interwoven into the US's strategic approach as it seeks to reinforce supply chains and lessen dependencies on China (Centre, 2023). This foreign policy approach, often referred to as "friend-shoring," aims to offer energy security to allied nations, particularly in the aftermath of Russia's destabilizing actions that have disrupted global energy dynamics (Centre, 2023). While the US primarily extends energy security through the provision of liquefied natural gas (LNG), its strategic focus is expanding to anticipate a future where hydrogen supersedes LNG. In the realm of pivotal hydrogen supply chain technologies, the US is displaying active involvement across diverse domains, even though it may not consistently possess the most advanced technology available. Aligned with the approach of many major economies, the United States is expected to prioritize retaining crucial hydrogen-related technologies domestically (Centre, 2023). This strategic inclination underscores the intention to safeguard proprietary knowledge and maintain a level of autonomy in the development and deployment of essential technologies within the emerging hydrogen economy. "Friend-shoring" thus stands in contrast to traditional offshoring, where sourcing occurs from distant, often overseas, suppliers. In the context of the supply chains established in this thesis, this means encouraging outsourcing production to friendly countries/regimes with whom Japan, The Netherlands or its allies share common values and ideas. Friend-shoring can be beneficial for building resilience in both hydrogen SCRES because of several effects it may bear. In the event of geopolitical tensions, supply chain actors can more quickly and efficiently respond and recover. Friend-shoring also encourages closer collaboration between suppliers and buyers due to cultural and diplomatic proximity(Centre, 2023). This can lead to better coordination, information sharing, and joint efforts to address geo-political challenges. In turn, this increases transparency throughout the hydrogen supply chain and allows the different players among the different elements in the supply chain configuration to have a more holistic view of the supply chain (Day, 2014), when all the trading partners routinely communicate information. Because friend-shoring involves the actors of the hydrogen supply chain's willingness to share risk, collaboration and transparency go hand in hand. A company that operates internationally faces challenges in the areas of politics, economy, competition, logistics, culture, and infrastructure (Kumar et al., 2017). In the context of hydrogen supply chains, friend-shoring can involve sourcing hydrogen production technologies, equipment, and components from trusted suppliers during the design phase. While friend-shoring offers resilience benefits, it's important to note that it may not be feasible for all components or technologies, and cost considerations should be weighed against the benefits. Additionally, supply chains should carefully balance the advantages of friend-shoring with broader strategic goals and market conditions.

Re-shoring and near-shoring

Re-designing the hydrogen supply chain stands as a core factor enhancing its resilience by redesigning robustness, security, and agility, with a specific emphasis on refining location strategies (Christopher and Peck, 2004). When executed dynamically, this element holds the potential to proactively alleviate risks and the aftermath of supply chain disruptions, and in some cases, preemptively avert disruptions (Pereira et al., 2014), which must not be confused with focus on mitigation strategies. When diversification design choices are made, reshoring and near-shoring are among the location refining strategies that can be used, if the designer notices that that diversified location attracts significant disruptions. Again, this would only be relevant if decision-makers have the option to relocate. Re-shoring is defined as "the relocation of production or supplier(s) to the country of a key production / assembly location" ((Soroka et al., 2016), p. 647), with significant resemblance to the definition of near-shoring: "the relocation of production or supplier(s) to the region / trade area of a key production / assembly location" ((Soroka et al., 2016), p. 647). (Soroka et al., 2016) outlines key determinants impacting re-+110 shoring decisions, such as the flexibility-referred to as agility in this thesis (refer to Chapter 6.2, "Ability to Respond") -of suppliers and the supply chain This agility serves as a catalyst for re-shoring and contributes to bolstering the supply chain's resilience. This is an example of how decision makers can move from the post-design phase to the design phase to increase resilience and alter the configuration that resonates throughout the hydrogen supply chain's operations. According to (Pettit et al., 2010), agility stands out as the primary capability that underpins resilience. Hence, it becomes evident why agility is also recognized as a pivotal driving force for re-shoring initiatives. (Pettit et al., 2010) additionally recognize human resource aspects, including training and knowledge acquisition, as qualities that elevate resilience. Consequently, the act of re-shoring to address skill-related challenges holds the promise of increasing supply chains resilience.

6.2.3 Partner securitization

Long-term contracting

Japan's approach to securing LNG supply through long-term contracts can provide a valuable lesson for the international hydrogen supply chain. In the LNG market, Japan has often entered long-term contracts with suppliers (IEA, 2022), which not only ensure a stable and consistent supply but also provide price stability over extended periods (Ritz, 2014). This strategy has helped Japan mitigate the impact of volatile market conditions and price fluctuations (Ritz, 2014). Both are examples of disruptions categorized under 'market economics' in Chapter 5. Decision makers must therefore recognize the importance of establishing long-term agreements for hydrogen (carrier) supply. By negotiating extended contracts with hydrogen producers, buyers can secure a reliable source of hydrogen while also reducing exposure to price volatility. This approach offers benefits to both parties involved: producers gain predictability in their revenue streams, even more favorable when considering the intermittent nature of their energy supply, while off-takers benefit from stable pricing, enabling them to plan their operations and investments more effectively. It is well-known that long-term contracts in the LNG market contribute to creating a more stable and resilient energy landscape (RN2, 2020b), and they establish a steady foundation for hydrogen supply chains involving Japan and The Netherlands, encouraging investment in infrastructure and technology. Risk-sharing is fostered through committed terms, mitigating market fluctuations and disruptions (Shin and Tunca, 2010). Such contracts align stakeholders' interests, promoting collaborative efforts to enhance SCRES (RN2, 2020b). The increasing number of bilateral agreements concerning hydrogen indicates that energy relationships are changing from the 20th century fossil fuel based energy relationships (IRENA, 2022). More than 30 countries and regions have plans for importing or exporting hydrogen, showing that trading hydrogen between countries is growing a lot. Even countries that didn't usually trade energy are now making deals related to hydrogen (IRENA, 2022). As countries' economic ties change, their politics might change too.

Price- and tariff setting

Price setting can play a pivotal role in building resilience within an international hydrogen supply chain, especially when confronted with sudden price changes. By adopting a well-thought-out pricing strategy, the supply chain can build a buffer against potential disruptions and uncertainties arising from these price fluctuations. In the face of sudden price spikes, a flexible pricing model can mitigate the impact by implementing mechanisms like responsive pricing allows for adjustments that reflect market dynamics, helping to avoid abrupt cost escalations and ensuring a more stable cost structure (Tang and Tomlin, 2008). Cost-plus pricing agreements establish the price of a component by adding a margin to its unit production cost, resulting in a component price that fluctuates in line with its unit production cost (Iida, 2012). Furthermore, such pricing strategies can foster closer collaboration between suppliers and buyers, which is a key element of resilience as presented in Chapter 6.3. During periods of abrupt price changes, open communication facilitated by transparency and information-sharing while using these strategies, as also explained in Chapter 6.2, can lead to negotiation and alignment on new terms, reducing the potential for supply chain disruptions. Clear tariff arrangements facilitate negotiations during sudden tariff shifts, minimizing the risk of supply chain disruptions. An instance of this is a form of tariff reduction applicable to cross-border tariffs and entry tariffs at LNG terminals. The EU Commission suggests in the FSR Debate in 2022 the complete removal of these tariffs (FSR, 2022). When viewed through the lens of the internal market, this proposition aims to guarantee the production of low-carbon gases in the most economically favorable locations and facilitate seamless trading across Europe.

6.2.4 Diversification

Diversification of suppliers and off-takers

Japan, a pioneer in the LNG market, is applying lessons learned from the market to the emerging hydrogen supply chain. In the aftermath of the 2011 Fukushima disaster, Japan sought to diversify its energy sources and reduce its reliance on nuclear power (IEA, 2022); (Murakami et al., 2017). This compelled the nation to significantly expand and diversify its LNG imports through cultivating a variety of relations with LNG exporting nations, to ensure a resilient supply chain and secure its energy needs (IEA, 2022); (Murakami et al., 2017). An international hydrogen supply chain should similarly seek to establish a network of trustworthy partners to mitigate risks associated with supply disruptions, which Japan also aims to do (Government, 2021b). This is underscored by the Business Development Director of Koole Terminals, talking about the importance of not going for a point-to-point supply chain with single off-take and single-supply (Koole Terminals, Key Quote 7).

Diversification of carriers

This thesis explores two supply chain configurations centered on a single hydrogen carrier. However, it's crucial to emphasize the significance of diversifying hydrogen carriers for building SCRES. Hydrogen production methods, as outlined in the Theoretical Framework, offer distinct advantages, challenges, and geographic implications. The current immaturity of the hydrogen market and the current absence of a universal optimal carrier underscore the need for diversification (Koole Terminals, Key Quote 7). A key component in Japan's adoption of hydrogen is the diversification of imported energy carriers, origin nations, and supply routes (Government, 2021b). The evolving market introduces uncertainties that make sole reliance on one carrier risky. As the market matures, no definitive carrier has emerged. Different carriers offer distinct advantages depending on factors such as transportation distance and technical requirements, storage, and end-use requirements among others. Consequently, channeling the supply chain through a single carrier could expose it to undue vulnerabilities should market dynamics shift or new carrier technologies emerge (Koole Terminals, Key Quote 6). Diversifying carriers aligns with the evolving hydrogen sector, adapting to technology, regulations, and consumer preferences. This approach captures opportunities as carriers advance and preferences evolve and reduces risks and potential disruptions, guarding against unforeseen challenges. Diversification also minimizes the impact of supply disruptions stemming from carrier-specific issues, such as production shortages or transportation bottlenecks. Additionally, diversified carriers distribute risk across multiple sources, reducing the chances of a single point of failure affecting the entire supply chain.

6.2.5 Standardization

Exploring the international gas market in the Netherlands offers a key lesson for designers crafting an international hydrogen supply chain: the power of strategic cross-border connections. The Dutch gas market's success in interconnecting with neighboring countries highlights the importance of collaboration and integration. The Netherlands, through its well-established gas infrastructure, has effectively interconnected with surrounding nations, facilitating efficient gas transport and distribution (RN2, 2020b). This strategy extends to designing resilient emerging hydrogen supply chains, emphasizing the significance of fostering cross-border cooperation. Designers of an international hydrogen supply chain can learn from the Netherlands' approach by prioritizing seamless connectivity throughout elements of the hydrogen supply chain configuration throughout different countries. This includes harmonizing regulatory frameworks, standardizing transport methods, and creating interoperable infrastructure(Commision, 2023). Such cross-border collaboration enables the efficient sharing of hydrogen resources, enhances supply security, and bolsters market stability, all adding to resilient performance (Pettit et al., 2013). Applying this strategy to the hydrogen sector promotes a harmonized, interconnected network capable of swiftly responding to demand fluctuations and optimizing resource utilization. Standardized equipment and procedures could enhance safety, streamline regulatory approvals, and encourage innovation by providing a clear framework for the industry (Commision, 2023). Similarly, the hydrogen industry can benefit from standardized practices and regulations to ensure uniformity and consistency across the supply chain (Stöckl et al., 2021). The LNG market has also seen efforts to harmonize regulations across different regions to facilitate international trade (IEA, 2022). The hydrogen market can learn from this approach and work towards global regulatory alignment, reducing barriers to cross-border hydrogen trade. Japan's commitment to standardizing certification processes in the LNG industry offers an important technical lesson for the international hydrogen supply chain. In the LNG market, Japan established rigorous standards for LNG storage tanks, transport vessels, and handling equipment (IEA, 2022). This standardization not only ensured the interoperability of various components but also promoted safety, efficiency, and cost-effectiveness throughout the supply chain (Shin et al., 2008). Applying this insight to the hydrogen sector, stakeholders can recognize the value of establishing uniform standards and certification protocols for hydrogen production, storage, transportation, and utilization equipment. A study within the realm of social science (Edgerton, 2006) has emphasized the necessity of considering the social backdrop in which technologies are employed, rather than solely concentrating on individual decision-making. This social context encompasses not only the establishment of additional activities essential to support technology usage – for instance, the training of skilled personnel for installation and repairs – but also the evolution of

shared interpretations regarding how a technology should be employed (Edgerton, 2006). These developmental processes are commonly referred to as 'societal embedding'. This concept is manifested through the development of standardization and, to some extent, through the establishment of user practices associated with the implementation of the new technology.
In summation, the formation towards resilience in an IGHSC is a continuous trajectory. During the design phase, system resilience is dependent not only on itself but also on analogous systems, harnessing lessons to construct an inherently robust architecture by making the right design choices. Transitioning into the post-design phase entails the pursuit of adaption to (co-evolving) disruptions and its environment, learning and improving from adapting to disruptions. Together, these phases complete the establishment of resilience – a combination of design and adaptability, of learning from analogous systems such as the international LNG supply chain and learning from within. While drawing lessons from the LNG market is valuable when designing a hydrogen supply chain, since building resilience is also dependent on analogous systems, caution must be exercised not to blindly replicate its strategies. The emerging hydrogen market carries its own distinct challenges due to its relatively low maturity (Staffell et al., 2015). While the LNG and gas market's experiences offer insights, the hydrogen sector exhibits greater variability in its early stages (Staffell et al., 2015). The hydrogen market's evolving nature introduces uncertainties stemming from technological advancements and policy changes among others. Unlike the relatively established LNG market, the hydrogen market's immaturity implies a higher degree of unpredictability and the need for adaptable strategies. Copying the LNG market's approaches without considering the unique factors of the hydrogen sector can lead to ineffective solutions or missed opportunities. Instead, designers of hydrogen supply chains should tailor strategies to accommodate the market's dynamics, which will be discussed further in Chapter 6.2. This involves emphasizing establishing capabilities to swiftly adapt to disruptions stemming from shifts in the volatile hydrogen environment.

6.3 Post-Design Phase

After the design phase, an important distinction must be made, being that the supply chain system is now operational and subject to disruptions. In this section, a tractable but thorough structure is established for the breakdown of what operational resilience entails for an IGHSC, how it is built, maintained, and in the case of the development of historic data, assessed. This section will first present a way to organize the analysis of resilience in the post-design phase, by presenting three different levels of scopes. Afterwards, the scopes will be used to establish a framework for building and maintaining resilience in the post-design phase.

6.3.1 Shaping the Framework for the Post-Design Phase

Both (Cheng et al., 2021) and (Yang et al., 2023b) underscore the lack of a universal metric to quantify resilience or make it measurable. However, in the pursuit of establishing a guideline for designing resilience for the post-design phase of an IGHSC, the necessity of a resilience assessment approach becomes evident, as a foundation for a

guideline to build and maintain resilience in the operational phase, the post design phase. Resilience assessment can be categorized into three main scopes: conceptual, qualitative, and quantitative (Cheng et al., 2021). For the latter, this thesis argues that this level should be quantitative and measurable, so that measurable qualitative KPI's are also considered. The lowest hierarchy this is characterized by the KPI's that can tell stakeholders information about their qualitative metrics. This chapter contends that these three scopes follow a sequential progression, ultimately determining the depth to which the hydrogen supply chain's resilience is measured during both design and post-design phases. This section will explain how Chapter 6 will follow these three scopes and ends by proposing a method for stakeholders to start their resilience assessment practices through the performance measurement of the operational hydrogen supply chain. This approach will adapt the framework proposed by (Yang et al., 2023b) to suit the dynamics of an international hydrogen supply chain.
Conceptual resilience encompasses the notion of having a system that can sustain desired functions with minimal interruption when faced with disruptions, addressing potential disruptions and proposing mitigation measures (Cheng et al., 2021), while this thesis places less emphasis on the latter aspect. Therefore, within this thesis, conceptual resilience aligns with the definition established in the Theoretical Framework, suggesting that assessing conceptual resilience involves analyzing the supply chain's adaptive resilience capabilities as will be stated in Chapter 6.3. These capabilities encompass the adaptive ability to anticipate, respond, recover, and improve performance post-disruption. Conceptual resilience is thus not something that can be assessed quantitatively, but more so assessing if the basic capabilities of resilience as established in this thesis are present throughout the configuration of the operational hydrogen supply chain. The extent of performance deterioration during response and recovery depends on factors such as reliability design, supply chain configuration, design choices, maintenance, reparability, and the severity of the disruption ((Cheng et al., 2021); (Yang et al., 2023b)). The resilient capabilities can be to some extend assessed by the shape of the system performance curve. Systems that have a concave shape are anticipated to possess greater resilience compared to those that display a convex shape (Cheng et al., 2021)(Tukamuhabwa et al., 2015a). A schematic overview of conceptual resilience is presented below in 4.

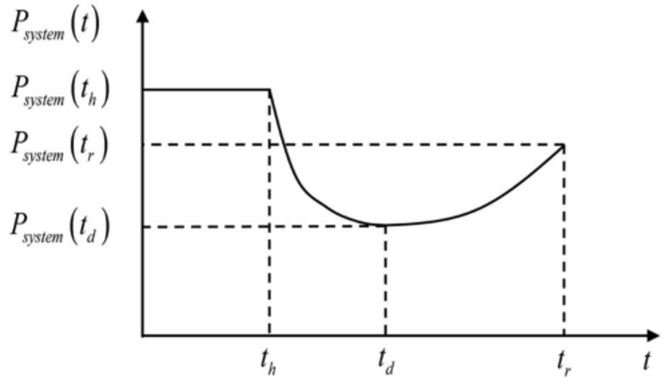

Figure 4: The conceptual overview of resilience as presented by (Cheng et al., 2021), adapted to fit the definition of resilience presented in this thesis.

Where

- $P(t)$ performance level at arbitrary time t
- $P(t_h)$ steady-state performance level
- $P(t_d)$ the lowest performance level at t_d
- $P(t_r)$ performance level when recovery action ends at time t_r

Here, the performance curve is given, before, during and after a disruption. Assessing conceptual resilience thus entails assessing whether the operational supply chain subject to a disruption behaves according to this conceptual idea of resilience. It becomes more constructive when resilience is assessed a level deeper.
Subsequently, qualitative resilience lays the groundwork for measuring resilience (Cheng et al., 2021). It involves defining metrics that designers deem important for building and maintaining resilience. In the paper by (Cheng et al., 2021), these qualitative metrics, such as preparedness, robustness, recovery speed and reliability, are on the same hierarchy as the elements that built the adaptive capabilities for maintaining resilience that will be established in Chapter 6.3. The overview presented in Chapter 6.3 thus outlines the qualitative framework (elements for adaptive capabilities), this thesis has established for evaluating the resilient performance of a post-disruption hydrogen supply chain. In real life scenarios, this is usually obtained through focus groups of subject matter experts (SME), where discussions provide the understanding of the disruptions and the solicitation of disruption's mitigation countermeasures (Cheng et al., 2021). This thesis contends that, ideally, all the elements that form the adaptive capabilities in Chapter 6.3 (essentially qualitative metrics) should be designed for and assessed to ensure maximum resilient capabilities. However, under most circumstances, specific contexts might involve the utilization of only one or several of the elements to form adaptive capabilities (Cheng et al., 2021). Nonetheless, the resilient capabilities and elements outlined in Chapter 6.3 have been carefully selected to suit the unique context of IGHSC.
Consequently, this progression of conceptual to qualitative resilience assessment

paves the way for laying the foundation for quantifying resilience (Cheng et al., 2021). In this thesis, it is argued that instead of just aiming to quantify resilience, one should aim to establish measurable KPI's that could be both qualitative as quantitative. Nonetheless, the same hierarchy as found in the paper by (Cheng et al., 2021) is acknowledged. Most KPI's of the resilient metrics (elements of resilient capabilities) can be derived as functions of one or multiple of the values as demonstrated in the Table 2 below as given in (Cheng et al., 2021). Therefore, this thesis argues that it is important to keep track of at least these indicators when historic data can be gathered. What this means is that the elements as presented in Chapter 6.3 form the qualitative metrics that can be subject to measuring with the established KPI's also present in Chapter 6.3 by using historic data of the indicators. For doing this, it is advised to gather the indicators as proposed by (Cheng et al., 2021) in Table 2. An overview of the conceptual, qualitative and measurable assessment of resilience, built in Chapter 6.3 and 6.4 is provided in Appendix G.

Point in performance curve	Notation	Indicator
(a)	P(t)	performance level at arbitrary time t
(b)	$P(t_h)$	steady-state performance level
(c)	$P(t_d)$	the lowest performance level at t_d
(d)	$P(t_r)$	performance level when recovery action ends at time t_r
(e)	$\int_{tb}^{ta} P(t)dt$	total performance throughout a time period ($t_a \rightarrow t_b$)
(f)	$t_d - t_h$	the length of the hazard period
(g)	$t_r - t_d$	the length of the recovery period

Table 2: Important indicators obtained from historic data useful for measuring KPI's as provided by (Cheng et al., 2021)

The next step is to establish an approach on how to organize the resilience assessment. For this, the framework by (Yang et al., 2023b) is proposed. In analyzing resilience, the designer of the hydrogen supply chain must envision how a system responds to and handles disruptions given specific system characteristics and configurations (Yang et al., 2023b). Generally, resilience assessment then answers the following questions, as given by (Yang et al., 2023b):

1. What are possible disruptions to a system?
2. If the disruptions occur, what are their impacts on the system functionality?
3. How well can the system handle these disruptions while maintaining acceptable system performance?

The first question was answered in Chapter 5 and forms a guideline on the different domains that should be considered and in what way the provided disruptions should be considered. The functionality, the system characteristics and the two hydrogen supply chain configurations were provided in Chapter 4, forming a guideline on the level of description and research that is required for this question and the foundation for the functionality analysis and -tree that are required in the framework. Based on the functionality- and disruption analysis and the system characteristics and configuration, system performance metrics can then be developed, which will be done in Chapter 6.3, namely the elements of the adaptive capabilities for maintaining resilience. The framework by (Yang et al., 2023b) proposes to work by following five steps, for which this thesis thus laid significant groundwork for the first four, as the last requires historical data. The steps in the framework by (Yang et al., 2023b) are:

1. **Defining scope and context:** here, the goal of the assessment and the system boundary are defined. Subsequently, the traceability of causality, depending on the system's complexity, and the manageability are determined, to assess the degree of the need for resilience assessment.

2. **Stakeholder analysis:** The scope and context analysis address the query of "resilience of what". To further elucidate this "what," a stakeholder analysis could aid in pinpointing the key principles linked to the designated system, thereby establishing the foundation for the analysis of disruptions and functionality.

3. **Disruption identification & analysis:** The process of identifying, categorizing potential disruptions, and assessing the magnitude of their impact encompasses four key stages:
   - Data collection.
   - Disruption identification and classification.
   - System structure analysis.
   - Disruption impact analysis.

4. **Functionality assessment** In addition to recognizing basic functions, the assessment of functionality establishes the correlation between functions and the physical components involved, and involves performing a system performance variation analysis.

5. **System resilience quantification metrics:** While quantifying resilience, it's important to acknowledge that not all aspects can be encompassed, but rather those that are identifiable. Acquiring the performance profile becomes imperative within the current framework for quantifying resilience. Consequently, the suggested approach can solely measure the resilience of the system in relation to disruptions whose effects on system performance are quantifiable.

Now, the structure for forming the qualitative framework for building and maintaining resilience in the post-design phase is established. Thus it is time to use the three scopes to break down the concept of resilience into an actionable framework, adding to the guideline that this thesis will design.

6.3.2 Forming the Qualitative Framework for Resilience

For using the three scopes, the first goal is to divide the definition formed in the Theoretical Framework into abilities that together built resilience in the hydrogen supply chain. This forms the conceptual scope. Subsequently, these capabilities

will be broken down into elements that form the backbone for the capabilities that built resilience. This is done by analyzing scientific papers and their way of defining operational resilience in supply chains, for which the literature study structure can be found in Appendix D. These will be the qualitative metrics for resilience, and thus form the qualitative scope. Additionally, measurable KPI's are provided connected to these elements, forming the last scope; measurable. An important criterium that was established in this thesis stemmed from the findings that a lot of the elements for building resilience as found in the papers were not on the same hierarchal level and not "Mutually Exclusive, Collectively Exhaustive" (MECE). MECE is a crucial principle in building structured overviews and frameworks for effective problem-solving and communication (Schmidt et al., 2017). In essence, it emphasizes the necessity of organizing information in a way that ensures clarity, avoids overlaps, and encompasses all possible scenarios.
For structuring the capabilities for resilience using the MECE principle, first the definition of resilience is broken down into distinct and non-overlapping categories (mutually exclusive) that encompass all potential aspects or components (collectively exhaustive). The same approach is subsequently used for forming the elements that built these capabilities. This approach not only helps prevent confusion and double counting but also aids in uncovering insights, identifying gaps, and making comprehensive decisions (Schmidt et al., 2017).
For establishing the overall structure of the capabilities for resilience, the paper of Ali et al. (2017), analyzed 103 articles from the time span of 2003 to 2015. What they found is that resilience can be defined in three dimensions. The first dimension is related to the reaction time: before, during, or after the disruption. The second component is concerned with the strategies used, which include proactive, concurrent, and reactive. The proactive strategy addresses the pre-disruption phase, the concurrent strategy addresses the disruption phase, and the reactionary strategy addresses the post-disruption phase. The third dimension they identified described the capabilities that are required for establishing resilience. The capabilities Ali et al. (2017) identified are:

1. the ability to anticipate (proactive)
2. the ability to adapt (concurrent)
3. he ability to respond (concurrent)
4. the ability to recover (reactive)
5. the ability to learn (reactive)

When we compare these capabilities to those outlined in the thesis's definition, we find a similar set, with the addition of adaptability as a distinct element. However, in the theoretical framework's definition of resilience, adaptability is posited as a critical factor that intersects with all the other four resilience elements, leading to a lack of mutual exclusivity (MECE). It's important to note that adaptability isn't tied to a specific phase during a disruption; rather, it represents a holistic, overarching capacity. These five distinct elements can be differentiated based on the phases in which their corresponding strategies are applied: proactive, concurrent, and reactive (Ali et al., 2017a). Although (Ali et al., 2017a) elements and capabilities are comprehensive, drawn from an extensive review of 103 articles, a critical perspective was applied, resulting in substantial enhancements to their framework. Below, the modifications made are detailed.

Dissecting the definition that was established in the theoretical framework, key requirements of resilience can be identified. For these requirements, abilities can be established. First, the definition of resilience as established in the Theoretical Framework is broken down into components as below:

The adaptive capability of the global hydrogen supply chain to anticipate and respond to unexpected disruptions, to make a timely recovery to the desired level of connection and control over the structure and function, and thereafter improve to a post-disruption state of performance that is ideally a better state than before the disruption.

Adaptive capabilities of resilience:

1. Anticipate.
2. Response.
3. Recovery to desired performance.
4. Improve performance after response.

Now, four abilities are identified: the ability to anticipate, the ability to respond, the ability to recover and finally, the ability to improve. The second dimension of resilience by Ali et al. (2017) will be adopted. This means that the ability to anticipate is proactive, the ability to respond is concurrent, and the abilities to recover and learn is reactive. As of now, the ability to adapt is taken out of the five abilities proposed by Ali et al. (2017). This ability contained four elements; flexibility, redundancy, collaboration, and agility. These elements will be added to other abilities of resilience where they fit better, or merged with other elements of capabilities that implied the same thing or were complementary, which will be explained in more detail below.

In 5, the conceptual framework for resilience in the post-design phase is presented, showing the abilities that will be described in more detail in the next section.

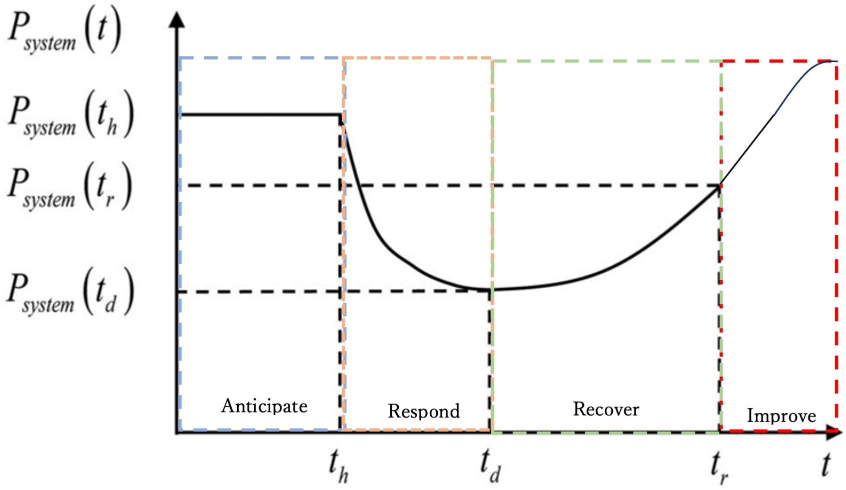

Figure 5: The conceptual overview of resilience as presented by (Cheng et al., 2021), adapted to fit the definition of resilience presented in this thesis.

Per ability, the adaptations to the analyzed papers made in this thesis are explained. All definitions of the elements that define the resilience capabilities per disruption phase, were established in this research by critical reflection of the concept and merging the papers as given in Table D.1. Per ability, the elements (qualitative metrics) and subsequently the KPI's, are summarized in Appendix G, forming an essential framework that adds to the guideline.

6.3.2.1 The Ability to Anticipate As the definition of disruptions tells us, they are occurring with low frequency but large impact. This means that they are not expected and so the argument is made that effort can and should not be directed on prevention. This is the core of the ability to anticipate. In the ability to anticipate, the element of "disruption knowledge" as presented by (Ali et al., 2017a) was moved to the ability to improve, described as using knowledge management before a disruption phase through practices such as education and training (Christopher and Peck, 2004); (Jüttner and Maklan, 2011). This is however related to the ability to improve and overlapped the element of "knowledge implementation" in the ability to improve. This thesis regards the ability to improve as creating the input to the ability to anticipate. The elements of developing and implementing knowledge are all elements that belong to the ability to improve. This will be discussed in more detail later. The input from the ability to improve to the ability to anticipate is shown in Appendix F and is an adaption that is made to the schematic overview of resilience by (Tukamuhabwa et al., 2015a).
Situation awareness involves comprehending the potential weak points within the supply chain configuration and formulating strategies to handle unforeseen events. Contingency planning is an important part of this element, involving pre-emptively identifying potential disruptions and creating plans to address them (Tukamuhabwa et al., 2015a). This includes outlining protocols for immediate response, resource allocation, and coordination among actors (Hosseini et al., 2019), all of which are ensured by proper collaboration and situation awareness. Re-routing strategies entail

diverting hydrogen flows through secondary routes to circumvent disrupted pathways, ensuring continuous supply. Additionally, the development of alternative technologies, like flexible storage methods or on-site generation, provides fallback options to maintain supply during disruptions This demands the skill to detect potential disruptions by effectively interpreting ongoing occurrences (Priya Datta et al., 2007). Employing early warning strategies (Saenz and Revilla, 2014) alongside continuity planning (Pettit et al., 2010) becomes essential for this purpose. These approaches not only aid in identifying vulnerabilities in the supply chain but also play a pivotal role in mitigating, containing, or managing risks (Manuj and Mentzer, 2008). Nonetheless, situation awareness requires seamless collaboration (under ability to respond) and transparency (under the same ability), the exchange of critical information by proper knowledge management (under the ability to improve, and a foundation of pre-existing knowledge, provided by the connection between the ability to improve subsequently anticipate among partners within the supply chain. In essence, developing a heightened sense of situation awareness necessitates the proactive involvement of all stakeholders in understanding, predicting, and reacting to the challenges that might arise. A quantitative KPI that can be used for situation awareness, that this thesis established, is the amount of workforce and tools dedicated to monitoring possible threats, the domains from which disruptions arise and the connected forward-looking aspect. A second quantitative KPI established by this thesis is the amount of workforce and tools dedicated to weakness identification and contingency planning.

A resilient supply chain possesses the capacity to function seamlessly even in the face of disruptive factors. It not only endures but also flexibly adjusts to shocks, maintaining its reliability amidst dynamic shifts (Singh et al., 2019). Furthermore, according to (Scholten et al., 2014), the cultivation of robustness provides companies with the means to uphold operational efficiency, countering significant disruptions effectively. Building redundancy is among the most important measures, and a quantifiable KPI, that built robustness, as is corroborated by (Koole Terminal, 2022) the maintenance of extra capacity in production, transportation, stock, storing, and reconversion installations in case of sudden disruptions of supply chain elements. This is also corroborated by (Hohenstein et al., 2015), which emphasize that practices promoting robustness (such as stockpiling inventory and diversifying sourcing) play a proactive role in enhancing SCRES, which can be regarded as quantitative KPI's. These measures act as a buffer against abrupt shocks, diminishing the potential negative impact of disruptions on overall performance.

Additionally, the element of "visibility" was changed to the element of "transparency". There was chosen to put more emphasis on information sharing and the ability to see the supply chain holistically, as also provided by CAS theory, which "transparency" embodied better. Transparency embodies the importance of an integrated supply chain configuration that provides end-to-end interaction (Smith, 2004). Within the hydrogen supply chain framework, the ease of exchanging information related to organizational resources or potential occurrences within distinct supply chain elements assumes a pivotal role in furnishing actors with tools to navigate and surmount disruptions (Ambulkar et al., 2015a). As a result, this practice constitutes the primary stride towards attaining the coveted state of transparency (Ali et al., 2017a). A qualitative KPI can be found in observations of (Cho et al., 2012), emphasizing the vital role that the contentment of customers KPI plays in aligning product or service design with customer demands within the hydrogen sector. Other qualitative KPI's include the level of trust among actors and the amount of information shared.

6.3.2.2 The Ability to Respond In this ability, the elements of agility and increasing flexibility were merged as the definitions were overlapping and were not MECE. The joint definition is now described by the established definition of agility alone. Additionally, the element of "building redundancy" was moved to the ability to anticipate. The redundancy is built during the ability to anticipate and is also not on the same level as the other elements but more so a metric for robustness, as corroborated by the Business Development Director of Koole Terminals. The effects of redundancy, however, are beneficial for the ability to respond.

Agility pertains to the hydrogen supply chain's swiftness in addressing changes, a trait that minimizes the repercussions of disruptions and expedites the reaction timeframe (Ali et al., 2017a). In relation to this aspect, Bhagwat and Sharma (2007) highlight that the extent of capacity utilization holds a direct influence on the promptness of response. These authors further assert that this approach fosters adaptability and timeliness. Similarly, closely overseeing redundancy throughout all elements of the configuration (extra carriers, storage plants, hydrogenation plants etc.) becomes an essential practice amid disruptions to ensure that existing the function of the hydrogen supply chain remains operational. This is again connected to the building of redundancy, as The Koole Terminal Business Development Director stressed so often (Key Quote 4). Redundancy is therefore also a quantitative KPI suitable for assessing agility. Another quantitative KPI suitable for agility assessment is the rapidity of failure identification, measured in time (Umunnakwe et al., 2021).

Collaboration entails the capacity to jointly address supply chain disruptions alongside actors, achieved through collaborative planning efforts (Christopher and Peck, 2004). It is about increasing trust among actors facilitated by the accelerated exchange of information (Singh et al., 2019). It brings forth two primary advantages: incentive alignment and decision synchronization throughout the configuration (Papadopoulos et al., 2017). These factors stand as pivotal outcomes and play a crucial role in effectively addressing disruptions at the organizational level. The level of incentive alignment and decision synchronization are both qualitative KPI's that can be assessed. Another measurable quantitative KPI that can be used for the metric of collaboration is system level agreement (SLA), which is the level of agreements between actors in the supply chain about measurable metrics like uptime, responsiveness, and responsibilities (Atlassian, 2023).

6.3.2.3 The Ability to Recover In contrast to the notion of "contingency planning" as being part of the ability to recover (Ali et al., 2017b); (Hosseini et al., 2019); (Singh et al., 2019); (Tukamuhabwa et al., 2015b) this thesis contends that such categorization is flawed and on a lower, more quantifiable level. Apart from that, the ability to recover is the phase in which contingency plans are used, but not made. This happens in the ability to anticipate. Instead, two novel factors, restoration

efficiency and restart efficiency, emerged as superior descriptors of the capacity to restore operational functionality. As a result, the concept of contingency planning is part of situation awareness within the realm of enhancing overall restorative capabilities.
Restoration efficiency refers to the capability to systematically and swiftly repair both infrastructure and operational functions following disruptions. This involves the strategic utilization of contingency planning, re-routing strategies, the development of alternative technologies (Singh et al., 2019) and supply chain reconfiguration (Ambulkar et al., 2015a) all of which act as fundamental components in ensuring a seamless restoration process. A quantitative KPI connected to restoration efficiency is rapidity of failure resolution and re-routing strategies, measured in time (Umunnakwe et al., 2021). Restart efficiency then relates to the ability to resume operations to the desired performance with high ramp-up speed, affecting the steepness levels of the performance curve in the recovery phase This ramp-up speed, also known as the rapidity of system restart or mean time, is also a quantitative KPI to assess restart efficiency (Umunnakwe et al., 2021). Collaboration and agility, in combination with a strong market position and efficient information sharing, play crucial role (Singh et al., 2019) supporting the ability to recover.

6.3.2.4 The Ability to Improve The ability to improve relates to the importance of learning from operations to enhance a system's resilience and adaptability. Understanding how learning processes are associated with adaptations in work performance in the face of disruptions is crucial (Wiig et al., 2020). Knowledge development is required post-disruption phases, recognizing that all knowledge must be recorded to be further used to mitigate and excel any type of disruptions. Knowledge implementation then resonates through all abilities, by feeding back into the ability to anticipate after the disruption occurred and the performance is at the desired level again. Consequently, collaboration through information sharing and transparency are also elements that must be developed as it is the basis for enhancing knowledge implementation. Understanding the supply chain configuration, operations, needs and possible disruptions, as well as human and capital resources are key factors to creating a resilient supply chain (Ali et al., 2017a); (Scholten et al., 2014). In addition, resilience must start being built in the anticipation phase through practices of knowledge acquired from past experiences (Christopher and Peck, 2004). Re-designing the hydrogen supply chain stands as a core factor enhancing its resilience by re-designing robustness, security, and agility, with a specific emphasis on refining location strategies (Christopher and Peck, 2004), which is also an important design choice as presented in 6.1. When executed dynamically, this element holds the potential to proactively alleviate risks and the aftermath of supply chain disruptions, and in some cases, preemptively avert disruptions (Pereira et al., 2014), which must not be confused with focus on mitigation strategies. For the knowledge development, a quantitative KPI would be the amount of workforce and tools dedicated to the analysis of the established metrics. A really important quantitative KPI for knowledge implementation is the system performance comparison with the baseline, which is the desired performance (Umunnakwe et al., 2021).

6.3.3 Framework for Design and Maintenance of Resilience in the Post-Design Phase

The previous sections dissected the concept of resilience for the post-design phase of the IGHSC, establishing the abilities that are required to design and maintain resilience. Afterwards, elements were formed that built these abilities, and the connected KPI's that can assess them. The framework for the abilities required to design and maintain resilience in the post design phase is provided below. The detailed framework including the KPI's is provided in Appendix G.

1) **The capability to anticipate** (proactive)

    a. **Situation awareness:** The ability to understand SC vulnerabilities and plan for disruption events

    b. **Robustness:** The ability of the supply chain to resist and absorb change and anticipate change proactively and maintain continuity in the process

    c. **Transparency:** The ability to see needs of the supply chain holistically from one end to another and find the place of a disruptive event, by creating mutual trust and willingness to share information with other actors within the supply chain.

2) **The capability to respond** (concurrent)

    a. **Collaboration:** The ability to communicate effectively and execute supply chain operations jointly with other actors

    b. **Agility:** The ability to react and adjust rapidly and flexibly to an unpredictable change in supply operations

3) **The capability to recover** (reactive)

    a. **Restoration:** the ability to repair infrastructure and operations orderly and swiftlyefficiency:

    b. **Restart efficiency:** the ability to resume operations to the desired performance with high ramp-up speed

4) **The capability to improve** (reactive)

    a. **Knowledge development:** The ability to gather useful historic data and measure the identified metrics

    b. **Knowledge implementation:** The ability to share relevant information and solutions with actors throughout SC elements, learn from each other, and re- design the supply chain configuration and network adequately and swiftly

In the unfolding narrative of this thesis, a comprehensive exploration has been undertaken, elucidating the process of designing and maintaining resilience within an IGHSC. This process has led to a structure that is distinguished by two distinct phases and three pivotal scopes. The initial phase, characterized as the design phase, emerges as a critical starting point where the blueprint for the IGHSC resilience takes shape. The design choices laid out in this phase have the potential to substantially influence the entire configuration's resilience. Following this phase, the post-design stage is analyzed through the lenses of three distinct scopes: conceptual, qualitative, and measurable. These scopes converge to provide a structured way to enriches the guideline with a framework that can be found in Appendix G. An overview of how all KPI's can be measured, to what abilities and elements they belong and if they are qualitative or quantitative, is provided in Table G.1

6.4 Synthesis of Resilience into Guideline

As these two phases are now concluded, a comprehensive synthesis emerges—an overview that encapsulates the essence of the guideline formed by this thesis. This synthesis will also unravel the way the resilience guideline is embedded in the overarching landscape. Throughout the thesis, the notion of resilience for a future IGHSC is though out. By first analyzing what two of such configurations would entail, embedded in completely different parts of the world, using different carriers. Next, the disruptions that such supply chains would be subject to were analyzed, establishing an extensive list, categorized by disruption domain. These two Chapters brought an important level of understanding of the IGHSC system, its function, boundaries, internal and external disruptive inputs and thus the basis for designing resilience in such a system. In this section, a synthesis will be established, providing the reader with an overview of designing and maintaining resilience in an IGHSC. This guideline delineates the way the design phase- and the post design phase are interdependent, the way the hydrogen supply chain is tightly interconnected with its environment and landscape, and the way resilience is designed and maintained, in an ever-ongoing process.

6.4.1 Capturing Two Phases into an Overview

In the context of establishing resilience for an international hydrogen supply chain, a profound understanding emerged, delineating the process into two pivotal phases. Initially, during the design phase, when the supply chain is yet to be operational, the foundation of resilience takes form. Subsequently, as the supply chain becomes operational and faces disruptions, the post-design phase emerges, further shaping the resilience capabilities. In the overview, this distinction is also made, denoted by the titles above the two connected parts of the overview. Delving into the characteristics of these two phases underscores the multifaceted nature of resilience design. An important aspect lies in the design phase, wherein the key is to design the supply chain configuration with as much resilient design choices as possible. Since historical data is absent at this stage due to the pre-operational status of the supply chain, the approach involves adopting choices that have proven to be resilient in similar systems, such as the international LNG system. This means aiming to create a resilient configuration by following a sequence of steps with its attached design choices of location selection, partner selection, partner securitization, diversification, and standardization. This strategic approach leads to a robust supply chain configuration that resonates throughout its operational lifespan. In the overview, resilience is present on the y-axis, as a conceptual scope. The arrows that slowly rise from the bottom-left corner towards a higher level of resilience represent the way the design choices increase resilience during the design phase, in the process described in Chapter 6.1, with the sequence of design choice domains being the same as described in Appendix E. The dotted arrow parallel to the x-axis in the design phase represents an important nuance that demands attention; the degree of freedom afforded to decision makers while configuring the design choices for the supply chain. Chapter 6.1 provides a spectrum of design choices, yet a subset of these choices could be predetermined and rigid. For instance, consider a stakeholder from Chile, asked to harness the region's renewable energy abundance for global hydrogen distribution. In scenarios where the off-taker's geographical location is already predetermined by the contracting company, opting for stability-driven location choices as stated in Chapter 6.1 loses its status as an option. In another example, the decision maker might want to diversify the renewable energy supplier for the electrolysis plant and finds the that would be contending with pre-existing long-term contracts with a single power plant.

Moving on to the post-design phase, resilience takes on a different facet. Here, resilience is perceived based on the performance curve's shape, which tracks performance over time. Therefore, a new y-axis emerges, measuring performance. This is the distinction between the design phase and the post-design phase. A critical characteristic of this curve is its ability to absorb disruptions, effectively minimizing the impact on performance during disruptions throughout the operational lifetime of the supply chain. This is showcased by the arrow that must be "minimized over time" parallel to the post-design phase y-axis. Additionally, the goal is to minimize the duration of disrupted performance instances, denoted by the arrow that must be "minimized over time" parallel to the post-design phase x-axis. Also, as the definition of resilience tells us, the ability to improve aims to ideally improve performance over time after disruption by learning processes, denoted by the arrow that must be "maximized over time" parallel to the post-design phase y-axis. In essence, the performance curve's shape acts as the indicator of the supply chain's resilience, capturing its capacity to endure and recover from disruptions over time. The four abilities to maintain resilience are also denoted, together with the elements that shape them as explained in Chapter 6.2. The overview also shows the way in which the learning process takes form, in which knowledge development and knowledge implementation ultimately aim for learning and improvement in the ability to anticipate, respond and recover.

Re-designing the supply chain is one of the elements that makes supply chains more robust, secure and agile by focusing on for instance location strategies (Christopher and Peck, 2004). This would mean going back to the design phase. If re-designing is performed in real time, it is possible to mitigate risks and consequences of supply chain disruptions or even to avoid looming disruptive events (Pereira et al., 2014). As already explained, some of the design choices might not be choices for decision-makers. However, the overview shows that the more freedom of choice is granted, the higher the resilience of the configuration. Options like location setting using re-shoring or friend-shoring, or diversification of suppliers are all possible re-design options that can make the configuration more resilient. Historic data during the post-design phase should show that optionally some design choices of the configuration need to be re-assessed. This is depicted by the position of the re-design text after the first the ability to improve. After re-design, the arrows climbing together with the design choices depict the way resilience can be improved again by ending up higher up on the y-axis of the post-design phase after re-design.

6.4.2 Interconnection of the Landscape and the IGHSC Resilience Guideline

The interplay between these design choices and the current global landscape and state of the market introduces another layer of nuance. This state of the external eco-geo-political state often runs in sequences, occurring in cycles spanning approximately in the order of decades, as found to the Williamson Four Layer Model framework (Williamson, 2000). These macro-level institutions can be defined as "the humanly devised constraints that structure political, economic, and social interactions"((North, 1991), p. 97). This is denoted by the overarching cylinder with all the political, economic, regulatory, technical, and social characteristics that form the state of the current landscape in which the hydrogen supply chain is deigned and operated. This interaction between design choices and the prevailing landscape and market conditions, denoted by the double-sided arrows from the top-down, holds significant importance. This is particularly true in the context of the emerging hydrogen market, because of the unique characteristic of sustainability transitions in which most 'sustainable' solutions do not offer obvious user benefits (because sustainability is a collective good), and often score lower on price/performance dimensions than established technologies (Geels, 2011). It is therefore unlikely that environmental innovations will be able to replace existing systems without changes in economic frame conditions (Geels, 2011). The landscape of taxes, subsidies, regulatory frameworks all influence the design choices related to standardization, regulatory harmonization, diversification of carrier etc. These changes will require changes in policies, which entails politics and power struggles, because vested interests will try to resist such changes.

The socio-technical regime, embedded under the overarching landscape in the overview, constitutes the foundation responsible for upholding the stability of an existing socio-technical system (Geels, 2004). It denotes the collection of guidelines that guide and synchronize the actions of the actors responsible for the different components of socio-technical systems, in this case the IGHSC (Geels, 2004). Examples of regime rules relevant to the emerging hydrogen supply chain are capabilities and competences, utility practices, favorable institutional arrangements and regulations and the form of legally binding contracts (Geels, 2004). Because existing regimes are characterized by lock-in, innovation occurs incrementally, with small adjustments accumulating into stable trajectories (Geels, 2004). These trajectories occur not only in technology, but also in cultural, political, scientific, market and industrial dimensions. While science, technology, politics, markets, user preferences and cultural meanings have their own dynamics, coordinated by different sub-regimes, they also interpenetrate and co-evolve with each other (Geels, 2004). The socio-technical

regime concept aims to capture the meta-coordination between these different sub-regimes (Geels, 2004). Following (Murmann, 2003), we can say that "two evolving populations coevolve if and only if they both have a significant causal impact on each other's ability to persist" ((Murmann, 2003), p. 22). These causal influences can arise through two avenues. The first one is by altering selection criteria, e.g. a new incentive in the institutional structures increases the likelihood of a particular technology being adopted. The second one is by changing the replicative capacity of individual entities, e.g. a firm adopts a new business strategy causing it to increase its investment in technological innovation relative to promotion of existing technologies (Geels, 2004). This is the case for the interplay between design choices and the regime, and why double-sided arrows are chosen for this connection. An example was found during the interview with IHI, that is heavily focused on the design choice standardization and certification of the green ammonia market (IHI, Personal Communication, Date). This is a form of technical investment that influences standards being adopted and increases the likelihood the green ammonia technology being adopted. But also, during the post-design phase this interplay can be found, from the bottom up when user preferences arise, technical issues are solved forming new competencies and abilities, or knowledge implementation leads to rigorous re-design of the supply chain configuration causing a rapid increase in utility of a specific carrier. Of course, top-down institutional structures affect the operational phase of the IGHSC, optionally demanding re-design or causing an existing operational configuration to be even more favorable.
There are three main reasons why macro-level institutions matter for resilience in the hydrogen supply chain. First, institutions co-determine locational strengths, in addition to choosing location with geographical stability (Hennart and Verbeke, 2022). Locational strengths are sometimes called country-specific advantages, but they can also be relevant at the subnational and supranational levels (Hennart and Verbeke, 2022). Thus, the location selection during the design phase is affected by these institutions. Second, macro-level institutions can affect the forms taken by governance at the micro-level, for instance the relative importance attached to formal versus relational governance features (Hennart and Verbeke, 2022). This has profound affect not only during the design phase when selecting partners and choosing contract forms, but also during the post-design phase when organizing collaboration, transparency and knowledge management and implementation. Third, significant differences in macro-level institutions between countries, e.g., in institutional quality, can greatly affect how internationally operating firms conduct their activities and organize for economic success (Hennart and Verbeke, 2022), affecting the agility and information flow throughout all elements of the international hydrogen supply chain. For instance, in cases of high institutional distance between countries or when facing low institutional quality and related information and reliability challenges in a particular host country, a firm may opt out of investing or even stop from conducting any business there (Hennart, 1989). This is an example of when the operational supply chain needs to be re-designed, for instance by incorporating friend-shoring.

During partner securitization, another way the institutional landscape affects the design phase becomes apparent, as three primary categories of governance choices emerge: those that influence the boundaries of firms (such as choosing between 'make' or 'transact in the market'), those concerning the management of the interaction between firms and their external surroundings (such as deciding between short-term and long-term contracts), and those related to the internal structure of organizations (such as opting for functional versus multidivisional structures) (Hennart and Verbeke, 2022). When looking through the Williamsonian perspective, the sequence of whether a market or a firm came first is of less importance; instead, the focus shifts to which governance structure proves more efficient given the specific circumstances (Hennart and Verbeke, 2022). What holds significance is determining the most effective way to arrange interdependencies among supply chain actors and how changes in circumstances, be they external or internal disruptions, or landscape changes, lead to modifications in the optimal governance approach, affecting the elements of collaboration, transparency, and knowledge implementation.

6.4.3 Importance of Forward-Looking Aspect

Because of the embeddedness within the landscape as described above and in the overview in Appendix F, a forward-looking aspect is important, for which this thesis proposes analyzing long-term socio-technical and techno-economic change towards a green hydrogen future, combining insights from the socio-technical transitions and coevolutionary approaches as provided by (Foxon, 2011). The forward looking approach that a hydrogen supply chain designer should incorporate can use the coevolutionary framework that (Foxon, 2011) proposes as a lens, illustrated in 6. Building on the approaches reviewed in the previous section, ecosystems, technologies, institutions, business strategies and user practices as key coevolving systems relevant for analysis of a transition to a sustainable low carbon economy, for which an IGHSC can add significantly. Hence, the continuous forward-looking analysis should examine the evolution of each of these systems and their causal interactions.

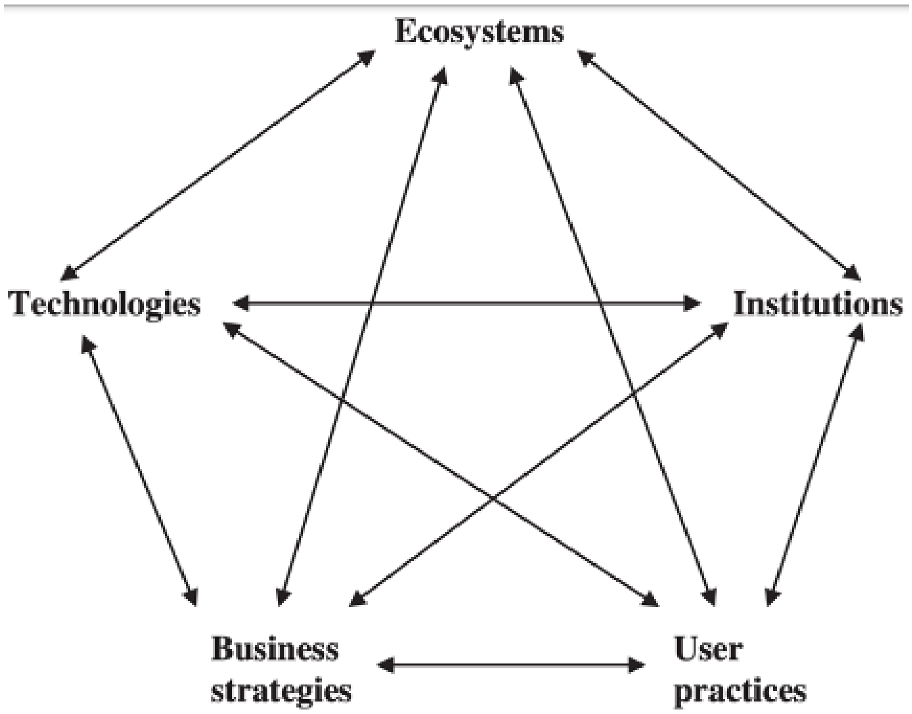

Figure 6: Co-evolutionary framework, (Foxon, 2011).

This chapter has delineated the extent to which resilience can be defined. Upon establishing potential KPIs for each qualitative metric, historical data becomes essential. Presently, such data is unavailable due to the absence of a realized IGHSC in a real-world setting. Consequently, the process of defining the design and maintain of resilience for an IGHSC has reached its conclusion. However, this thesis considered the importance for a decision maker of gaining a tool for shaping this assessment methodology, as provided in section 6.3.1.

First, resilience was framed as a construct developed across two successive phases: the design phase and the post-design phase. In the design phase, the design choices made construct the resilient configuration of the IGHSC, which then resonates throughout its operational lifespan. Subsequently, the post-design phase is characterized by the capabilities and elements that perpetuate resilience and the potential to re-design and recalibrate as required. More specifically, in the post-design phase, four key capabilities were established, based on the formulated resilience definition within this thesis. These capabilities were further deconstructed into the constituent elements necessary to shape and sustain these resilient capabilities. These elements constitute the qualitative metrics for evaluating resilience within the IGHSC. Consequently, only one level further is feasible: quantifiable KPIs that can facilitate the assessment of resilience. This completes the three scopes of resilience as identified by (Cheng et al., 2021) and slightly modified by this thesis: conceptual, qualitative, measurable. By encapsulating these three scopes of resilience, the guideline for establishing and maintaining resilience within an IGHSC concluded. The synthesis given in section 6.4 provides stakeholders, engaged in the construction of an IGHSC with resilience as a core design criterion, with an analysis of the considerations for shaping resilience spanning from the design phase to the post-design phase. The design phase and the post-design phase of building and maintaining resilience for an IGHSC are captured together in an overview, forming an essential deliverable for the guideline that is formed throughout this thesis. Moreover, considerations involving the connection to the prevailing landscape, the implications of re-designing, the degree of freedom of design choices and the overall resilient lens are captured in this overview, as presented in Appendix F. The overview illustrated in Appendix G provides an overview of the guideline for constructing and maintaining resilience within an IGHSC.

7 Conclusion

This chapter will present a comprehensive overview of the discoveries and explicitly addressing both the research sub questions and the main research question. The primary findings related to each SRQ can be located at the end of their respective chapters. Within this section, the findings corresponding to the SRQs will be discussed across four segments aligned with the structure of the thesis, resulting in an answer to the MRQ.

The core objective of this research was to develop a comprehensive guideline for stakeholders involved in designing and maintaining resilience within an IGHSC. To attain a profound comprehension of the operational dynamics, IGHSC configurations, and considerations for managing disruptions within such a system, the research employed IGHSC's involving Japan and The Netherlands as exploratory examples.

Consequently, this study identified and introduced two novel optional IGHSC configurations, cataloged relevant disruptions along with their respective domains. Next resilience was defined, categorized into two distinct phases and three scopes, providing a structure for analysis. This thesis was executed through a blend of literature research and analysis, and interviews, all orchestrated within a qualitative multidisciplinary exploratory approach.

A theoretical framework was established to unveil interconnections amidst diverse theories and fields of study. This framework not only aided in identifying previously unnoticed associations but also served to define the disruptions and the mechanisms of resilience intrinsic to an IGHSC. An overview was established forming the basis of the guideline, capturing both phases and all attached considerations in Appendix F. Attached, this thesis established a framework for building and maintaining resilience in the operational supply chain, found in Appendix G.

7.1 System and Concept Exploration

In the Theoretical Framework, SRQ1 aimed to explicate the problem by defining the concepts core to the research problem and formulating definitions for resilience and disruptions, suitable for the context of an IGHSC subject to disruptions. For this, the CAS theory was used as a lens, as it was found that it captured the dynamics of an IGHSC well. In Chapter 4, SRQ2 aimed to obtain a thorough grasp of the configuration and functioning of an IGHSC. For this, two examples were used with Japan and The Netherlands as large future importers, embedded within completely different contexts in the world. This was done so that the IGHSC became less of a theoretical concept, was given descriptive context and to investigate the considerations required in real world examples. This marked an important step for the formation of the guideline, as a thorough understanding of an IGHSC was obtained. Two configurations were established, that can both be found in Appendix A. The first configuration entails a green ammonia supply chain, with its energy and ammonia production in Australia, and off-take and utility in Japan. The second configuration was a MCH supply chain, with its energy and MCH production in Scotland, and its off-take and utility in The Netherlands. These two examples formed a thorough understanding of the system under investigation, both for the reader as the writer, and formed an important conceptual basis and way of thinking for the Chapters and RSQ's ahead.

7.2 Disruption Analysis

In Chapter 5, RSQ 3 aimed to identify all disruptions that are relevant for the performance of an IGHSC. After critically analyzing all found research about disruptions and the corresponding categorization that was utilized in these studies, this thesis established a structure to list all disruptions that can occur in an IGHSC, categorized based on domain from which the disruption can occur. The domain categorization and the underlying identified disruptions were based on the system's characteristics, function, and environment as analyzed in Chapter 2 and 4. This categorization is not limited to the example supply chains and can be used for a generic IGHSC. Subsequently, the two examples that were established in Chapter 4 were used again, to show the reader how these disruptions should be considered for an IGHSC. This was done with the goal of showing the approach for disruption consideration in different parts of the world, and the way different contexts demanded different disruption considerations within the identified domains. A surface level analysis was performed, because this goal was not a core objective of this thesis.

7.3 Establishing guideline for designing and maintaining resilience in an IGHSC

In Chapter 6, resilience was framed as a construct developed across two successive phases and in three different scopes. The two phases are the design phase and the post-design phase. In the design phase, the design choices made construct the resilient configuration of the IGHSC, which then resonates throughout its operational lifespan. It was found that the design phase implicated that system resilience is a function not only of itself, but also of other systems, by learning from analogous systems. The international LNG market was an example of an analogous systems that posed lessons for establishing resilience for an IGHSC. Subsequently, the post-design phase is characterized by the capabilities and elements that maintain resilience, but also the possibility to re-design and recalibrate as required. Resilience in the post-design phase was then first described conceptually, posing the first level of resilience. This included dissecting the established definition of resilience in the Theoretical Framework, and forming the four abilities that are required to build and maintain resilience in its operational life; the ability to anticipate, respond, recover and improve. Next, the second level of resilience was reached by establishing the elements that built the abilities. These elements could be seen as the qualitative metrics for stakeholders to approach resilient design. In the third level, measurable quantitative and qualitative KPI were provided, that could be used by stakeholders to assess the metrics for resilience. Subsequently, RSQ4 was answered, concluding the guideline for building and maintaining resilience for an IGHSC. The resilient approach, divided in the design phase with its identified design choices, the post design phase with its identified abilities and elements for resilience and the way the concept of resilience is embedded within- and dependent on the socio-techno-eco-political landscape was then captured in an overview, which can be found in Appendix F. Also, the guideline for building and maintaining resilience with its connected three scopes was captured in a framework which can be found in Appendix G.

7.4 Answering Main Research Question

The Main Research Question finds its resolution through the synthesis of theoretical constructs, answers to the five Research Sub Questions, and insights extracted from the synthesis presented in the established framework (Appendix G) and overview (Appendix F). The precise formulation of the MRQ is as follows: What guideline can be established to design and maintain resilience in an international green hydrogen supply chain, using the role of The Netherlands and Japan as large future importers as exploratory examples?
This MRQ is successfully answered in this thesis, which will now be outlined by a descriptive example. Let us picture a stakeholder from Chile, asked by a company to be in charge of designing a new IGHSC, with the goal of exporting green hydrogen from Chile internationally, using Chile's abundant renewable capacity. Resilience is one of the main criteria for the design and operations of this to be formed supply chain. The stakeholder can subsequently use this thesis as a guideline for the design and ultimate maintenance for the to be formed IGHSC by:

1. Learning how an IGHSC configuration is formed, what considerations are important when choosing this configuration and what the options of each element of the configuration are, while seeing this applied to possible real-world examples involving The Netherlands and Japan.

2. Learning what the nature of the disruptions is that the IGHSC is subject to, from which domains these disruptions can occur and what these disruptions are, by analyzing the structure this thesis formed that provides the categorization and overview of all relevant disruptions. Subsequently, the stakeholder can learn how these disruptions need to be considered by using the examples of two supply chains involving The Netherlands and Japan.

3. Learning what the concept of resilience entails, where the concept stems from, how it is conceptually formed for an IGHSC in the design phase and post design phase and how the concept of resilience is embedded within the socio-techno-eco-political landscape the stakeholder operates in, using the overview in Appendix F.

4. Use the established overview for the abilities that form and maintain resilience in the post-design phase (Appendix G), from which elements (qualitative metrics) these abilities are shaped, choosing which elements the stakeholder deems important and how they should be designed for. Subsequently, the stakeholder can use the overview of the KPI's as a starting point to assess its designed abilities and elements the stakeholder formed to build and maintain resilience for the IGHSC.

5. Learning how the stakeholder's design choices constitute to a resilient configuration and how these resonate throughout the operational life of the IGHSC.

With these takeaways this thesis will provide a solid foundation and guideline for the stakeholder that deems resilience to be a key design criterium for a new IGHSC, thus answering the Main Research Question.

7.5 Placing the resilient lens in the EU security of supply crisis

Energy supply security has risen to the forefront of the European Union's (EU) agenda due to recent geopolitical turmoil and ensuing energy crises (EPRS, 2023). With the EU heavily reliant on energy imports, reaching 57.5 percent in 2020, and all EU Member States functioning as net energy importers (European Commission, 2023a), the region's energy stability is a paramount concern. In 2021, Russia held a pivotal position as the primary energy supplier to the EU, contributing 45 percent of its coal, 36 percent of its gas, and 25 percent of its oil imports (European Commission, 2023b). However, the landscape underwent a profound transformation throughout 2022. Multiple rounds of sanctions were imposed on Russian energy products, prompting the EU to initiate policies aimed at reducing dependence on Russian energy sources. Additionally, Russia imposed limitations on gas transmission.

Significantly, in May 2022, the European Commission introduced the REPowerEU plan to decrease energy imports from Russia and accelerate the transition to greener energy sources (EPRS, 2023). This plan featured a legislative proposal for resilience, particularly within the REPowerEU sections pertaining to Recovery and Resilience Plans (Regulation (EU) 2023/435, adopted in February 2023). Consequently, during 2022 and 2023, the EU implemented various measures to reduce reliance on Russian energy. These measures included diversifying energy supplies, filling gas storage facilities, promoting collective gas procurement, reducing energy consumption, encouraging energy conservation, enhancing energy efficiency, and facilitating the adoption of renewable energy sources (EPRS, 2023). Many of these actions not only address immediate concerns but also enhance long-term energy security by reducing Europe's dependence on fossil fuel imports from non-EU countries (EPRS, 2023). Notably, the EU successfully managed to maintain a stable energy supply without disruptions or gas shortages during the winter months.

However, a recent report from the IEA has raised alarms about potential gas shortages in the winter of 2023, should Russian supplies further decrease, demand for LNG surge in China, and Europe experience prolonged cold weather conditions. Despite the reductions in Russian energy imports, the EU continues to face a persistent long-term energy security challenge due to its high overall energy dependence. Shifting away from Russian imports towards other suppliers introduces new risks, including geopolitical considerations, global economic competition, and potential dependencies on undemocratic regimes (European Commission, 2023).

Consequently, the EU is confronted with the task of intensifying its efforts, transitioning from short-term crisis management to addressing the broader challenge of ensuring enduring energy security and bolstering its strategic autonomy in the energy sector. In this endeavor, adopting the resilient approach proposed in this thesis could prove beneficial for policymakers.

While diversifying gas imports away from Russia reduces dependency on one big supplier, reliance on several other third countries implies new supply risks. If the European Union continues on this trajectory, it will become heavily dependent on LNG in the long term. By 2030, the continent will be importing more than 150 billion cubic meters of the fuel each year, an increase of about 70 billion cubic meters from 2019, according to BP (Bloomberg, 2023).

In light of the potential gas supply-demand gap in 2023, The IEA has provided analysis of this gap and has suggested practical actions that can be taken to close it while avoiding excessive strains for European consumers and international markets (IEA, 2023). Some of the measures that could be implemented include increasing energy efficiency, promoting renewable energy, and investing in heat pumps (IEA, 2023). These are all examples of the EU trying to counteract the looming problems for their security of supply. But while EU legislation is in place to help prevent and respond to potential gas supply disruptions, the concept of resilience as provided in this thesis could be a relevant lens for policymakers in the EU to approach the long-term solution for their security of supply issues.

So with this crisis in mind, the resilient can once again offer a relevant policy framework, showcasing its suitability outside the paradigm of an IGHSC. Shaping resilience for supply chains and energy security, revolves around preparing for and effectively responding to disruptions, all while developing the capacity to absorb shocks. Incorporating this resilient perspective into policy-making can provide EU policymakers with invaluable insights for shaping their strategies, particularly during periods of the just described geopolitical volatility and security of supply issues in current times. At its core, resilience encourages policymakers to proactively identify potential disruptions and vulnerabilities within the energy supply chain. As can be seen in the situation awareness element during the ability to anticipate, this is where resilient capabilities start. This encompasses scenarios related to current geopolitical tensions, trade interruptions as with the Russian gas and attached abrupt shifts in energy sources. The more situation awareness is achieved, the more policymakers can proactively design policies and strategies that anticipate and mitigate the impacts of such disruptions, like for instance start friend shoring, as described in Section 6.2.2. This might also entail diversifying energy sources, securing backup supply routes as a part of building redundancy, and ensuring strategic reserves. Also, resilience underscores the necessity of robust response mechanisms stemming from the robustness element. In the event of a disruption, having predefined response plans in place is vital for minimizing the impact on energy supply. Contingency planning is an important part of policy making, involving pre-emptively identifying potential disruptions and creating plans to address them (Tukamuhabwa et al., 2015). These mechanisms can include coordination with neighboring countries for emergency energy sharing, activating strategic reserves, and implementing crisis communication plans. Furthermore, resilience is not solely about responding to crises; it also emphasizes quick response and recovery in an adaptive way as described in Chapter 6. After a disruption, policies should facilitate a rapid return to normal energy supply conditions. This could involve taking steps to speed up economical repairs by streamlining regulatory procedures in the EU, offering financial incentives to impacted sectors, and promoting innovation in energy supply and distribution technology. Collaboration, transparency, and thus international cooperation are also fundamental components of resilience as discussed in Chapter 6. Policymakers should collaborate closely with neighboring countries and international partners to enhance collective energy security. This can involve developing agreements for mutual assistance during crises, sharing best practices, and harmonizing energy policies to create a more resilient regional energy ecosystem. Incorporating the resilient perspective into policymaking ensures that EU policies are adaptive, forward-thinking, and capable of addressing the intricate

8 Recommendations and Discussion

This Chapter is dedicated to contextualizing the research outcomes, culminating in the formulation of actionable recommendations. These recommendations constitute essential proposals that delineate the most logical path forward based on the interpretation of the research findings and conclusions. Subsequent to the recommendations, an in-depth discussion will be outlined. This discussion serves as a platform for elucidating the limitations intrinsic to this study, offering an expanded understanding of their implications. Furthermore, the chapter concludes with a reflective examination of future research that could be highly relevant for the context of designing resilience for an IGHSC.

8.1 Recommendations

Within this section, a comprehensive application of this research's findings and synthesis is undertaken to form recommendations. They are intended to provide action points for addressing identified resilience design in an IGHSC, thereby facilitating the enhancement of the existing toolkit. These thematic components converge to construct a pragmatic recommendation formed for stakeholders entrusted with the responsibility of incorporating resilience considerations into the design of an IGHSC. Last, these recommendations offer a basis upon which future investigations can be cultivated and developed, thereby advancing the scholarly discourse surrounding IGHSC resilience.

Assessing Design Scope Freedom:

The initial and pivotal step in the design process pertains to evaluating the extent of design choice freedom available. In the realm of IGHSCs, designers are unlikely to encounter carte blanche scenarios, where total design freedom is given and every design aspect aligns with their preferences. Thus, it becomes imperative to gauge the degree of freedom allocated for IGHSC design. Clearly delineating which design choices and elements remain open for shaping is essential to prevent fruitless efforts in redesigning rigid configuration elements. By doing so, designers can focus their energy on malleable design choices and abilities. For instance, if the contractor mandates a non-negotiable stance on re-designing as a resilient measure, designers can concentrate on tailoring their solutions within the scope of knowledge implementation under the ability to improve. Fixed factors such as for instance locations, partners, carriers, communication methods, and information sharing systems should be identified as possible predetermined elements that influence the potential for resilience building.

Another important point is the acceptance of cooperation of public and private parties. In the context of an IGHSC, it's essential to differentiate the roles of governments and businesses and the balance of public and private involvement. This naturaly effects the design choice freedom. A noteworthy example of this balance can be found in Japan, where the government has assumed a substantial role, particularly in LNG contracting, the establishment of joint ventures and the cooperative role the Japanese government takes (Euronews, 2022). The Japanese government also plays a pivotal role in shaping the direction of the hydrogen sector through policy development and regulation (Japanese Government, 2021). These incentives can encourage private sector investments and innovation. In cases like Japan, the governments invests in critical infrastructure, such as liquefied natural gas (LNG) terminals and hydrogen import facilities (of Economy, 2023b). Another example based on the LNG market is the fact that executives from energy companies and Japanese ministry representatives discussed plans to purchase LNG (Oda, 2022). By allowing the government to purchase LNG on the spot market in the event that businesses are unable to, Japan has been taking steps to increase its energy security (Oda, 2022). Companies, on the other hand, drive innovation to improve the efficiency and cost-effectiveness of hydrogen production and utilization. They continuously work on scaling up operations. Private companies are often at the forefront of developing cutting-edge hydrogen technologies, including electrolyzers, fuel cells, and hydrogen storage solutions. IHI and Chiyoda, both interviewed for this thesis, are two examples. There will be a mutual dependence between the responsibilities that corporations and governments play in global hydrogen supply networks. Businesses drive innovation, manufacturing, and distribution while governments provide the infrastructure and regulatory framework. A successful synergy between public and private sectors has the potential to speed up the expansion of the global hydrogen economy. This means that cooperation in the design choices to build resilience between public and private parties is crucial.

Actor Analysis:

A comprehensive analysis of all stakeholders involved in the IGHSC is paramount, encompassing their relationships, compatibility, and transparency. Given the importance of collaboration and transparency, acquiring extensive knowledge about these aspects early on can inform the design plans for aligning incentives, synchronizing decisions, and establishing system-level agreements. This analysis not only provides in formation for the design of collaboration elements but also guides the development of trust among stakeholders and the extent of information sharing, contributing to the transparency element. Consideration should be given to incorporating system-level agreements with all involved stakeholders already throughout the design phase to ensure adherence to collaboration and transparency in the post-design phase.

Incorporate Design Alternatives:

As the saying goes; "never bet on one horse". A recurring theme both during and after the design phase is the importance of not relying on a single alternative. Enhancing resilience in IGHSC involves creating alternatives across various dimensions, including carrier diversity, partner options, off-takers, and suppliers, as well as building redundancy and contingency plans. Here again, an early assessment of the level of freedom is crucial to determine how many alternative options can be realistically integrated. Ideally, designers should strive to account for all potential alternatives within the boundaries of their design freedom.

Continuous Evaluation:

Recognizing the CAS nature of an IGHSC, design and management teams should embrace continuous evaluation as an integral practice. This entails adapting to a perpetually co-evolving landscape of disruptions, responses, and IGHSC dynamics. Developing robust situation awareness plans is essential, enabling deep insight into the current and potential future state of the IGHSC, including forward-looking considerations. Organizing resources dedicated to monitoring threats and disruptions, identifying weaknesses, and planning contingencies is crucial. Similarly, allocating resources for analyzing the established metrics is essential, as knowledge implementation plays a pivotal role in resilience, particularly through systematic performance comparison with the desired performance baseline.

Acknowledge Resilient Lens Characteristics

To navigate the complexities of the IGHSC in an unpredictable emerging hydrogen economy, it is advisable to leverage the resilient lens provided in the guideline. Appendix F provides a valuable overview for maintaining a deep understanding of resilience within its environment and its connection to the evolving landscape. This perspective emphasizes the importance of designing adaptable abilities over simply mitigating disruptions. Given the characteristics of IGHSC in an ever-changing hydrogen economy, the resilient lens serves as a potent tool to enhance reliability and robustness throughout the design and post-design phases.

8.2 Discussion

8.2.1 level of speculation and depth of socio-techno-eco-political analysis

Given the current absence of an existing IGHSC, it is essential to acknowledge that a certain level of hypothesis and speculation is inherent in the analysis. This limitation restrains the direct application of the thesis's findings to real-world scenarios due to the unavailability of historical data that could validate the precise outcomes described within the research. This limitation is particularly relevant for Chapters 4 and 5, where the formulation of IGHSC configurations for specific regions like Japan and The Netherlands is explored. Crafting these configurations unavoidably involves an element of speculation, as historical precedent and empirical evidence are not readily accessible. Consequently, the degree of certainty in these chapters may be tempered by the speculative nature of the analysis. It's important to emphasize that the primary focus of this thesis was to establish comprehensive guideline with an attached framework for building and maintaining resilience within an IGHSC. While the analysis does encompass a surface-level exploration of the political drivers, utility, and future role of hydrogen within the contexts of Japan and The Netherlands, an exhaustive examination of these aspects is not within the scope of this work. Emerging technologies such as green hydrogen within energy transitions are embedded in a difficult environment in which factors ranging from political, technical, economic and social factors all play an important role in the development of the system at hand. This makes it hard to analyze disruptions and resilience thoroughly without a degree of speculation involved. Despite this, the thesis aims to strike a balance, aiming to provide readers with a sufficiently substantive understanding of the considerations that must be taken into account. By synthesizing theoretical findings, answers to research sub questions, and insights drawn from existing literature, the thesis nevertheless offers valuable insights that aid in the pathway toward a resilient IGHSC, even in the absence of empirical evidence from an established system.

8.2.2 Interviews

Above all, it's important to note that the interviews are guided by an interview framework to ensure that each interviewee addresses common overarching themes. The interviews themselves take on a semi-structured format, deliberately designed to permit a degree of flexibility. This approach enables interviewees to freely articulate their opinions and potentially delve deeper into their viewpoints on specific subjects. However, it's essential to recognize that these articulated viewpoints reflect the subjective stance of each individual interviewee. Naturally, each interviewee is inclined to hold stronger sentiments toward certain aspects or facets of resilience and the IGHSC. Nonetheless, they provided valuable context and a form of validation for the configurations formed in Chapter 4 and insightful discussions about the concept of resilience.

8.2.3 Real life implications of re-designing

The thesis states the potential necessity for stakeholders to undertake re-design efforts to maintain resilience in an the IGHSC. For instance, diversification of carriers or adopting strategies like friend-shoring might be recommended after the IGHSC's already entered the post-design phase. However, it's crucial to underscore that implementing such re-design strategies entails a multitude of unanticipated real-world implications. The practical reality is that re-designing an established IGHSC, as emphasized by a Shell interviewee, can entail significant costs, potentially running into billions of euros. Beyond the financial implications, the re-design process can lead to substantial downtime, disrupting ongoing operations and impacting the supply chain's reliability. These implications extend beyond financial considerations and can encompass severe logistical challenges that are far from viable options for stakeholders in the real world. Consequently, while the thesis presents valuable insights into potential re-design strategies to maintain resilience, it is imperative to recognize the intricate nature of incorporating this insight into actionable steps within the real-world operational context of an IGHSC. This shows the importance of finding practical re-design solutions that can actually be put into action without causing problems for the supply chain's continuity and ongoing operations.

8.2.4 Methodological limitation

The qualitative method used in this study allowed for the integration of theoretical concepts and putting them into a practical structure. Nevertheless, opting for this qualitative approach comes with its own methodological limitations.

To elaborate, the frameworks presented in Appendix F and G joined and linked the examined theoretical ideas and data from the scientific papers analyzed. However, it's important to note that this doesn't automatically prove that these theories can smoothly fit together in practice. Thus, these proposed frameworks need to undergo a theoretical validation before they can be labeled as suitable for real-world application. To solidify this, if the frameworks in Appendix F and G, along with the research outcomes, were to be employed in a real decision-making process for designing an IGHSC, and if they indeed led to the intended resilience outcomes, it would serve as further confirmation of the research's validity and its conclusions.

8.2.5 Relevance to the CoSEM program

This thesis represents a fulfillment requirement for the completion of the Master of Science (MSc) degree in Complex System Engineering and Management (CoSEM) at Delft University of Technology. The CoSEM program is dedicated to addressing challenges inherent to socio-technical environments. In this thesis, the investigation centers around the theme of establishing an IGHSC and its integration within two distinct global contexts: Japan and The Netherlands. The objective of this study is to develop a comprehensive guideline for assessing pertinent disruptions and formulating strategies to design and maintain resilience within the IGHSC. This thesis therefore involves a holistic consideration of interdisciplinary domains, including geo-political, technical, economic, and political dimensions. The thesis encompasses well-defined design components that outline the application of resilience principles to the configuration of an IGHSC. It elucidates how the concept of resilience should be applied to both design phase and subsequent post-design phases, encompassing three distinct dimensions of resilience assessment: conceptual, qualitative, and measurable. To establish the qualitative and measurable framework for resilience, as illustrated in Appendix G, this study synthesizes insights from process management strategies and system engineering approaches drawn from existing literature. The research aspires to engineer a robust system design by employing qualitative research methodologies, culminating in actionable recommendations aimed at enhancing the existing toolkit for designing resilient IGHSC's, imperative within the context of an emerging global hydrogen economy. By examining the interconnection between technological advancements, market dynamics, policy frameworks, strategic considerations, and societal interests, the knowledge generated herein holds substantial value for enriching the scholarly domain of the CoSEM MSc program.

8.2.6 Future research

The proposed frameworks, while promising, necessitate further theoretical validation before being categorized as a theoretically sound framework applicable in real-world contexts. While this thesis draws upon literature to interlink its findings, the emphasis on scrutinizing the actual compatibility among these theories has been less of a focus. It would be very relevant for future IGHSC design teams to have knowledge about the compatibility of all strategies, metrics and elements included in the guideline for designing and maintaining resilience. Second, to ascertain the suitability of the proposed KPIs in constituting a resilient IGHSC, historical data emerges as a pivotal testing ground. Such an empirical assessment could pave the way for future research endeavors aimed at constructing a comprehensive resilience assessment methodology, taking the exploration one step beyond the boundaries found by this current thesis. Third, a crucial augmentation for the guideline would involve delving into the discrete aspects of specific resilience abilities and their interconnected elements. Designing and maintaining resilience demand an increased level of depth and nuance. A dedicated research pursuit could focus on unraveling the intricacies of organizing for instance the shaping of situation awareness as an autonomous entity, contributing substantively to the robust design of the ability to anticipate disruptions. Last, a consequential avenue for future investigation would be the analysis of optimal strategies for re-design. As underscored in the interview with Shell, the process of re-design entails substantial financial and logistical complexities. Thus, developing a framework that encompasses criteria dictating when re-design becomes more advantageous than adhering to the existing configuration, despite the inherent financial and logistical challenges, would be a very valuable contribution to the toolkit of IGHSC management.

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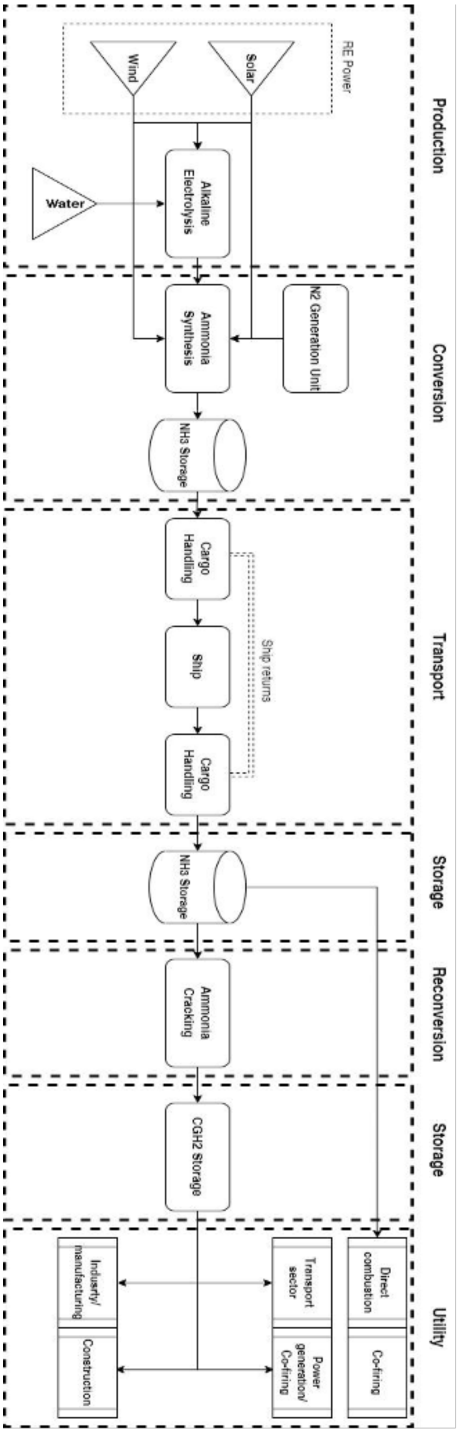
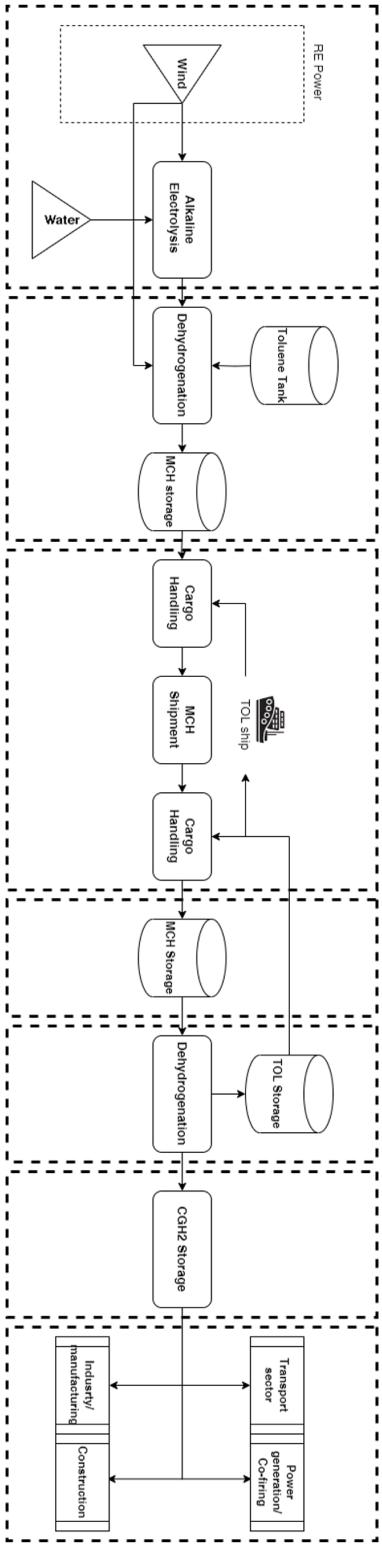
9 Appendix

Appendix A): overview of hydrogen supply chain configuration for Japan and NL



(a) Green ammonia supply chain configuration.



(b) MCH supply chain configuration

Appendix B): Research flow diagram

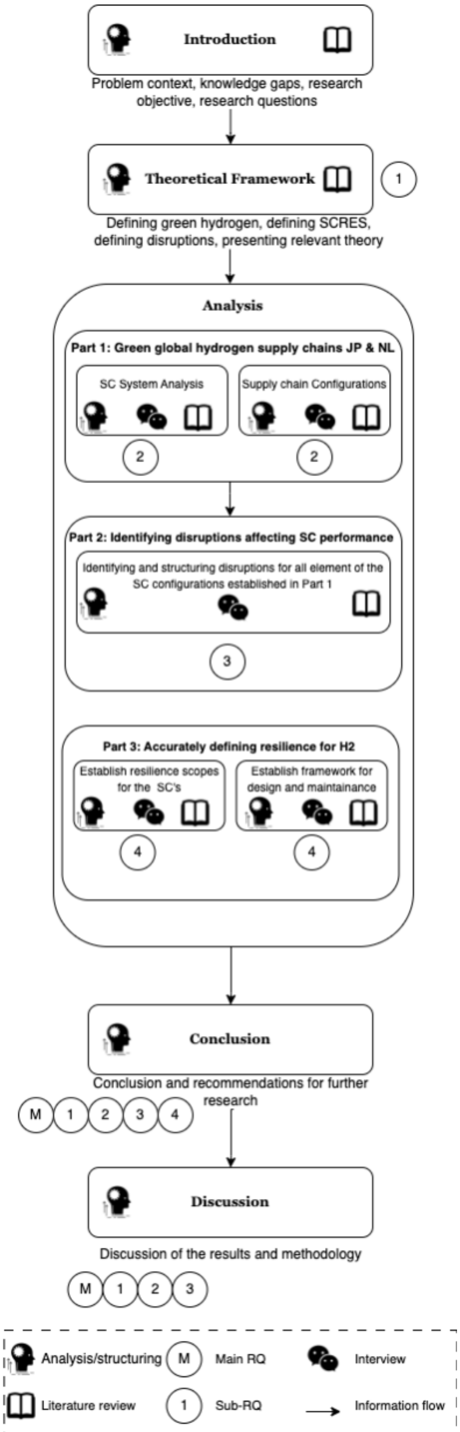


Figure 8: The research flow diagram

Appendix C): Data collection disruption analysis

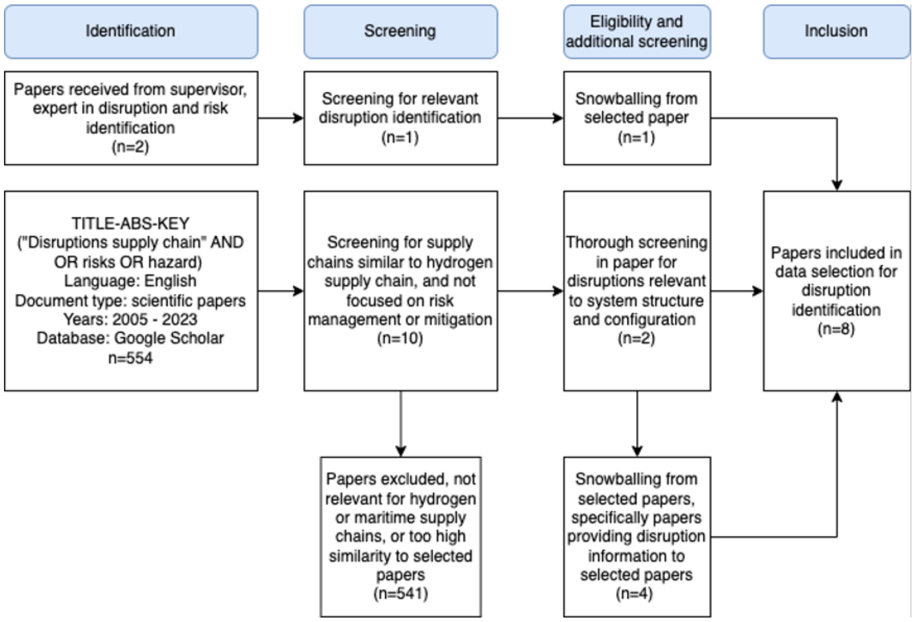


Figure 9: Literature search and selection process for disruption analysis

	Papers	Year
1	(Azadnia et al., 2023b)	2023
2	*Kleindorfer et al	2009
3	*(Vakharia and Yenipazarli, 2009)	2008
4	*(Craighead et al., 2007)	2007
5	*(Roscoe et al., 2020b)	2020
6	*Ricci et al	2021
7	*(Ambulkar et al., 2015b)	2014
8	*(Yang et al., 2023a)	2023

* Papers obtained using snowballing

Table 3: * Papers included for the data selection for disruption analysis

Appendix D: Literature review for overview adaptive capabilities of resilience

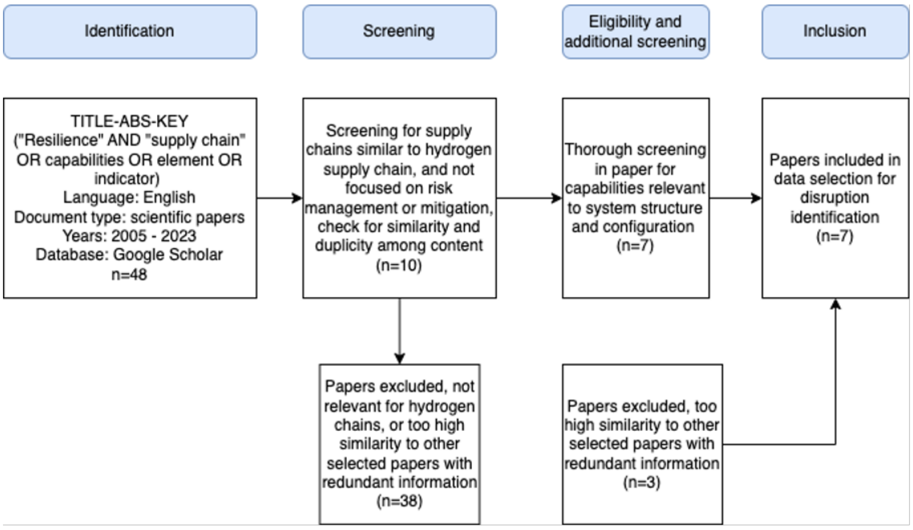


Figure 10: Literature search and selection process for adaptive capabilities of resilience

	Papers	Year	Adaptive capabilities included
1	Ali et al.	2017	situation awareness, robustness, building redundancy, collaboration, agility, knowledge Management
2	Karl et al.	2018	robustness, building redundancy, collaboration, agility, knowledge management
3	Singh et al.	2019	Robustness, building redundancy, collaboration, agility,
4	Hosseini et al.	2019	Robustness, agility, collaboration, building redundancy
5	Tukamuhabwa et al.	2015	Transparency, building redundancy, knowledge management, agility, collaboration
6	Marinagi et al.	2018	Situation awareness, Robustness, Building redundancy, Collaboration, Agility, knowledge management
7	Ponomarov et al.	2009	Transparency, collaboration, agility, building redundancy, knowledge management

Table 4: Papers included for the data selection for adaptive capabilities for resilience

Appendix E: Overview of the design choices process and hierarchy

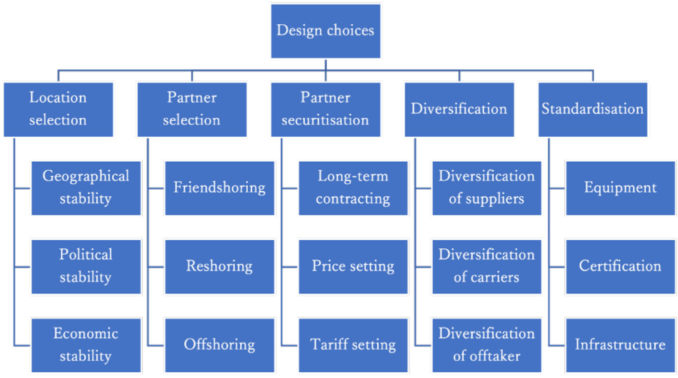


Figure 11: Overview of the design choices process and hierarchy

Appendix F: Overview of the synthesis framework

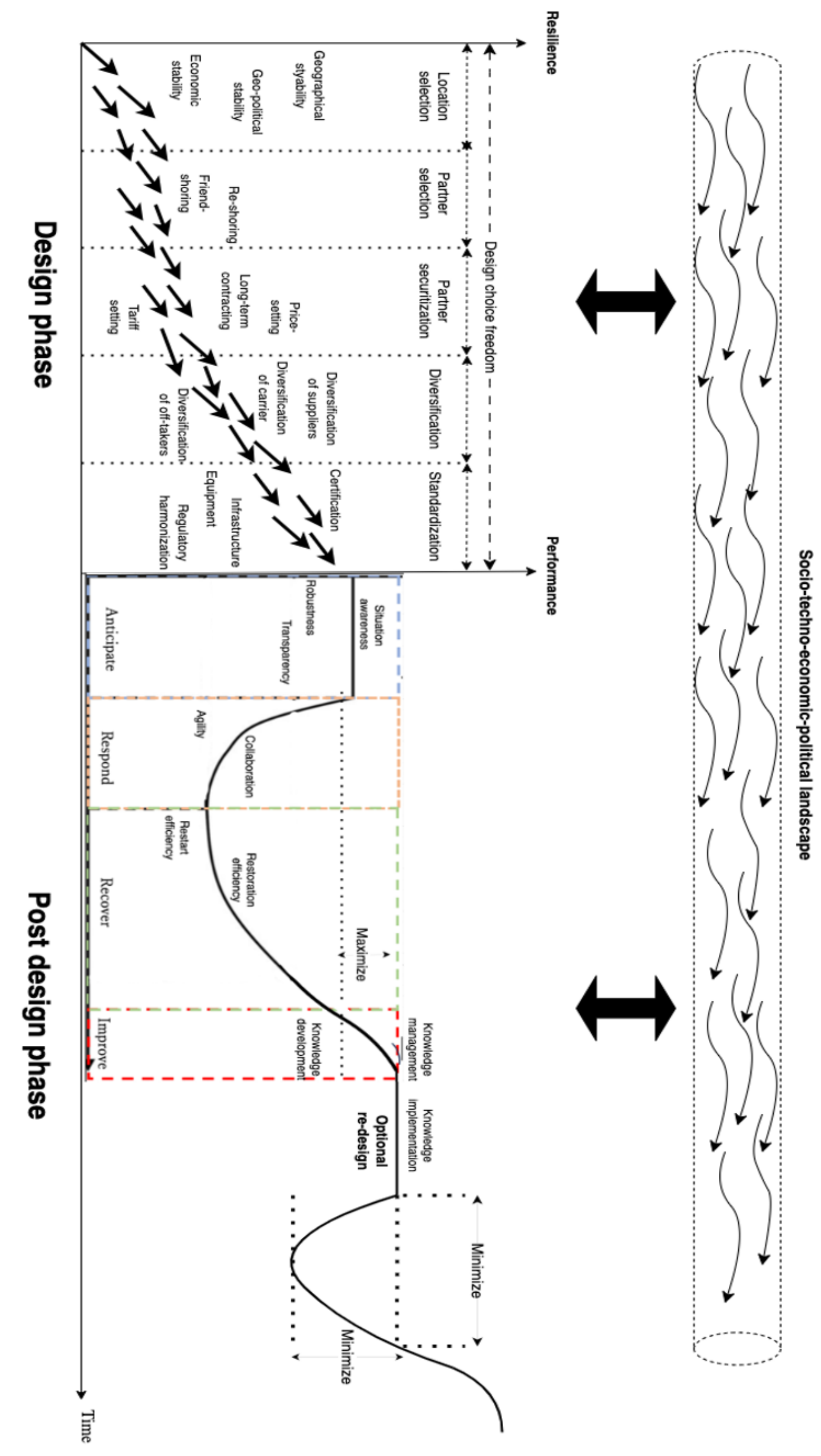


Figure 12: Framework showcasing the process of the design and maintenance of resilience

Appendix G: Overview of three scopes of resilience in IGHSC

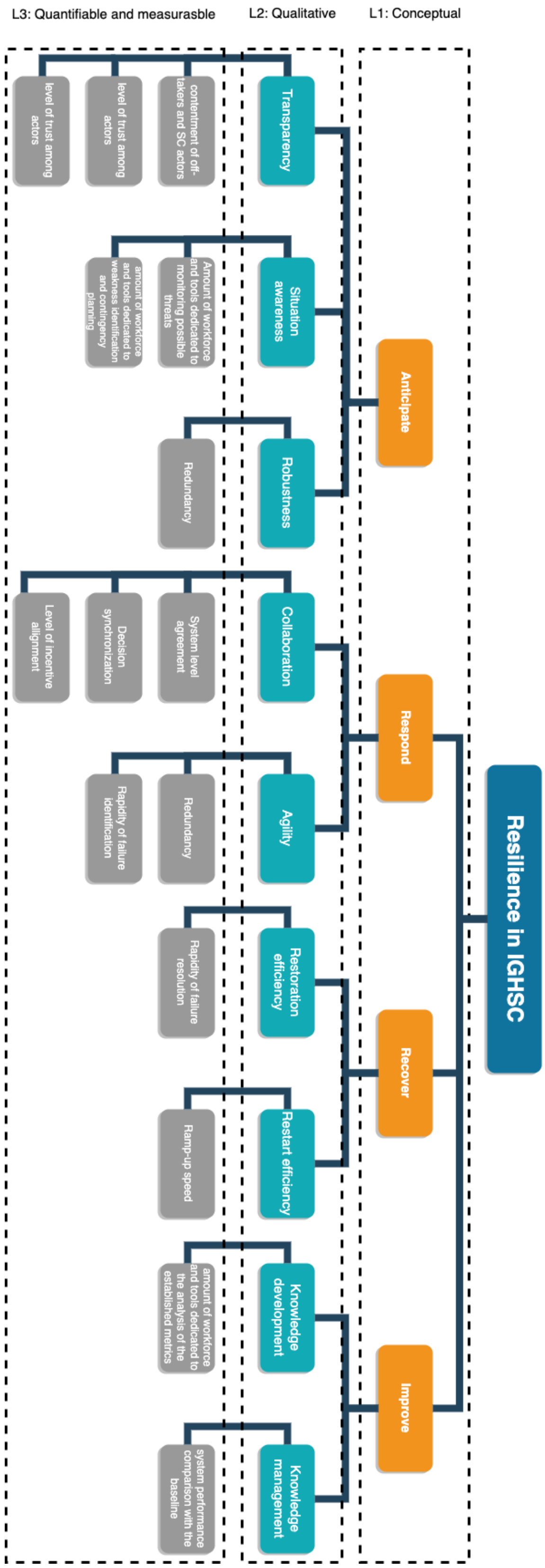


Figure 13: Framework showcasing the process of the design and maintenance of resilience

KPI	Element	Ability	Quan orqual	How to assess
Contentment of off-takers and SC actors	Transparency	Anticipate	Qualitative	Develop qualitative survey with open-ended questions to capture opinions and experiences of off-takers and supply chain actors.
Level of trust among actors	Transparency	Anticipate	Qualitative	Organize trust-building workshops or focus groups, bringing together key IGHSC actors, facilitating discussions on trust-related issues. Collect qualitative data during the workshops/focus groups through note-taking, audio recordings and transcripts.
# workforce and tools dedicated to monitoring possible threats	Situation awareness	Anticipate	Quantitative	Calculate # employees or dedicated workforce members responsible for monitoring threats within the supply chain. This includes personnel involved in risk assessment, threat detection, and situational analysis.
# workforce and tools dedicated to monitoring weakness identification and contingency planning	Situation awareness	Anticipate		Calculate # employees or dedicated workforce members responsible for monitoring weaknesses, identifying vulnerabilities, and developing contingency plans within the supply chain. Include personnel involved in risk assessment, vulnerability/disruption analysis, and contingency planning
Redundancy	Robustness, Agility	Anticipate	Quantitative	Compare the number of backup components, alternatives, processes, or resources compared to the total number of essential components or processes in the IGHSC.
SLA	Collaboration	Respond	Quantitative	Develop a survey or assessment tool that covers key aspects of the supply chain, including goals, objectives, processes, roles, and responsibilities. Distribute the survey to all relevant actors within the IGHSC
Decision synchronization	Collaboration	Respond	Quantitative	The amount of key decisions that have been done with the same outcome compared to the total level of key decisions
Level of incentive alignment	Collaboration	Respond	Qualitative	Develop a qualitative stakeholder survey capturing perspectives and perceptions of key actors within the IGHSC. Include open-ended questions that encourage respondents to share their views on the alignment of incentives within the supply chain.
Rapidity of failure identification	Agility	Respond	Quantitative	Amount of time passed from failure occurrence to identification

Rapidity of failure resolution	Restoration efficiency	Recover	Quantitative	Amount of time passed from failure identification to failure resolution
Ramp-up speed	Restart efficiency	Recover	Quantitative	Time passed from failure resolution to desired IGHSC performance
# workforce and tools dedicated to analysis of established metrics	Knowledge development	Improve	Quantitative	Quantify # and types of tools, software, or technologies dedicated to analysis of established metrics during the same measurement period. Also # of employees/dedicated workforce members responsible for analyzing established metrics within the defined measurement period.
System performance comparison with baseline	Knowledge implementation	bImprove	Quantitative/ qualitative	This can be done in numerous ways and can be subject to a thesis topic on its own. A clear and specific baseline for the system's performance should be derived. The baseline serves as the benchmark against which current performance will be evaluated. Additional KPI's should be established to measure this KPI, that can be both qualitative and quantitative.

Table 5: overview of all KPI's advised to assess for building resilience in operational IGHSC

Appendix H: Interview Questions and Answers for Chiyoda Corporation

Key quote 1: "Yes, this supply chain configuration appears to be a logical setup for an international green MCH supply chain. It connects the key points of production and distribution. However, I would recommend making a slight adjustment to the diagram. Adding an arrow directly from the toluene tank to the ship is often seen in real life scenarios. Additionally, there seems to be a minor error in the process description. Instead of "dehydrogenization" at the origin, it should be "hydrogenation." Overall, with these adjustments, the configuration offers an accurate international green MCH supply chain configuration."

Key quote 2: "I do see a lot of them that would from an insurance standpoint be something called force majeure events: beyond human control, and significant contributors to disruptions in the supply chain. These events include natural disasters, extreme weather conditions, geopolitical conflicts, etc. Chiyoda places a strong emphasis on accounting for these events in the their design, but cannot take responsibility for them and therefore does not see them as more important than others. So, while efforts are made to build infrastructure that can withstand and respond to heavy disruptions, it's acknowledged that no system can have a perfect response to such events, as they are unpredictable and not anyone's fault."

1) What role do H2 supply chains play in your company? How are you involved in H2 supply chains today?

Hydrogen supply chains play a crucial role as a part of our expertise and experience in providing engineering solutions. Our background in LNG equips us with valuable knowledge and a network of contacts, which we use to contribute to hydrogen supply chain projects. Our role in hydrogen supply chains primarily revolves around assisting in different aspects and components for various contractors, whether they are corporations or entire countries, who seek our expertise in engineering solutions. While we don't initiate the supply chains themselves, we play an important role in shaping their operations by providing tailored engineering solutions that align with the specific needs and goals of our contracting partners. We can use our prior experience in LNG and draw upon our established relationships, we work closely with contractors to design, plan, and optimize critical elements within possible hydrogen supply chains.

2) How does Japan (their policies, resources, society) influence your choices of H2 supply chains? Do you foresee changes in the future?

Japan's influence on our choices for projects in Japan is significant. Japan's rich history as a contractor for Chiyoda Corporation, particularly in numerous LNG projects, has made a strong relationship and an understanding of energy infrastructure development. This collaboration has laid the groundwork for our exploration of hydrogen-related projects. Japan's forward-thinking hydrogen strategy offers a promising avenue for hydrogen-projects in the future. Japan's dedication and strategic direction to advancing hydrogen technologies and infrastructure has created a supportive environment for innovation and collaboration. An aspect of our engagement with hydrogen initiatives revolves around our development of the MCH technology, a technology that we hold the patent for. We expect that it will be a game-changer in hydrogen transportation and storage. With Chiyoda's MCH technology we find ourselves at the forefront of advancing hydrogen supply chain solutions. Specifically, our role involves helping contractors who want to establish hydrogen supply chains utilizing the MCH carrier. We expect that Japan's influence on the hydrogen economy will continue to evolve and so hopefully we even more projects emerging. We also want to say that we do acknowledge that not one carrier will be leading, and still diversification is necessary as each carrier has its (dis-)advantages and suitable applications.

3) If you look at the overview of the global green MCH supply chain with Japan as importing country I constructed, which elements of the supply chain is your company most involved in?

Our involvement in this configurationprimarily focuses on the elements of the supply chain related to conversion until storage. We play a significant role in designing and constructing the processes involved in producing MCH, ensuring also quality control. We are not really involved in the utilization phase, as MCH can not be utilized as itself and needs to be dehydrogenized. Our role is during the earlier stages of the supply chain. We are also not engaged in producing the energy required for the supply chain but contribute to the the conversion process ensuring MCH is produced and stored. In summary, our company's core involvement in the MCH supply chain is centered around the conversion process until storage.

4) When looking at this supply chain configuration, would you say this is a logical configuration for a global green MCH supply chain configuration?

Yes, this supply chain configuration appears to be a logical setup for an international green MCH supply chain. It connects the key points of production and distribution. However, I would recommend making a slight adjustment to the diagram. Adding an arrow directly from the toluene tank to the ship is often seen in real life scenarios. Additionally, there seems to be a minor error in the process description. Instead of "dehydrogenization" at the origin, it should be "hydrogenation." Overall, with these adjustments, the configuration offers an accurate international green MCH supply chain configuration.

5) Let's talk about resilience and take a technical stance, (show graph), do you think this is also the way Japanese companies and the government thinks about resilience?

This is a very interesting explanation and representation on the topic of resilience. I think that indeed for Japanese companies and the government, it is not desired to have a disruption in the performance curve, and most of the time, efforts are made to avoid such disruptions. In the context of Chiyoda, as an engineering company, our focus revolves around preventing accidents and implementing rigorous safety measures to ensure avoidance. As you pointed out, a crucial aspect of designing resilience is to shift the emphasis from attempting to mitigate any form of disruption at all costs to also encompassing the design of effective responses to disruptions when they inevitably occur. This aligns with Chiyoda's approach, as we understand that a comprehensive resilience strategy involves not just prevention, but also strategies to mitigate and recover from disruptions. As Chiyoda operates globally and collaborates with companies from diverse cultural backgrounds, we do not strictly adhere to a single Japanese mindset or risk-averse approach in every project. Instead, our goal remains to work for contractors that hire us to minimize errors and ensure the successful execution of projects.

6) If you look at the overview of required abilities to develop and maintain resilience, what abilities do you recognize as being important for Chiyoda when designing new supply chains or operations?

The overview of required abilities to develop and maintain resilience seems to focus on an already running supply chain. But when it comes to Chiyoda's involvement in designing new solutions for elements in a supply chain, there are several critical abilities and considerations that we can recognize as already during the design and construction phases. During the design phase, we can assess the possible weak points and risks within the proposed supply chain, taking into account factors such as transportation modes, and potential points of failure. By addressing these vulnerabilities in the design phase, we can significantly enhance the system's resilience from the very beginning.

7) In my thesis, I define disruptions as having a very low frequency but very high impact. What do you think are the most important causes for disruptions in a green ammonia supply chain?

Some important causes of disruptions and their implications can indeed by found in this overview, but I do see a lot of them that would from an insurance standpoint be something called force majeure events: beyond human control, and significant contributors to disruptions in the supply chain. These events include natural disasters, extreme weather conditions, geopolitical conflicts, etc. Chiyoda places a strong emphasis on accounting for these events in the their design, but cannot take responsibility for them and therefore does not see them as more important than others. So, while efforts are made to build infrastructure that can withstand and respond to heavy disruptions, it's acknowledged that no system can have a perfect response to such events, as they are unpredictable and not anyone's fault. Additionally, one of the main advantages of MCH is its stability under ambient conditions. Unlike other carriers, such as green ammonia, which come with additional technical and safety concerns, MCH is relatively stable and safe to handle. This stability contributes to the resilience of the supply chain and minimizes the risk of disruptions related to hazardous reactions or other technicalities. But a drawback of the MCH production process is the necessity to send ships loaded with toluene back to their source after the dehydrogenation process that forms hydrogen from MCH. From a market economics disruption perspective, this requirement can pose challenges and potentially cause delays, because the ships necessary for the shipment have to go back and forth more often to ship a hydrogen carrier.

Appendix I: Interview Questions and Answers for IHI Corporation

Key quote 3: "Yes, this supply chain configuration for the green ammonia supply chain appears to be well structured from the standpoint of IHI. However, I recommend revisiting the utilization of resources in Japan within this configuration. Rather than treating all utilizations in Japan as equally significant, it could be beneficial to prioritize based on their respective contributions and potential."

Key quote 4: "Our focus is on developing and optimizing facilities that enable the conversion of energy sources into ammonia. This involves the utilization of cutting-edge equipment and systems to achieve high production efficiency and minimize environmental impact. Also, our commitment extends to the certification and standard-setting processes within the international green ammonia supply chain. So in a way that might contribute to the utilization stage. IHI collaborates with relevant stakeholders to establish and adhere to rigorous quality standards, safety protocols, and sustainability criteria. By participating in certification and standard-setting initiatives, we contribute to the establishment of a framework that ensures the feasibility of green ammonia as a clean energy carrier."

1) What role do H2 supply chains play in your company? How are you involved in H2 supply chains today?

At IHI, focus providing engineering solutions, and for hydrogen a particular emphasis on ammonia. We are dedicated to driving global adoption of ammonia as a prominent hydrogen carrier. We do realize the significance of diversification among carriers, but our primary area of expertise revolves around the utilization of ammonia due to our involvement and specialization in this field. So, this does not mean that we do not know that each carrier has unique characteristics. Also an important aspect of our engagement in the hydrogen supply chains pertains to actively developing the certification and standards framework for ammonia as a hydrogen carrier. We hope this will ensure the safe and efficient transportation and utilization of ammonia in hydrogen contexts but also boost the overall credibility and acceptance of ammonia as a viable carrier option.

2) How does Japan (their policies, resources, society) influence your choices of H2 supply chains? Do you foresee changes in the future?

We are of course aware of the factors shaping our choices regarding hydrogen supply chains from which Japan's hydrogen strategy undoubtedly holds influence over. Japan's approach to hydrogen is clear through its well-articulated hydrogen strategy. This strategy also underscores the potential of direct combustion of ammonia and hydrogen as key methods of energy production. So, Japan's latest version of the hydrogen strategy aligns with our business of working with ammonia.

3) If you look at the overview of the global green ammonia supply chain with Japan as importing country I constructed, which elements of the supply chain is your company most involved in?

Our involvement primarily spans from production through storage stages and not really on utilization, and we are not engaged in energy production. Our focus is on developing and optimizing facilities that enable the conversion of energy sources into ammonia. This involves the utilization of cutting-edge equipment and systems to achieve high production efficiency and minimize environmental impact. Also, our commitment extends to the certification and standard-setting processes within the international green ammonia supply chain. So in a way that might contribute to the utilization stage. IHI collaborates with relevant stakeholders to establish and adhere to rigorous quality standards, safety protocols, and sustainability criteria. By participating in certification and standard-setting initiatives, we contribute to the establishment of a framework that ensures the feasibility of green ammonia as a clean energy carrier.

4) When looking at this supply chain configuration, would you say this is a logical configuration for a global green MCH supply chain configuration?

Yes, this supply chain configuration for the green ammonia supply chain appears to be well structured from the standpoint of IHI. However, I recommend revisiting the utilization of resources in Japan within this configuration. Rather than treating all utilizations in Japan as equally significant, it could be beneficial to prioritize based on their respective contributions and potential.

5) Let's talk about resilience and take a technical stance, (show graph), do you think this is also the way Japanese companies and the government thinks about resilience?

This is a very interesting view on the topic of resilience. At IHI, we believe that resilience is a crucial aspect of our engineering processes and operations, and recently it has arisen as an important topic within our company. We understand that in order to thrive in today's rapidly world, it is essential to build systems and strategies that can withstand disruptions. IHI is very invested in rigorous safety planning. By identifying potential hazards and vulnerabilities, we try to address them and enhance the overall resilience of our solutions and we place a strong emphasis on avoiding all errors in performance.

6) If you look at the overview of required abilities to develop and maintain resilience, what abilities do you recognize as being important for Chiyoda when designing new supply chains or operations?

In this answer, we went a bit off topic and had a good discussion about the element of transparency. We talked about ways in which IHI takes a holistic approach in the supply chains they are involved in. It was something fairly new to think about ways to develop the ability to see the supply chain holistically from one end to another and find the place of a disruptive event, by creating mutual trust and willingness to share information with other actors within the supply chain. Also, it came to light that the topic of resilience was indeed a theme that IHI was actively having discussions on and was pursuing. However, because it was still very new and needed a lot of further discussion within IHI, due to confidentiality reasons it could not be discussed further.

7) In my thesis, I define disruptions as having a very low frequency but very high impact. What do you think are the most important causes for disruptions in a green ammonia supply chain?

Of course, ammonia comes with properties of how to handle it properly. Ammonia is a corrosive and toxic substance and can be explosive under the wrong conditions. Obviously, the technical disruptions are the ones that stand out to me. IHI is an engineering company that is focused heavily on safety, and the technical disruptions are the ones you would look at the soonest. Primarily, the technical have our immediate attention. These disruptions include a range of factors such as equipment failures, process inefficiencies, or unexpected technical incidents that can hinder the performance of the green ammonia supply chain. Disruptions for us are mainly considered as having an effect on the technical performance and safety of the system. So when we think about a typhoon, we would rather think about how to make the technical equipment of the elements we were involved in typhoon proof, than to consider what the disruption would do to the entire supply chain performance.

Appendix J: Interview Questions and Answers for Business Development Director of Koole Terminals

Key Quote 5: "Let me take a look. I would change "cargo handling" to "loading and unloading" in the transport section. That makes it clearer."

Key Quote 6: "But you really need to do that redundancy. Building redundancy is actually a kind of execution of capability 1D. So, indeed, in that sense, it doesn't fall in the same hierarchy, so to speak, it falls under that. Have you included "alternatives" in it? We were just talking about that, so alternatives. Yes, diversification, have you incorporated that?"

Key Quote 7: "So, they strive to build resilience within the system by ensuring sufficient supply sources or off-takers at both ends. This is one way to make the performance of a single producer, plant, or off-taker less dependent, particularly when facing significant disruptions. This is why, as a country like the Netherlands, we shouldn't dictate from which countries hydrogen must come, or what kind of carrier it should be. We need to be open to multiple carriers from different countries."

Q1) Do you encounter different approaches to resilience among partners while working on the LHyTS-project?

That's actually the discussion. I don't really know. I do notice though a lot of investigation is being done by Japanese parties, with whom also work. They are delving into many details and find it challenging to provide indicative figures or such at an early stage, because they want everything to be thoroughly researched and contemplate various scenarios. On the other hand, some other parties take a more relaxed approach. For instance, they might give cost estimates or provide early indications. What I find peculiar is that the case studies we often discuss, like the NL-Scotland case study, but also other case studies involving Japanese companies, there are often point-to-point. A single source, single off-taker setup. And if you have something that's sensitive to disruptions, such a point-to-point arrangement is that. For instance, a Scottish producer shipping to a single buyer, as in the project you mentioned. Other parties, at least some of them, focus more on multi-offtake setups, especially if they are producers, or they emphasize multi-sourcing if they are consumers. So, they strive to build resilience within the system by ensuring sufficient supply sources or off-takers at both ends. This is one way to make the performance of a single producer, plant, or off-taker less dependent, particularly when facing significant disruptions. This is why, as a country like the Netherlands, we shouldn't dictate from which countries hydrogen must come, or what kind of carrier it should be. We need to be open to multiple carriers from different countries. If we firmly believe that hydrogen should not come from Iran due to sanctions, that's fine. But we shouldn't mandate that it must come from Europe or must be MCH. Well, this is an important concept in terms of what I think about resilience and what I observe in my work. It's a small example within a specific chain and a broader example related to the hydrogen import strategy.

Q2) Do you also think that Japanese parties often prefer to work with a single off-taker and a single producer?

Well, no, I think that's more generic. It's related to the status of the project. But it's a generic notion to say that this is specific to Japanese parties. It has to do more with their desire to make things very tangible. So, they want to work out a very tangible point-to-point system. Instead of thinking more broadly about how something could be designed to serve multiple sources. But perhaps it's too broad to attribute it to culture. However, this is what I currently observe in the examples.

Q3) I have an overview of the supply chain configuration for the Netherlands and Scotland. Could you briefly go over it? Do you think this is indeed a logical configuration?

Let me take a look. I would change "cargo handling" to "loading and unloading" in the transport section. That makes it clearer. Yes. The storage, the origination, and it's just piped in. How would you fit the pipeline here? It's called the National Hydrogen Backbone by Gasunie. Then, hydrogen goes to all sectors. So, storage can, in principle, be removed. Well, maybe it happens in a very small part.

Q4) What, in your opinion, is the biggest drawback of MCH?

What makes it less feasible is a long, real, international supply chain. But between Scotland and the Netherlands, this isn't a major issue, of course. It's not even about the distance. That doesn't matter much, whether the ship is sailing or not. It's about the volumes. If you want to ship really large volumes of hydrogen, you have to transport very large amounts of Toluene, around 16 or 18 times in weight, and then transport it back. At some point, it becomes physically limiting. Because you're talking about millions of tons of hydrogen needed in Germany, for instance. If you do that 15 or 20 times, it quickly adds up. Consider that the Rotterdam port receives 50 to 100 million tons of crude oil currently, and that's quite a clear transport. Then you need 4 or 5 times more volume. So, it's just not feasible. There won't be that many carriers for Toluene. The infrastructure can't handle it either. In any port, really. So, the main limitation is dealing with very large volumes. So the scalability isn't great, and it's definitely never going to become a main carrier. But you're still hoping for one carrier to bring about a breakthrough. I still think it will be ammonia, to be honest. Because it has the highest energy density and no carbon, so you can produce it in many different places. So, you don't need CO2 for that, as you do for making methanol, for example. Truly green CO2 is only available in very few places and in small quantities. You need a carbon-free carrier. And ammonia is basically the only option. Not cracked but used directly in power generation, just direct combustion. I have high expectations for ammonia in power generation.

Q5) During the feasibility study you conducted, was resilience a design criterion? Did you or any other involved party find it important?

Yes, we were ourselves. This is mainly because what you often see in these kinds of chains is that many of the operators are not people who are currently active in the value chain. They are not logistics parties. Because we are a logistics company, we know that something always goes wrong in logistics. The ship breaks down, the ship arrives late, the tank leaks, the pipeline leaks, and so on. The customer is in a shutdown or turnaround. And there's always an Excel truth about how much tank volume you need, how many ships, and how efficiently that can work. Then there's the practical truth. It's always closer to the practical truth than the Excel truth. And this has to do with resilience, with the reliability of certain steps. A ship getting caught in a storm. A malfunction during unloading a ship. A tank not being available due to maintenance. A customer performing maintenance. There are always disruptions, so we've said that in that chain, you need to incorporate certain buffers. And we often do this by adding a bit of extra storage. To be slightly less just-in-time. Because if you design this according to the Excel truth, you need to build in a buffer. We've had that discussion. By actually wanting a bit more slack in the design, the chain suddenly becomes much more reliable. And essentially, building redundancy is what you're talking about in the ability to anticipate. So, proactively knowing that you need that redundancy.

Q6) These are the elements I've devised for each ability to maintain resilience, would you go over them and see if you agree with them?

Because many of those other things, everyone will always say in the design "Yes, but of course, we do that. And we are very transparent. We collaborate well". But you really need to do that redundancy. Building redundancy is actually a kind of execution of capability 1D. So, indeed, in that sense, it doesn't fall in the same hierarchy, so to speak, it falls under that. Have you included "alternatives" in it? We were just talking about that, so alternatives. Yes, diversification, have you incorporated that?

Appendix K): Key Quote important from the Shell Interview

Note: due to sensitive data and the numerous names of other companies, I have decided to just incorporate the quote that was relevant for the discussion point for re-design

Key Quote 8: It strongly appears that the design phase is a one-time event, followed by a more or less fixed configuration. It is understandable that this is the desired scenario for large-scale hydrogen projects, given the massive capital investments involved. The redesign cycles are substantial in size, with development budgets easily reaching tens of millions, if not more. Therefore, a balance must be struck between what your model suggests regarding the redesign process and what is feasible in practice. Your model seems to aim for flexibility, even extending into the operational phase. This ideally applies to technical aspects and other areas as well. However, technical aspects may become problematic at some point and may need to be documented. At that point, little room is left for change, and if a return to a previous phase is necessary, it requires a complete redesign. This is where the biggest conflict between your model and reality may lie. It is important to recognize that large-scale hydrogen projects require a delicate balance between flexibility and stability. While your model appears to embrace flexibility, real-world practice often leans more toward documenting technical specifications and processes. Understanding and navigating this tension is essential for the successful implementation of resilient and effective hydrogen projects.

turn to normal energy supply conditions. This could involve taking steps to speed up economical repairs by streamlining regulatory procedures in the EU, offering financial incentives to impacted sectors, and promoting innovation in energy supply and distribution technology. Collaboration, transparency, and thus international cooperation are also fundamental components of resilience as discussed in Chapter 6. Policymakers should collaborate closely with neighboring countries and international partners to enhance collective energy security. This can involve developing agreements for mutual assistance during crises, sharing best practices, and harmonizing energy policies to create a more resilient regional energy ecosystem. Incorporating the resilient perspective into policymaking ensures that EU policies are adaptive, forward-thinking, and capable of addressing the intricate and dynamic challenges of energy security in a volatile geopolitical landscape. By adopting this holistic approach to resilience, policymakers can enhance the EU's capacity to withstand shocks, maintain a stable energy supply, and safeguard the well-being of its citizens, even in the face of adversity.