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Navigating Hydrogen Horizons - Mapping the Technological Innovation System of Mid Sweden Hydrogen Valley

A case study in collaboration with CIT Renergy

Master's thesis in Management and Economics of Innovation

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Acknowledgements, dedications, and similar personal statements in this thesis, reflect the authors‘ own views.

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Abstract

The transition towards a sustainable energy future necessitates the adoption of low-carbon technologies, with hydrogen emerging as a pivotal element in achieving climate neutrality. Hydrogen valleys – a geographical area where several hydrogen applications are combined into a more cost-efficient and integrated hydrogen ecosystem, are identified by the European Commission as important enablers for transitioning into a full-scale hydrogen economy. This master's thesis investigates Mid Sweden Hydrogen Valley (MSHV) – a hydrogen valley in early stages of formation in Sweden, using a Technological Innovation System (TIS) framework. Due to the novelty of hydrogen valleys, few studies have analyzed hydrogen valleys using system level frameworks like TIS – which could provide valuable insights regarding how a hydrogen valley should be developed. By employing a qualitative case study approach, data was collected through 21 interviews with members of MSHV and actors closely related to it. Key findings reveal that a hydrogen valley is a complex system, including diverse networks of actors both in the main hydrogen value chain, through supporting value chains, and other influences such as grant providers and authorities. The findings also reveal that MSHV performs relatively well based on the appraisal of its seven functions. Still, six challenges (labeled blocking mechanisms) are identified that prevent the hydrogen valley from moving smoothly from a formative phase into a growth phase. These challenges are addressed by proposing six recommendations for policymakers and three recommendations for managers, which emphasize the need for collaboration, improved economics, and political support. Finally, the study concludes by suggesting directions for future research.

Keywords: Hydrogen Valley, Technological Innovation System, Fossil-free Hydrogen, Low-carbon Hydrogen, Socio-technical Transformation, Sustainable Transformation

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1. Introduction

In this section, an introduction is given to the study, which includes: (1) background, (2) aim, (3) limitations, and (4) research questions. The thesis is thereafter structured by the following: a description of the theory that is used throughout the report, a method chapter where the research process is presented, an analysis of the collected data using an analytical framework, and finally, the research questions are answered in the conclusion, followed by limitations as well as suggestions for further research.

1.1 Background

Achieving the future climate goals outlined by the European Union, including climate neutrality by 2050 (European Council, 2022), requires decarbonization of various sectors. Many studies agree that hydrogen will be critical in reaching the sustainability goals (Jodry et al., 2023; Majka et al., 2023; Weichenhain et al., 2022; Ficco et al., 2022; López et al., 2023). It is estimated that hydrogen will account for more than 13% of the world's total energy consumption by 2050, whereas this number was 1% in 2020 (López et al., 2023). This opportunity for growth in hydrogen demand can be attributed to its characteristics, for example: close to zero pollution when integrated with renewable energy sources, flexibility and sector coupling possibilities (i.e. interconnecting the energy consuming sector with the energy producing sectors), and use-cases in several sectors (Genovese et al., 2024). Further, studies such as Ficco et al. (2022) and López et al. (2023) explain that hydrogen could be used to neutralize the emissions of the so called "hard-to-abate" sectors where electrification is currently challenging, e.g. long-distance and heavy goods transport. Other industries that could benefit greatly from hydrogen include the chemical and steel industries, primarily because hydrogen does not emit any CO_2 when consumed unlike other fuels (Ficco et al., 2022).

Today, most hydrogen is so-called gray hydrogen, meaning that it is derived from fossil fuels – for example through reforming of natural gas. The total worldwide hydrogen production, which was 94 megatons in 2021, resulted in 900 megatons of CO_2 emissions. Only 0.7% was produced by low-emission methods, with even less (35 kilotons) being produced through water electrolysis (López et al., 2023). In Sweden, there are currently no official statistics on hydrogen usage, but Fossilfritt Sverige (2021) estimated that the country's total hydrogen production and usage was 180 thousand tonnes per year (approximately 6TWh/year). The hydrogen was mainly fossil-based, with less than 3% being produced through water electrolysis. According to the report, most of the hydrogen produced in Sweden is consumed near to its production sites.

To reach the sustainability goals, it is estimated that all hydrogen production will need to be either green hydrogen (i.e. water electrolysis powered by renewable energies such as wind or solar) or blue hydrogen (i.e. using the same methods as gray hydrogen but with carbon capture and storage) by 2050 (López et al., 2023). Further, López et al. (2023) highlights how different agencies have come up with scenarios for the future hydrogen demand, which are summarized in *Figure 1*. As shown in the projections, the current production of hydrogen by low-emission methods is practically negligible compared to what is needed in the future. There also exist other forms of hydrogen which are not mentioned as frequently in the literature, e.g. pink hydrogen, which is produced through nuclear powered electrolysis (Shirizadeh & Quirion, 2023). Throughout this study, the term hydrogen will be used to refer to low-carbon hydrogen (unless stated otherwise), which includes all production methods with a carbon footprint close to zero.

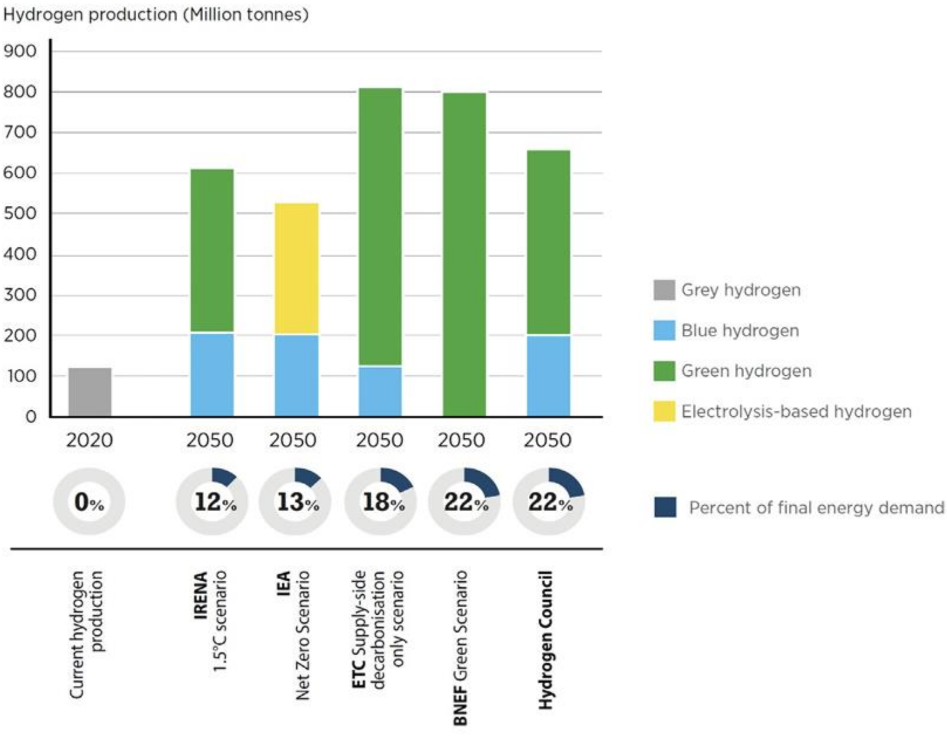

Figure 1. Projections of future hydrogen demand (López et al., 2023).

The European Union sees low-carbon hydrogen as a decarbonization enabler, pushing different policies to support its development. For example, the "REPower EU" plan aims to speed and scale up usage and production of low-carbon hydrogen and to double the amount of hydrogen valleys in Europe to reach 100 by 2030 (Weichenhain et al., 2022). A hydrogen valley is defined by the European Commission as:

> "a geographical area – a city, a region, an island or an industrial cluster – where several hydrogen applications are combined together into an integrated hydrogen ecosystem that

> consumes a significant amount of hydrogen, improving the economics behind the project. It should ideally cover the entire hydrogen value chain: production, storage, distribution and final use." - European Commission (n.d.)

Even though hydrogen valley formation is in its infancy, it is expected to be a considerable driver towards a full-scale hydrogen economy (Weichenhain et al., 2022; López et al., 2023). By leveraging synergies through collaboration between actors, hydrogen valleys have the possibility to overcome many of the challenges associated with novel and disruptive technologies. Such challenges include deficient cost competitiveness, lack of scale in production, and infrastructure needs (International Energy Agency, 2019; López et al., 2023). For example, the production of blue hydrogen, which requires CO_2 capture, is currently an expensive process, costing $1.4-$4.7 per kilo to produce, while green hydrogen is even more costly at $4.5-$12 per kilo – compared with gray hydrogen which only costs $0.98-$2.93 per kilo (BloombergNEF, 2023). Another example is the need for infrastructure, e.g. pipelines, storage facilities and equipment for loading and unloading, that would allow for distribution of large volumes of hydrogen from producer to end users (Steen, 2016) – which currently does not exist. These challenges constitute important reasons why collaborating, producing, and using hydrogen within a confined geographical area, like a hydrogen valley, is beneficial.

A hydrogen valley under formation in Sweden – called Mid-Sweden Hydrogen Valley (MSHV), will be the case of analysis. The mid-Sweden area has a well-established industry, with strong competence within hydrogen, making it an appropriate geographical area to create a hydrogen valley (Region Gävleborg, 2022). Recent developments in the area include the University of Gävle taking the lead of hydrogen research, efforts by Gävle Harbor to establish an energy-optimized harbor cluster (Region Gävleborg, 2022), Inlandsbanan planning for large-scale hydrogen distribution and converting diesel-powered freight trains to hydrogen power (Inlandsbanan, 2021), hauliers like MaserFrakt launching the first hydrogen-powered heavy trucks on the roads in Sweden (Hynion, 2024), and steel companies like Ovako which invest in large-scale electrolyzers for hydrogen production (Vätgas Sverige, 2023). The actor roles in MSVH's value chain include renewable energy providers, hydrogen producers, hydrogen storage/distribution providers, hydrogen users, grant providers, incubators and research institutes, authorities, and OEMs. MSHV was formed in 2021 based on the shared interest of authorities and industry to strengthen the regional industry, enhance collaboration, and to reach the climate goals (Region Gävleborg, 2022). As it stands, the organization is not a legal entity, which means that MSHV itself cannot initiate projects or allocate funds. The organization is instead used as a platform for collaboration and knowledge-sharing between the members. Coordinated by the regional government, it is free to join for any actor involved in or aspiring to be part of the hydrogen value chain. The hydrogen valley is still in its infancy and does not fully align with the European Commission's definition yet, as many projects are still in the ideation phase rather than the implementation phase.

Because the development of hydrogen valleys is a novel phenomenon, both in theory and practice, it raises a series of questions. Potential questions with hydrogen valleys relate to (1) how the hydrogen valleys should be structured, (2) what influences its development, and (3) what challenges and opportunities exist that both policymakers and managers need to address to create a well-performing hydrogen valley. Given the pressing need to scale up low-carbon hydrogen production and given that there are currently many challenges that prevent it, research needs to be conducted to support managers and policymakers when navigating this challenging terrain. In the innovation systems literature, much has already been written about how policymakers should act in similar environments, e.g. the development of technological innovation systems (TIS) for novel energy solutions (see Bergek et al., 2008a), but none have analyzed the specific case of hydrogen valleys.

The literature on technological innovation systems is used for the analysis in this thesis. TIS can be defined as a "network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion and utilization of technology" (Carlsson and Stankiewicz, 1991). This provides a promising framework for analyzing hydrogen valleys due to several reasons. Firstly, it provides a systemic perspective considering *actors*, *networks* and *institutions*, and the interactions between them (Bergek et al., 2008a). Hydrogen valleys – a socio-technical system aimed at contributing to a sustainable future – involve many stakeholders, ranging from companies within the value chain, supporting actors like research institutes and incubators, to governments. The TIS framework could therefore be used to address the first question by understanding the interactions between these stakeholders and gaining insights about how the hydrogen valley should be structured. Secondly, the TIS framework allows the researcher to analyze the dynamics of some key processes (called *functions*) that influence the development, diffusion and use of a new technology (Bergek et al., 2008a). Exploring how different *functions* in the TIS are affecting the development of a hydrogen value chain, and linking these to the structural components, could reveal insights about the strengths and weaknesses of the TIS. The *functions* could therefore prove useful when addressing the second question regarding what factors influence the hydrogen valley development. Lastly, building on the previous two reasons, TIS offers a holistic understanding of innovation dynamics, including technological, legal and socio-economic perspectives (Bergek et al., 2008a), which therefore provides an integrated and systemic approach for studying hydrogen valleys. Accordingly, the TIS framework could be used to address the third question by identifying opportunities and challenges (referred to in the TIS literature as *inducement and blocking mechanisms*), which in turn could be used to form recommendations for policymakers and managers.

1.2 Aim

This master's thesis aims to establish new knowledge and a better understanding of the development of hydrogen valleys – a multi-stakeholder innovation system centered around a disruptive new technology. This aim will be addressed by mapping the technological innovation system of a newly founded hydrogen valley called Mid Sweden Hydrogen Valley.

1.3 Delimitations

This master's thesis is made on a system level, and thus, detailed descriptions of technical and chemical components related to hydrogen valleys are left out. Due to restrictions on resources and access, not all actors in Mid Sweden Hydrogen Valley are interviewed. Since the thesis is a case study of MSHV, there are also limitations in terms of generalizability for hydrogen valleys on a more global level. Finally, since this study employs a research method that sometimes involves subjective measurements, such as when evaluating the performance of the hydrogen valley, there may be inherent biases that could potentially limit the objectivity of some findings.

1.4 Specification of the issue being investigated

Based on the background, aim, and limitations, three research questions are presented:

RQ1: What are the structural components, i.e. actors, networks, institutions and infrastructure, in a hydrogen valley and how are they interconnected?

RQ2: How do the functional dynamics affect the development and performance of a hydrogen valley?

RQ3: Which inducement and blocking mechanisms are present in a hydrogen valley, and how do they impact the valley's development?

2. Theory

In this section, relevant literature on technological innovation systems is presented, followed by descriptions of the structural components, functions, and inducement and blocking mechanisms. In addition, the last section presents critique of the TIS literature.

2.1 Introduction to technological innovation systems

The analysis of innovation processes and socio-technical transformations is one of the classical research fields within the innovation literature. The creation of innovation processes to accelerate innovation is crucial, as it significantly impacts economic growth, societal welfare and the environment (Hekkert et al., 2007). While the current use of technologies often has a negative impact on the environment, development of sustainable technologies is important to reduce the environmental footprint. Sustainable technologies alone do not drive sustainable technological change; rather, they need to be aligned with the social perspective, including user behaviors, regulatory frameworks and industrial networks (Hekkert et al., 2007), which explains why studying socio-technical change is a complex process.

Markard & Truffer (2008) argue that, even though socio-technical transformations span many decades of research, they lack understanding of the complex underlying innovation processes – which often include a myriad of stakeholders throughout the value chain. The TIS literature was developed to advance the comprehension of these innovation processes and societal transformations, by providing holistic frameworks that explore the dynamics and interactions between stakeholders in an innovation system (e.g., see Bergek et al., 2008a; Markard & Truffer, 2008; Hekkert et al., 2007). TIS has reached widespread diffusion among innovation scholars (Bergek, 2019), where one of the most prominent papers is Bergek et al. (2008a). The paper presents a framework for mapping the structural components of the TIS and assessing the performance by analyzing the dynamics of the key functions that influence the development, diffusion and use of the new technology (i.e. in the form of an artifact or knowledge).

As mentioned in the introduction, a TIS is defined as:

> "a network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion and utilization of technology" – (Carlsson and Stankiewicz, 1991)

The ultimate goal of TIS analyses is to outline the challenges and opportunities that exist within the TIS and in turn provide policy recommendations that mitigate and promote these respectively (Bergek et al., 2008a). If new and innovative TISs are to be developed successfully, Kivimaa & Kern (2016) argue that policies need to be in place that enable creative destruction of the old and competing TISs. For energy transitions, this implies having policies that for example disincentivize the use of fossil fuels. Their key argument is that sustainability transitions should have a mix of two kinds of policies: the first ones being the policies that incentivize the niche-innovations (i.e. less established innovations) and building effective innovation systems around them, and the second ones being the policies aimed at destabilizing the current dominant regimes (i.e. the more established technologies and practices) and creating openings for the take-off and sustained growth of niche innovations to replace the incumbent technologies.

2.2 Constituents of technological innovation systems

TIS analyses are differentiated between structural components and functional dynamics, which are two complementary ways to describe how a TIS works. These two constituents are described below. Additionally, inducement and blocking mechanisms explain why the TIS works the way it does, which will also be presented.

2.2.1 Structural components

The structural components refer to actors, networks and institutions (Bergek et al., 2008a; Hekkert et al., 2007). A fourth structural component is proposed by Wieczorek & Hekkert (2012), that also adds infrastructure. Mapping the structural components creates a more in-depth understanding of how the TIS works, and also provides the foundation for the functional analysis. Below, each of the structural components are introduced.

Actors

Actors are the organizations that in some way contribute to the emerging technology, either directly as a developer or adopter, or indirectly as a financer or regulator (Suurs, 2009). Since it is the actors who are creating, diffusing and using the technologies, the development of a TIS is dependent on actors' presence, skills, activities, and collaborations with other actors. The latter could be explained by, for instance, grant providers not knowing where financial support is needed if developers do not provide them with information (Suurs, 2009). Actors include companies, government and non-governmental agencies, research facilities, universities, venture capitalists, and associations (Bergek et al, 2008; Markard & Truffer, 2008).

Networks

Networks could be defined as a particular group of actors with strong linkages (Suurs, 2009). Networks describe how and where communication and interactions take place and can either be formal or informal

(Bergek et al, 2008). Musiolik et al. (2012) describes formal networks as an organizational structure with easily identified members that collaborate to achieve common aims or to solve specific tasks. The authors argue that formal networks are important in the development of TIS as they facilitate coordination of strategies and enable collective action among participants (Musiolik et al., 2012). According to Bergek et al. (2008), informal networks are more difficult to identify and often require discussions with industry experts or other actors. This process is iterative, with additional information being incorporated as the analysis progresses. Furthermore, networks play a crucial role in the development of TIS because they facilitate exchange of knowledge, fosters a learning process, and create synergies between actors (Suurs, 2009).

Institutions

Institutions are described as the culture, norms, laws, regulations, and routines that need to be aligned for the technology to diffuse (Bergek et al, 2008). Suurs (2009) makes a distinction between formal and informal institutions, where the formal are rules set by some authority, and informal are tacit and developed organically through collective interactions of actors. The institutional rules for a TIS in a formative phase are often underdeveloped and typically not suitable for the emerging technology. According to Suurs (2009), visions and expectations are the primary reasons for supporting an emerging technology.

Infrastructure

Infrastructure as a structural component is often neglected in the TIS literature, and there is no common consensus about what infrastructure covers. Wieczorek & Hekkert (2012) takes a broad perspective on infrastructure and divides it into three categories, including physical, financial and knowledge. The physical infrastructure for example covers buildings, machines, and power grids. The financial infrastructure covers subsidies and grants, while knowledge infrastructure includes expertise and know-how. Furthermore, Smith (1997) argues that physical infrastructure significantly influences the establishment of technological dominance and the forming of technological trajectories, which impacts the performance of an innovation system.

2.2.2 Functional analysis

Having addressed the structural components, the second major part of the TIS framework is about analyzing seven key functions, to determine the extent to which the functions are currently filled in that TIS (Bergek et al, 2008). A well-performing system should ideally have all functions fulfilled at a satisfactory level. However, this could provide a challenge for analysts, since there is no exact way to appraise satisfactory performance. How the performance of each function is appraised is presented later in the method chapter.

The key functions are: (1) *knowledge development and diffusion,* (2) *influence on the direction of search,* (3) *entrepreneurial experimentation,* (4) *market formation,* (5) *legitimation,* (6) *resource mobilization, and* (7) *development of positive externalities*. The identification of functions complements the structural analysis, since it emphasizes what the system does and how it works in comparison to how it is composed or structured (Bergek et al., 2005). However, structure and function are two intertwined sides of the same object; the system, since functions influence the system structure and vice versa (Markard & Truffer, 2008). Even though structure and functions are intertwined in a system, functions are still an important indicator of system performance (Markard & Truffer, 2008), and therefore important to analyze separately.

Knowledge development and diffusion

Knowledge development is essential for the development of new technologies, and involves learning activities, which range from basic science to learning by practicing (Suurs, 2009). Hekkert et al. (2007) distinguishes these activities as “learning-by-searching” and “learning-by-doing”. Suurs (2009) argues that universities and research institutes have the main responsibility for knowledge development, but that other actors often contribute with “learning-by-doing”. Furthermore, there are different types of knowledge, such as scientific, technological, production, market, and design – which all could take various forms; e.g. R&D, learning from new applications, production, and imitation (Bergek et al., 2008a). While knowledge development is a central function in a TIS, its tendency to create variety causes uncertainty in the system, which is mitigated by the two other functions of *influence on the direction of search* and *entrepreneurial experimentation* (Suurs, 2009).

Knowledge diffusion is closely related to networks, considering the exchange of knowledge between the actors in a network (Suurs, 2009). Usually, knowledge diffusion occurs in partnerships between actors and in meetings like seminars and conferences. While there is a tendency that actors within a certain community shares more knowledge than actors from different communities, it is nevertheless crucial that there is knowledge diffusion between actor groups for the development of a TIS (Suurs, 2009). Technology developers, for example, need to provide policymakers with information to allow them to establish suitable policies. It is therefore important that knowledge is shared widely between actors in a TIS.

The *knowledge development and diffusion* function is commonly mapped through R&D projects (quantity and size of investments), number of patents, learning curves (Bergek et al., 2008a; Hekkert et al., 2007), bibliometrics, professors, and assessments by managers (Bergek et al., 2008a).

Influence on the direction of search

Influence on the direction of search, also called guidance of the search by Hekkert et al. (2008) and Suurs (2009), refers to the incentives actors have to enter a TIS and also to the factors that influence the direction of search within a TIS (Bergek, 2008). Hekkert et al. (2008) relates the latter to the fact that resources are always limited and that a selection has to be done to allow a sufficient amount of resources to each option. This also explains how this function reduces the uncertainty created in the *knowledge development and diffusion* function which was described above. However, Suurs (2009) points out that there is a fine balance between creating and reducing variety, because too much focus could lead to a lack of variety. The author further concludes that the selection in this function is important to create a clear sense of direction regarding the technology. Otherwise, efforts within the functions *knowledge development and diffusion* and *entrepreneurial experimentation* are unlikely to yield meaningful results. Since *influence on the direction of search* also involves incentives that actors have to join a TIS, the function is also important in attracting new entries to the TIS (Suurs, 2009).

Influence on the direction of search function is commonly influenced through an interactive process where actors share ideas and knowledge about the technology (Hekkert et al., 2007). This forms visions and expectations that steer the direction of the innovation system. In case an actor shows success within some specific area, this often has a large impact on the direction of search (Hekkert et al., 2007).

The influence on the direction of search function is often indicated by expectations on growth potential (Bergek et al., 2008a; Hekkert et al., 2007), economic incentives (e.g. taxes, subsidies etc.), regulatory pressures, interest from leading customers (Bergek et al., 2008a) and targets set by governments and industries (Hekkert et al., 2007).

Entrepreneurial experimentation

Entrepreneurial experimentation involves testing of new technologies and applications (Bergek et al., 2008a). Entrepreneurs have a central role in the development of a TIS and are responsible for transforming the potential of new knowledge, networks and markets into practical actions that create new business opportunities (Hekkert et al., 2007). Since experimenting is a way to learn more about how technologies are functioning under different circumstances, it creates a learning process that reduces the uncertainty within a TIS (Hekkert et al., 2007). The development of emerging technologies is often unpredictable because they are not aligned with the existing structural components. However, through continuous experimentation and adaptation, these technologies could gradually be adjusted to fit its structural environment, and the structural components can be shaped to better support the emerging technologies (Suurs, 2009).

An entrepreneur can be either a new entrant contributing to the formation of a new market, or an incumbent company diversifying its current business to influence and capitalize on new developments (Hekkert et al., 2007; Suurs, 2009). When analyzing this function, it is therefore important to map the number of new entrants and diversifying incumbent companies (Bergek et al., 2008a; Hekkert et al., 2007), the number of different types of applications, the breadth of technologies used (Bergek et al., 2008a), the number of diversification activities of incumbent actors, and the number of experiments with the new technology (Hekkert et al., 2007).

Market formation

For an emerging TIS, a market may be very limited or not exist at all (Bergek et al., 2008a). The authors describe that market formation goes through three phases, including “nursing market, bridging market, and mature market”, and it is important to understand in which phase the specific TIS is in to give a fair assessment of the function. A nursing market indicates that a TIS is in a formative phase, while a bridging market indicates that a TIS is in a growth phase (Bergek et al., 2008b).

Furthermore, it is often difficult for new technologies to compete with existing ones, due to their weaknesses (Hekkert et al., 2007), such as for example price/performance gap to incumbent technologies (Jacobsson & Johnson, 2000). This will lead to that diffusion will be slow and the new technologies will require some sort of support. The *market formation* function therefore involves activities that contribute to the creation of demand for an emerging technology, including for instance financial support or higher taxes on existing technologies (Hekkert et al., 2007; Suurs, 2009). Hekkert et al. (2007) also argue that forming temporary niche markets for specific applications is a possible solution to the challenges that new technologies are facing, since actors could learn more about the technology and form expectations on the technology.

To analyze the *market formation*, it is important to identify the market development and what drives the market formation (Bergek et al., 2008a). To accomplish this, the analyst could map what phase the market is in (i.e. nursing, bridging, or mature), market size, customer behaviors, institutional stimuli for market formation (Bergek et al., 2008a), number of niche markets, tax regimes and environmental standards for new technologies (Hekkert et al., 2007).

Legitimation

Legitimation describes the social and industrial acceptance for the underlying technology. In order for a TIS to perform optimally, the underlying technology needs to be considered appropriate and desirable by a majority of actors (Bergek et al., 2008a; Hekkert et al., 2007). This legitimation is essential for demand to form, for mobilization of resources to occur, and for political strength to form in the TIS

(Bergek et al, 2008). In addition, *legitimation* also affects managers expectations and hence the *influence on the direction of search* function.

This function can be analyzed by mapping interest groups and their efforts to influence policy and decision-makers (Hekkert et al., 2007), stakeholders' social acceptance and activities within the TIS that could increase the legitimacy (Bergek et al., 2008a). This will increase the understanding of the relative strength of the legitimacy, what influences the legitimacy and how it influences the market and legislation (Bergek et al., 2008a).

Resource mobilization

Resource mobilization emphasizes the necessity for different kinds of resources to be allocated for the successful development of a TIS. The different kinds of resources are: (1) human capital (e.g. technical competence and managerial competence), (2) financial capital, and (3) complementary assets (e.g. complementary products, services, and network infrastructure) (Bergek et al., 2008a).

This function can according to Bergek et al. (2008a) be analyzed by "identifying rising volume of capital, increasing volume of seed and venture capital, changing volume and quality of human resources, changes in complementary assets". However, Hekkert et al. (2007) argue that it is difficult to map this function by specific indicators and instead propose that the best way is to through interviews ask actors if they perceive access to the resources as problematic or not.

Development of positive externalities

Development of positive externalities acts as a reinforcement mechanism of the other six functions rather than as an independent function (Bergek et al., 2008a). According to Suurs (2009), the positive feedback loops, resulting from interaction between functions, are crucial in the development of a TIS. For example, as more and more actors enter the TIS, *legitimation* may strengthen, which in turn creates a virtuous circle where the functions *resource mobilization*, *influence on the direction of search*, *market formation*, and *entrepreneurial experimentation*, continuously strengthens. In addition to more actors entering the TIS, *development of positive externalities* could be strengthened by mechanisms such as resolution of uncertainties, combinatorial opportunities, pooled labor markets, specialized intermediates, and knowledge spillovers (Bergek et al., 2008a).

2.2.3 Inducement and blocking mechanisms

A TIS in an early phase usually shows weak functional dynamics and develops slowly, since the environment tend to favor established TISs (Bergek et al., 2008a). The reasons for this partially derive from the underdeveloped structural components, but also from the larger context that surrounds the TIS (Bergek et al., 2008a). Hence, the third major part of the TIS framework is to identify mechanisms that either promote or inhibit the development of the functions in a TIS (Bergek et al., 2008a; Johnson & Jacobsson, 2001). These mechanisms are referred to as inducement and blocking mechanisms.

Previous studies by Johnson and Jacobsson (2001) show that most inducement mechanisms within the renewable energy technologies field derive from governmental policies. For example, these include funding programs, investment subsidies, and policies aimed at stimulating market formation by changing relative prices. In addition, the authors also highlight general environmental concern as a factor that stimulates the market formation of renewable technologies. Jacobsson and Johnson (2000) argue that the inducement mechanisms need to be strong enough to overcome the weaknesses of a new technology.

Moreover, Johnson and Jacobsson (2001) discuss several blocking mechanisms within the same field. The first blocking mechanism is related to the weak price/performance ratio that new technologies have compared to incumbent technologies. Incumbent technologies typically benefit from economies of scale making them more cost-effective. Secondly, the weak and underdeveloped relationships between actors within a new TIS create another blocking mechanism. This mechanism results in slow knowledge development and diffusion and affects the influence on the direction of search negatively (Johnson & Jacobsson, 2001). A lack of communication between actor groups also implies uncertainty regarding the demand, which in turn inhibits the market formation. Furthermore, governments commonly lack a clear vision with long-term goals regarding sustainable technologies, creating a third blocking mechanism. Other identified blocking mechanisms include lock-in to incumbent technologies, customers lack knowledge to invest in the technology and articulate demand and firms' limited influence on policy-making (Johnson & Jacobsson, 2001).

2.3 Critique

Authors such as Coenen et al. (2012) address the issue of focusing too much on the functional domain, which they critique Bergek (2008a) for doing. Their argument is that every TIS is unique spatially and that too much focus on the functional domain leads to overgeneralization. In other words, just because a system performs well in one economic geography does not mean that the same functions will perform as well in other economic geographies. The economic geography does not only emphasize the physical geography, i.e. that actors are close in proximity to each other, but also include the non-physical connections, e.g. how the actors cooperate and communicate with each other. This argument emphasizes the importance of thoroughly mapping and analyzing the structural components, since it creates a better understanding of the TIS and results in more meaningful findings. Bergek et al. (2015) responded to the critique from Coenen et al. (2012) by complementing their previous framework with four additional structural considerations: (1) interaction between a focal TIS and other TISs, (2) interaction between a focal TIS and relevant sectors, (3) TIS development in geographical context structures, and (4) interaction between a focal TIS and the political context. Another criticism that has been put forward by Wieczorek & Hekkert (2012) is that infrastructure is a critical aspect of many TISs, but it is not included in the Bergek et al. (2008a) framework. These criticisms are incorporated into the method that is used to analyze MSHV, which is described in the next chapter.

3. Method

This thesis employs a qualitative research strategy. As described by Bell et al. (2019), qualitative research is concerned with words rather than numbers and a constructionist ontological position, meaning that reality is based on the subjective interpretation made by individuals rather than there being a truth “out-there” in a fixed state. This is a favorable strategy when applied to social sciences (as opposed to natural sciences), since answers are often ambiguous and situational (Franzosi, 1997), and therefore hard to quantify. The data gathered in the study of hydrogen valleys are of an ambiguous and non-quantifiable nature, e.g. due to the novelty and explorative character of a hydrogen valley, which therefore requires a qualitative research strategy.

Furthermore, our research applies an abductive approach, which can have the advantages of both deductive and inductive approaches while simultaneously overcoming the weaknesses associated with the respective approach (Bell et al., 2019). Our research has deductive components, since preconceived theories, such as the framework outlined by Bergek et al. (2008a), are used in a relatively sequential and linear way. However, we have remained open about revising theory, scope, and research questions as the research process unfolded, which in contrast indicate an inductive approach. Therefore, the research approach could be described as abductive, which is a favorable approach in this case because of two main reasons: firstly, the existing framework developed by Bergek et al. (2008a) provides a good basis for analyzing the dynamics of a hydrogen valley, and secondly, new insights from the data collection could simultaneously be used to make alterations to the framework and to realign the research objectives to yield more fruitful findings.

The research design is a case study, meaning that one specific organization, institution, location, person, or event is analyzed in depth, which therefore provides detailed and exact findings about that particular case (Flick, 2014). The case that is investigated is MSHV. One of the main disadvantages of the research design is that generalizability could be difficult when only focusing on a single case (Bell et al., 2019), which could make further theory-building problematic. However, rather than pursuing a sample-to-population logic, case studies have been shown to provide analytical generalizability, where findings can apply between cases of different natures (Yin, 2013). In addition, we have addressed the disadvantage of case studies in two ways: firstly, by approaching the research with caution, acknowledging the limitations inherent in the case study approach, and secondly, by avoiding overgeneralization – rather than asserting universal truths, articulating that findings are *likely* applicable to other cases.

An overview of the research methodology can be seen in *Figure 2* below. The arrow pointing backwards highlights that minor aspects of the study have been revised and iterated as the process unfolded. In the sections that follow, each step of the methodological process as outlined in Figure 2 is presented.

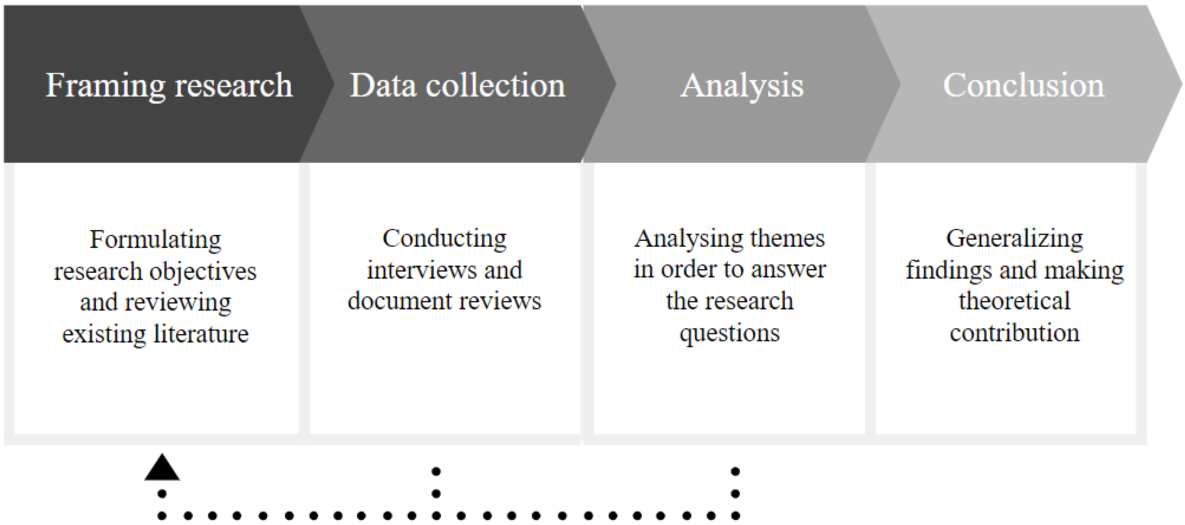

Figure 2. Overall research methodology. The dotted lines showcase the abductive approach.

3.1 Framing research

The first step of the research process was to frame the research, which was done by formulating research objectives and reviewing the existing literature. The research objectives were primarily based on an exploratory background search, which included both internal documents and internet searches. The preliminary research objectives were then formulated – including a preliminary description of aim, limitations, and research questions, and later revised several times as the writing process unfolded.

After the research had been framed, the next step was to review the literature. The literature review was conducted for three main reasons: (1) to get acquainted with the subject and learn about relevant theories, (2) to narrow the research scope in order to fit with existing theories, and (3) to provide a guideline for the analysis. The different theoretical fields that were investigated are presented in *Table 1* below. As showcased, the literature search started off much wider, encompassing different theoretical fields, e.g. innovation hubs, technological transformations, energy business models, but ultimately narrowed down to the TIS literature as the primary literature source.

Search terms	Titles read	Abstracts read	Articles skimmed	Articles read thoroughly
Hydrogen valley	30	9	9	6
Innovation hub, industrial clusters	220	20	20	3
Hydrogen value chains	65	7	3	2
Technological transformations	145	12	9	1
Energy business models	200	34	19	9
Technological innovation systems	45	24	20	14

Table 1. Articles in the literature search.

3.2 Data collection

The second step in the process was the data collection. Interviews were the main method for gathering data, which was complemented with secondary data collection. Since this thesis applies a qualitative research strategy, the data collection did not include many of the quantitative measurements suggested by Bergek et al. (2008a) and Hekkert et al. (2007). Another reason for not including quantitative measurements, such as number of patents when analyzing *knowledge development and diffusion*, is that we study a regional TIS in a formative phase where this type of data is limited or restricted, making it difficult to analyze.

3.2.1 Interviews

The primary method for gathering data has been through interviews with different actors and stakeholders in MSHV. The main reason for using interviews as the primary data collection method was that nearly all actors within the TIS could be interviewed, which could lead to comprehensive and relatively exhaustive results. Interviews in qualitative research are generally open to allow for flexibility (Bell et al., 2019), and since our research questions are of a qualitative nature, this openness has been employed in the interviews. More specifically, the interviews have been semi-structured, where topics or questions were prepared in advance, but where the interviewee had great flexibility in how they replied. Since our research is of exploratory character, semi-structured interviewing allowed the actors to give more nuanced answers that would otherwise not have been possible in a stricter interview format. In addition, this allowed us to ask follow-up questions based on the interviewees' replies if we needed clarification or found a new and interesting perspective to pursue. In turn, this allowed for a deeper analysis and better preparedness to answer the research questions.

To gain answers from different perspectives, interviewees were chosen from different actors along the value chain in MSHV. In order to increase the reliability of the answers, at least 2 interviews were conducted within each actor group in the value chain (including renewable energy providers, hydrogen producers, storage/distribution providers, hydrogen users, grant providers, incubators and research institutes, authorities, and OEMs). See *Table 2* for an overview of all the interviews (without a mapping of the actor groups – this is done in the analysis chapter). The sampling method used was purposive sampling, as described by (Bell et al., 2019), since the interviewees were chosen strategically to improve variety and quality of the answers. The interview questions were centered around the research questions and the TIS framework, i.e. by asking about the actors, networks, institutions, functional dynamics, and the challenges and opportunities in the hydrogen valley. An online video format was used in the interviews, since it is more flexible and less time- and cost-intensive compared to face-to-face interviews, especially given the geographical distances involved. Video interviewing also creates a similar interactional experience as face-to-face interviewing (Bell et al., 2019). The interview participants were predominantly senior executives or other employees with particular insight of the organization's sustainability strategy.

Organizations interviewed	
Alleima	Nitiu
Region Gävleborg (MSHV coordinator)	Nordion Energi
University of Luleå (Researcher)	Ovako
Dalavind	Plagazi
Energimyndigheten	Powercell
Green Iron	Skyborn Renewables
Gävle Harbor	Volvo Group
Hydri	Sandbacka Science Park
Klimatklivet	Sandvik
Länsstyrelsen	Statkraft
MaserFrakt	
Total interviews: 21	**Average length: 48 min**

Table 2. Interviews

The interview structure was set by an interview guide, which Bell et al. (2019) describes as a set of memory prompts that the interviewer can use to remember all areas that should be covered during the interview. We did not follow the interview guide strictly – instead, we allowed for flexibility in the interview process, e.g. by asking follow-up questions and investigating inconsistencies in the answers to find important nuances.

Since interviews are the main data collection method for this thesis, a thorough approach to interviewing was adopted. The process of transcription was used, since it can counteract the limitations of memory and biases, as well as allow for repeated examinations of the interviewees' answers (Bell et al., 2019). To aid in this process, interview sessions were recorded and inputted into transcription tools. Naturally, a prerequisite for this step is that the interviewees gave consent to being recorded. In addition to transcription, note-taking of key points was adopted during the interviews. As a last step in the interview process, segments in the analysis, which included specific information about the interviewee or the organization, were sent out after it was written for two distinct purposes: (1) to allow the interviewee to comment on the accuracy of the segment and give suggestions, and (2) to ask the interviewee of permission to include it in the report by not accidentally publishing sensitive or confidential information.

3.2.2 Secondary data collection

According to Bell et al. (2019), documents are often used as a supplementary data collection method to semi-structured interviews in a case study, since it can highlight important past managerial decisions and actions. The type of documents that was used are for example reports from different agencies, companies, or stakeholders in MSHV. Different news articles were also used from reputable sources. According to Bell et al (2019), it is important to consider that documents are written with a distinctive purpose in mind which does not always reflect reality. Therefore, to assess the quality of documents used in this research, four criteria have to be fulfilled, as suggested by Bell et al (2019): (1) authenticity, (2) credibility, (3) representativeness, and (4) meaning. Hence, the secondary data sources that were used were qualitatively evaluated based on these four criteria. The main purpose of the secondary data collection was to verify important factual information from the interviews and also to explore certain topics more in depth that were brought up in the interviews.

3.3 Analysis

An important question to answer is when to stop collecting more data and instead focus on theory building and drawing conclusions from the data. According to Bell et al. (2019), there comes a point in the data collection process where new data are no longer illuminating the themes further. This concept is called theoretical saturation, which was used to determine the point in time when further data collection was no longer beneficial. When theoretical saturation was reached, the first step was to do a thematic analysis of the data, by grouping the data into themes. Secondly, theory found in the literature search, e.g. from Bergek et al. (2008a), was used to analyze the themes. The analysis process, including the thematic analysis and the analysis based on the TIS theory, are described below.

3.3.1 Thematic analysis

For the analysis of the data, a thematic analysis was used. Bell et al. (2019) describes thematic analysis as one of the most common forms of qualitative data analysis, which is used to group data into themes before analyzing it further. When looking for themes, it is important to look for repetitions of topics, specific typologies, or similarities and differences between topics (Bell et al., 2019). Themes were found throughout the whole data collection process, and the themes centered around our research questions and the TIS framework, see *Figure 3*.

Figure 3. Themes in the thematic analysis

3.3.2 Steps in the analysis of technological innovation systems

Bergek et al. (2008a) presents a framework including six sequential steps that should be taken when analyzing a TIS. These include: (1) defining the TIS, (2) identifying structural components, (3) mapping the functional patterns of the TIS, (4) assessing the functionality of the TIS and setting process goals, (5) identifying inducement and blocking mechanisms, and (6) specifying key policy issues. The steps will be described in more detail below.

The first step is about deciding the scope of the TIS. Bergek et al. (2008a) mention three choices in this step: (1) the choice between knowledge field or product as a focusing device, (2) the choice between breadth and depth, and (3) the choice of the spatial domain. Depending on the research questions – focusing on the product (e.g. a hydrogen fueling station) or on an entire knowledge field (e.g. hydrogen as a technology) is the first choice. The second choice refers to the degree of specificity, i.e. if the analysis focuses on one application and studies it in depth – or if a wide range of applications are studied. The last choice of the spatial domain refers to whether the study is limited to a geographical area such as a hydrogen valley or if it takes a global perspective. These three choices have implicitly been presented in the background, which could be presented explicitly as (1) low-carbon hydrogen as a knowledge field – as the case study covers many use cases of hydrogen and not just a specific product, (2) a broad focus made on a system level, and (3) the spatial domain being MSHV – a regional hydrogen valley in mid-Sweden.

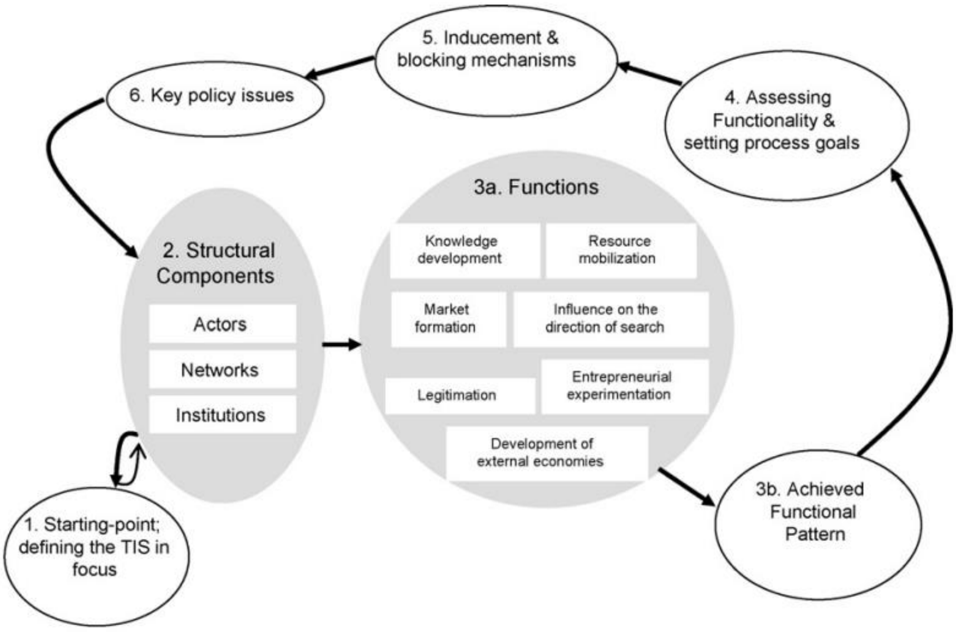

Figure 4. The six steps in the analysis of a TIS. From Bergek et al. (2008a).

The second step is about mapping the actors, networks, and institutions of the TIS (Bergek et al., 2008a). The mapping could for example be done through industry associations (e.g. through company documents) and interviews with experts. If the TIS is in an early formation phase like MSHV, structural components may be weak and hard to identify (Bergek et al., 2008a). According to the authors, this requires an iterative process where additional pieces of information are added as the analysis proceeds, e.g. by adding some informal networks that are often hard to identify initially, later in the analysis process. This step, together with all remaining steps, are based on the data collection, and presented in the analysis chapter.

The third step is used to understand how the TIS works rather than how it is structured, by analyzing a set of processes, which Bergek et al. (2008a) label as functions, that are important in the development of the TIS. The functions have been described in the theory chapter earlier. The purpose of this step is twofold; one part being the outlining of the functions and the second part being the appraisal of each function's strengths and weaknesses (as highlighted as 3a and 3b in *Figure 4*). The outlining is presented through a general description of what affects the function in the TIS, while the appraisal of strengths and weaknesses places more weight on how the findings affect the development of the TIS, i.e. in a positive or negative way.

The fourth step in the analysis is about assessing the functionality of the TIS and setting process goals, i.e. assessing the performance of the TIS based on the result of the functional analysis. However, this can prove problematic, since it is difficult to objectively assess the “goodness” of a particular function (Bergek et al., 2008a). Although the analysis of the functions in the previous step is important, it is not sufficient to determine if the TIS is well performing or not, since a function that is weak does not necessarily constitute a problem, and a function that is strong is not always an important asset. Bergek et al. (2008a) describe two ways of assessing the performance: (1) by identifying the phase of development of the TIS and (2) through comparisons between TISs. Depending on which phase of development the TIS is in (i.e. formative or growth phase), functions will need to be evaluated differently. For example, a common mistake is that a TIS within the formative phase will be evaluated based on criterias which are more suitable for a TIS in a growth phase (Bergek et al., 2008a). If a TIS in a formative phase is analyzed without considering that this phase is characterized by small volumes and slow diffusion, the TIS could inappropriately be identified as a failure even though the TIS may be very effective in reality. The analyst has to assess the functions based on the appropriateness of that function's performance in that particular phase. The formative phase is characterized by Bergek at al. (2008a) by the following:

- the time dimension, where formative periods often extend beyond a decade;
- large uncertainties in technologies, markets and applications;
- price/performance of the products being underdeveloped;
- a volume of diffusion and economic activities that is but a fraction of the estimated potential;
- absence of powerful self-reinforcing features (positive feedbacks) and weak positive externalities.

The second way to assess the functionality of the TIS and set performance goals could be made by comparing different TISs. These TISs should be similar or related to the focal TIS, and their performance should be evaluated to gauge what performance is reasonable for the focal TIS (Bergek et al., 2008a). Bergek et al. (2008a) suggest using phase analysis and comparative analysis in combination to reach a conclusion about the performance of the TIS and to set new functional goals. New functional goals may be to broaden the knowledge base or widen the range of experiments (if the functions *knowledge development and diffusion* and *entrepreneurial experimentation* are identified as weaknesses). It is important that the functional goals are not expressed as final goals – e.g. that a TIS in a formative phase should achieve higher growth – since this is not an indicator of functionally poor performance.

While these two ways showcase how the performance of the TIS could be evaluated, it is important to note that this evaluation is inherently qualitative and subjective. There are currently no "objective" ways to measure performance to our knowledge, nor are there any indications of this in the TIS literature. This is a significant limitation of the TIS framework. However, by using both these ways, together with the isolated analysis of the function, a relatively comprehensive overview could be given, which should give a very adequate appraisal of the function's performance.

The evaluation of the functions is assessed on a three-point ordinal scale, including weak, intermediate and strong (as done by previous TIS analyses). When there are clear arguments indicating that a function is performing poorly with respect to the TISs stage of development, the function is graded weak. Similarly, a function that has clear arguments showing good performance is graded strong. In case the arguments are ambiguous, and the function cannot be graded either weak or strong, the function is graded intermediate. Moreover, it is important to note that the actual grade a function is given is based on a holistic perspective, which implies that a function that is for example graded weak, could still have some strong components and vice versa.

Step five relates to finding key inducement mechanisms (opportunities) and blocking mechanisms (challenges) for the TIS. These can be both internal (i.e. related to the functions of the TIS) or external (i.e. not directly related to the TIS). An example of an external mechanism is global warming, which could constitute either as an inducement mechanism or as a blocking mechanism, depending on the TIS. The internal mechanisms are related to the functional analysis of the TIS (step 3).

Lastly, **the sixth step** of the TIS analysis is about specifying key policy issues based on the previous five steps. Policy should ideally be aimed at improving TIS performance by (1) strengthening/adding inducement mechanisms and (2) weakening/removing blocking mechanisms (Bergek et al., 2008a). In *Figure 5* below, an example of the result from the analysis in step 1-6 is presented for the case “IT in home care” (made by Bergek et al., 2008a).

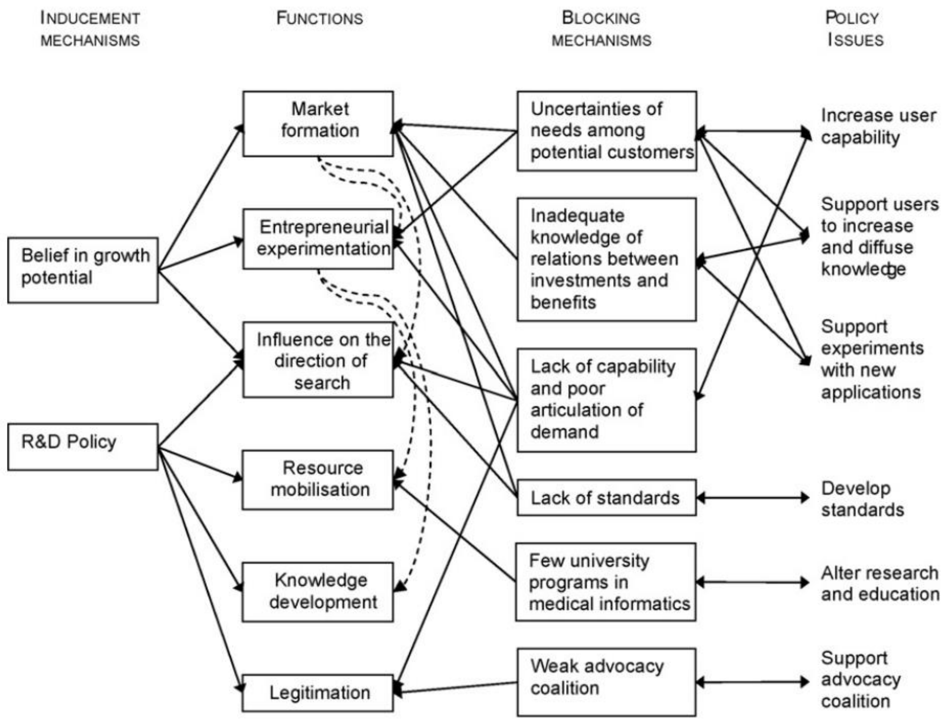

Figure 5. Example of findings from the TIS analysis. Results from step 1-6 within the case "IT in home care", made by Bergek et al. (2008a). The function of positive externalities is indicated by the dotted lines between the other functions.

3.3.3 Our analytical framework

The steps presented in the previous section is the core analysis, which is applied to the case of Mid Sweden Hydrogen Valley. However, some deviations from the steps presented in Bergek et al.'s (2008a) framework are made with the purpose of better answering the research questions. One of these deviations is in the second step when mapping the structure: we complement the Bergek et al. (2008a) framework by adding infrastructure as a fourth component, as suggested by Wieczorek & Hekkert (2012). However, we only choose to include the physical infrastructure, since financial and knowledge infrastructure are included in the other functions by Bergek et al. (2008a). We also complement the framework by including four additional structural considerations: (1) interaction between a focal TIS and other TISs, (2) interaction between a focal TIS and relevant sectors, (3) TIS development in geographical context structures, and (4) interaction between a focal TIS and the political context, in an attempt to make the findings more generalizable to other TISs, as suggested by Bergek et al. (2015). Additionally, since the blocking and inducement mechanisms for the TIS are both internal and external in nature, these findings are just as fruitful for managers operating within the TIS as it is for policymakers – thus justifying managerial implications of these findings as well. The analytical framework, including notable deviations from the steps proposed by Bergek et al. (2008a), are presented in the *Table 3* below.

Research questions	Theoretical frameworks (main framework – Bergek et al., 2008a)
RQ1: What are the structural components, i.e. actors, networks, institutions and infrastructure, in a hydrogen valley and how are they interconnected?	**Step 1:** Defining the TIS **Step 2:** Structural analysis Adding **infrastructure** as a fourth structural component (as suggested by Wieczorek & Hekkert, 2012) Adding four additional **structural considerations**: (1) interaction between a focal TIS and other TISs, (2) interaction between a focal TIS and relevant sectors, (3) TIS development in geographical context structures, and (4) interaction between a focal TIS and the political context (as suggested by Bergek et al., 2015)
RQ2: How do the functional dynamics affect the development and performance of a hydrogen valley?	**Step 3:** Functional analysis **Step 4:** Assessing the performance of the TIS
RQ3: Which inducement and blocking mechanisms are present in a hydrogen valley, and how do they impact the valley's development?	**Step 5:** Blocking mechanisms – both from internal analysis (expand from structural and functional) and external analysis. **Step 6:** Implications for policymakers Adding **managerial implications**.

Table 3. Analytical framework

3.4 Reflection on validity

The term validity refers to the trustworthiness of the conclusions drawn in the study, or in other words, if the study accurately measures what it claims to measure (Bell et al., 2019). Using an empirically validated and systematic approach, such as the TIS framework, should improve the validity of the study. However, some of the inherent limitations of the TIS framework is that the analytical steps are evaluated subjectively, meaning that the analysis can be influenced by biases and misconceptions, which risks decreasing the validity of the study. However, we have attempted to minimize this limitation in three main ways: (1) by relying on a robust foundation of interview data and reliable secondary sources for analysis (2) by being critical towards the interview data – realizing that the interviewees can themselves have biases and misconceptions, and (3) by double checking important or speculative information. It is also important to mention that the study was not conducted *for* MSHV, but rather for an independent company (CIT Renergy), thus minimizing potential conflicts of interest.

4. Analysis

The analysis is presented in four sections: (1) structural mapping, (2) functional analysis and performance appraisal, (3) inducement and blocking mechanisms, and (4) implications for policymakers and managers.

4.1 Structural mapping

The structural mapping includes a description of the actors, networks, institutions, and infrastructure that are either within MSHV or that have a close connection to it. The purpose of the structural mapping is twofold. Firstly, it can lead to interesting insights regarding the connections within MSHV. Secondly, it serves as a basis for the functional analysis by providing the characteristics of the hydrogen valley, which in some cases could explain why the functions perform the way they do.

In order to present the structural mapping in a coherent and clear way, the actors have been categorized into different actor groups. The overall connections between the actor groups are illustrated in the hydrogen value chain seen below in *Figure 6*. The figure includes the main hydrogen value chain, and also facilitators and producers of equipment as two supporting parts. Based on the interviews and previous studies that define hydrogen value chains (e.g. Masip et al., 2021), the main hydrogen value chain moves from energy provision, to hydrogen production, to storage and distribution, and finally to the end users. There is a logical flow of energy throughout the whole value chain, but it is important to notice the energy shift from electricity to hydrogen between energy provision and hydrogen production. The facilitators include grant providers, incubators and research institutes, and authorities. These play an important role in supporting the hydrogen value chains through financial capital, R&D and legal support, especially in this early stage where the market is still underdeveloped. The producers of equipment are another crucial set of actors that are enabling the creation of a hydrogen value chain, by for example manufacturing production equipment and fuel cells that are used in the main hydrogen value chain. However, it is important to note that neither the facilitators nor the producers of equipment are directly linked to the energy/hydrogen flow between the actor groups in the value chain, and therefore are illustrated outside of the main value chain.

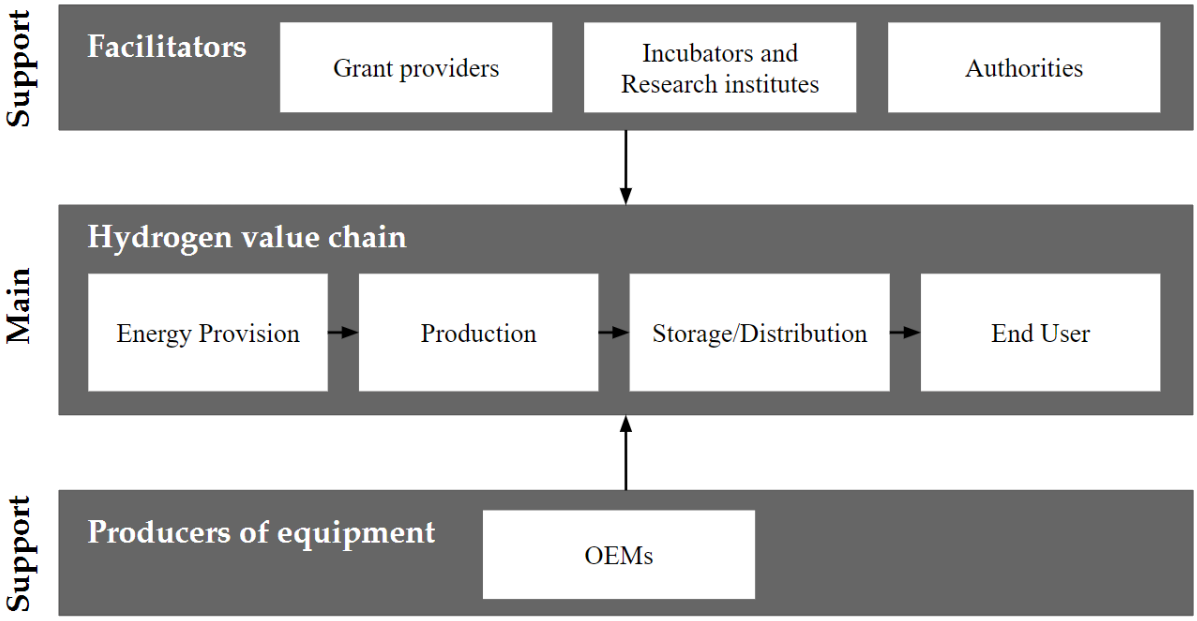

Figure 6. Hydrogen value chain

4.1.1 Actors

In this section, a mapping of the actors is presented, including each actor's connection to MSHV. The actors consist of members of MSHV and other influential entities contributing to the development of MSHV. They are classified into actor groups corresponding to the different stages of the hydrogen value chain (*Table 4*). Note that certain actors might fit into more than one actor group, depending on their involvement across various parts of the value chain.

Actor groups	Actors interviewed	Actors not interviewed
Renewable energy providers	*Skyborn Renewables, Dalavind, Statkraft*	*Svea Vind Offshore, Vattenfall*
Hydrogen producers	*Ovako, Plagazi, Statkraft*	*Linde Gas*
Storage/Distribution	*Nordion Energi, Hydri, Nitiu*	*Inlandsbanan, Hynion*
Hydrogen users	*Ovako. Alleima, Sandvik, MaserFrakt, Green Iron*	*Outokumpu, Inlandsbanan*
Grant providers	*Energimyndigheten, Naturvårdsverket*	*Tillväxtverket*
Incubators and Research institutes	*Sandbacka Science Park,* Hydrogen researcher at *Luleå University, Gävle Harbor*	*Dalarna Science Park, RISE, Mellansvenska Handelskammaren, Gävle University*
Authorities	*Region Gävleborg* (MSHV coordinator), *Länsstyrelsen*	*Region Dalarna*, Other policymakers from the Swedish government or local municipalities
OEMs	*Volvo, Powercell, Nitiu*	*Cellcentric*

Table 4. Identified actors in MSHV and actors that affect the development of MSHV, classified into actor groups. Some actors are present in more than one group.

Renewable energy providers deliver the electricity that is needed in the production of low-carbon hydrogen. *Skyborn Renewables* is an offshore wind-farm establisher that recognizes hydrogen as a value-adding commodity to their wind turbine farms, ensuring revenues even during periods with very low electricity prices. *Dalavind* is another renewable energy producer based in Dalarna that is building wind farms, who have recognized an opportunity to create industrial parks for hydrogen production. However, this requires partnering up with hydrogen producers – something that both *Skyborn Renewables* and *Dalavind* sees as an attractive possibility in the future. *Statkraft* is another renewable energy provider, who focus primarily on hydropower, but who aims to produce hydrogen by establishing their own electrolyzers (currently waiting for permit processes). Another use-case that was mentioned in the interviews was that renewable energy providers also could use hydrogen as an energy buffer, e.g. by converting electricity to hydrogen when there is overproduction and converting it back to electricity when there is shortage.

Hydrogen producers use different methods for hydrogen production, with water electrolysis being the most common. Actors within MSHV that currently use water electrolysis are *Ovako* and *Linde Gas*. *Ovako* inaugurated their facility in Hofors in September 2023 and is the first company in the world to use low-carbon hydrogen for heating steel. Currently, the hydrogen produced is only used in their own processes, but they have the capacity to produce more hydrogen that could be sold to other users. *Ovako* also has other sites in the region that could be converted to hydrogen production sites. For example, the company is planning to build another electrolyzer in Smedjebacken. *Statkraft* is another actor who is currently looking to expand into hydrogen production through water electrolysis, even though their current operation is primarily focused on hydropower. Although *Statkraft* are formal members of MSHV, they have no current hydrogen project within MSHV. However, they do have a smaller electrolyzer project in Gothenburg, where they aim to gain knowledge about hydrogen production to produce it more broadly in the future.

Even though water electrolysis is the most common method for producing low-carbon hydrogen, some actors have innovated alternative technologies to the electrolyzer, e.g. to circumvent the high electricity requirements of the electrolyzers. One of these actors is *Plagazi*, who has developed a process for producing hydrogen from waste material, which only uses one-fifth to one-eighth of the electricity compared to an electrolyzer. The interviewee from *Plagazi* claims that the process is also much cheaper than the electrolyzer and also produces heat as a byproduct – which could be sold to other actors. The drawback is that CO_2 is also a byproduct of the process, which means that CCS has to be used for the process to become low-carbon. There is currently no commercial scale hydrogen production based on this process, but a proof of concept has been demonstrated successfully. Even though the process is very novel, actors like *Alleima* – a steel manufacturer and hydrogen user, vouch for its legitimacy and see themselves becoming a possible buyer from them in the future.

Storage providers/distributors play a crucial role in driving the hydrogen economy forward by investing in infrastructure including pipelines, storage facilities, and carbon capture possibilities. One actor who is developing technologies for safe and effective storage of hydrogen is *Nitiu*. Since hydrogen is an explosive gas, safety is a high priority for all use-cases. Therefore, *Nitiu* has created an innovative storage solution with a durable structure, which they aim to sell to many actors in MSHV. *Nordion Energi* is an actor who is a transmission system operator (TSO) for the Swedish core grid for natural gas who now has the ambition to build the infrastructure that is required for the hydrogen economy. Today, *Nordion Energi* is engaged in two major hydrogen infrastructure projects, namely, Nordic Hydrogen Route and Baltic Hydrogen Collector. Both projects have received the labeled "projects of common interest" by the European Commission. Another actor is *Hydri*, who through strong financial support is building a national hydrogen fueling network (24 fueling stations finished by April 2025).

Furthermore, *Inlandsbanan* is a governmental owned actor who operates a 1000 km long railway that is planned to be used to transport hydrogen produced by *Plagazi*.

Hydrogen users are the actors who have an interest in buying and utilizing hydrogen, either in industrial processes, as fuel, or as energy storage. Hauliers are one actor type that could utilize hydrogen, since they consume high volumes of fuel on the road and need to find alternative fuels to reduce their climate footprint. *MaserFrakt* is a haulier that operates in the region who has established a hydrogen fueling station and bought their first truck fueled exclusively with hydrogen (MaserFrakt, n.d.). According to the interviewee from *MaserFrakt*, Hydrogen is one of three main alternatives in the change, besides liquefied biogas and battery electric. Moreover, steel producers could also be a major consumer in a hydrogen economy, since the fossil fuels currently used in their processes represents 10% of Sweden's total carbon dioxide emissions, which could be exchanged for hydrogen (Alpman, 2017). In an attempt to lower their substantial carbon footprint, steel producers are amongst the early adopters of hydrogen today. Besides being a hydrogen producer, *Ovako* has started to use hydrogen in its steel heating processes, where it replaces fossil fuels. *Alleima* is another steel producer who aims to be a significant user of hydrogen. They are currently using relatively small amounts of low-carbon hydrogen (135 tons/year) as a shielding gas in their processes, which are produced and transported (in pipelines) from *Linde Gas*. In the future, they aim to use considerably more hydrogen in their molding processes, where they currently use natural gas. Another actor in the region who aims to use low-carbon hydrogen from *Linde Gas* is *Green Iron*, which plans to use hydrogen in the production of their fossil-free sponge iron. Furthermore, *Sandvik* is another member of MSHV that is using hydrogen in their furnaces for heating and molding. Besides the mentioned hydrogen users, there exists other potential use-cases which no actor currently pursues, including glass production, fertilizer production, and electric grid services, which may become hydrogen users in the future.

Grant providers have the purpose of providing financing for investments for the green transition in Sweden, where hydrogen plays a central role. *Energimyndigheten* mainly finances projects within novel technologies that can reduce carbon dioxide emissions, where the risk for the investor is very high. The funding is provided through the initiative called Industriklivet, which is partly funded by the European Union. *Naturvårdsverket* sponsors other types of investments related to more proven and mature technologies, e.g. hydrogen fueling stations, pipelines and storage, through an initiative called Klimatklivet. Another grant provider is *Tillväxtverket*, which also provides financing for actors in MSHV.

Incubators and research institutes supports actors in the value chain by providing new knowledge and by creating networks between the actors. The interviewee from *Sandbacka Science Park* described that they aim to reduce uncertainty, connect actors with each other, and concretize ideas – where hydrogen is a field that they are currently exploring. Furthermore, *Gävle Harbor* is a logistical center that acts as a facilitator between actors by helping to initiate projects adjacent to the harbor. For this reason, the harbor could be labeled as an incubator in the value chain. Another interviewee, which is a hydrogen researcher at *University of Luleå*, has among other initiatives been a part of developing Sweden's national hydrogen strategy (currently not used) and is today responsible for CH2ESS – a hydrogen research network with over 100 researchers. Other incubators are *Dalarna Science Park*, *RISE*, *University of Gävle*, and *Mellansvenska Handelskammaren*, but they were not interviewed in this study.

Authorities have various tasks in driving the transition to a fossil-free society and act on a municipal, regional, or national level. Some public actors in the region, like *Region Gävleborg*, *Länsstyrelsen*, and *Region Dalarna* are directly engaged in MSHV with their geographical presence. A common role that these actors have is being facilitators and trying to bring actors together with the purpose of promoting the hydrogen development in the region. The coordinator of MSHV at *Region Gävleborg* is for example responsible for holding the conferences. Furthermore, *Länsstyrelsen* is working with regional strategies within energy and climate. Hydrogen does have very little presence in the current strategy but its role could possibly increase in the upcoming strategy. Regarding public actors on the national level, the Swedish government is the actor who decides the overarching hydrogen strategy, as well as establishes laws and regulations that have a large impact on MSHV.

OEMs are actors who are not directly involved in the hydrogen value chain, but who are nonetheless influencing the development of MSHV in significant ways. One OEM actor is *Powercell*, who play a central role within the transport industry, since they develop and produce fuel cells that are used in vehicles or for stationary applications. *Powercell* is a member of MSHV, and produces hydrogen fuel cells based on PEM (proton exchange membrane) technology. Additionally, besides selling their fuel cells, they also sell the services to help customers integrate their systems into their operations. Another OEM who can contribute greatly to the hydrogen development is *Volvo*, who aims to develop and produce trucks running on hydrogen – therefore providing hauliers the possibility to buy trucks that run on hydrogen. *Volvo* has invested heavily in developing their hydrogen trucks and related technologies, since they identify hydrogen fuel cells as a replacement for diesel engines, in addition to being a complement to electric engines. *Volvo* sees their future product portfolio as being a mix of hydrogen and electric vehicles, with different types of use-cases (e.g., hydrogen trucks being used for longer distances and where charging is inconvenient). In 2023, *Volvo* tested their first hydrogen trucks on public roads (Volvo Group, 2023).

4.1.2 Networks

A network is an interconnection between actors in the TIS. While the largest network in the region is the organized MSHV-platform, the interviews revealed several less organized networks between the actors (see *Table 5 or Appendix A for a visual illustration*). However, due to the sheer number of actors and possible network constellations, the identified networks are not exhaustive, but rather used to showcase the most important interconnections and collaborations in MSHV. In the following section the identified networks are presented.

Actor Groups	Network 1	Network 2	Network 3	Network 4	Network 5	Network 6	Network 7	Network 8
Renewable energy providers	MSHV		*Svea Vind Offshore*		*Skyborn Renewables*			
Hydrogen producers		*Ovako*					*Linde Gas/Plagazi*	*Ovako*
Storage/Distribution				*Nordion Energi*				
Hydrogen users		*Ovako*	*MaserFrakt*			*Green Iron, Alleima*	*Alleima*	*Volvo Group*
Grant providers		*Energimyn-digheten*						
Incubators and Research institutes			*Gävle Harbor*					
Authorities				*Muncipalities of Gotaland, Åland and Bornholm*				
OEMs		*Volvo Group*						*Volvo Group, Cellcentric*
Support outside MSHV		*Nel Hydrogen, H2 Green Steel, Hitachi Energy*		*Gasgrid Finland, OX2, Copenhagen Infrastructure Partners*	*Lhyfe, ABB*			*Daimler Trucks*

Table 5. Networks.

Network 1 - MSHV collaboration platform

The largest network in MSHV is the collaboration platform of the MSHV initiative itself, which includes over 30 different actors (Region Gävleborg, 2023). This network is facilitated mostly by inviting members to conferences and seminars, which are held one to two times per year. The get-togethers could have the following agenda: (1) an introduction by MSHV representatives from the regional authorities about news, trends and opportunities in the region, (2) presentation from selected actors who introduce their company and their existing projects related to hydrogen, (3) open discussions where a microphone is passed around, and (4) physical tours and showcases of different hydrogen projects.

The coordinator of MSHV explains that the purpose of the MSHV get-togethers is to provide a platform for discussion – to showcase collaboration possibilities amongst the members. The purpose is also to share risk among the members by, for instance, sharing investment costs, being transparent with supply and demand, and collectively applying for grants. The coordinator also mentioned that some actors are reluctant to share information about their innovation processes, and by having a platform that ensures mutual trust, more information can be shared between actors in the region. Since its inception in 2021, the MSHV collaboration platform has received great attention from actors, both in terms of new members joining and in participants on the get-togethers.

The majority of the interviewed actors had positive feedback about the get-togethers and felt that they were meaningful. Common examples that were brought up were good communication, solid coordination and leadership, and that a balanced mix of policymakers and representatives from industry were present. However, some actors expressed concern that the collaboration resulted in very few practical projects. For example, one actor expressed dissatisfaction that the get-togethers were merely talks with no action, and therefore a waste of time. This frustration was based on several experiences where the actor had approached other members and tried to enter into partnerships, but where the other actors had rejected the proposal. According to the rejected actor, other actors do not try hard enough, since they are reluctant to take financial risks. This resulted in the rejected actor having to enter into a sub-optimal partnership with another actor outside of MSHV much further away. From the perspective of the other actors, the uncertain financial gains from the proposed partnerships was indeed why they refused to collaborate, since this type of partnership would require large investments in infrastructure between the actors. This situation indicates that there is an inconsistency between the expectations of some members with high ambitions, and the actual purpose of MSHV – which is not specifically to initiate projects. This in turn creates a discrepancy in how MSHV is perceived.

When discussing the relatively few projects currently taking place in MSHV, the MSHV coordinator explained that the projects should be initiated by the members themselves – the coordinators of MSHV do not force actors to participate in a project. However, the coordinator acknowledges that more actors have to be willing to initiate projects and that more have to think long-term rather than maximizing profit in the short-term. If more actors would participate in projects, the financial risks of these projects would be lower, and the MSHV collaboration platform could also start applying some pressure on the actors who do not contribute.

Network 2 - Electrolyzer collaboration

Network 2 represents a collaboration that was formed in the creation of one of the most prominent hydrogen projects within the region – a hydrogen production plant in Hofors. *Ovako* had the central role in the project, where they built an electrolyzer from which they use to produce hydrogen that they use in their steel production. The project required partnership with companies like *Volvo*, *Hitachi Energy*, *H2 Green Steel* and *Nel hydrogen*, who contributed with different components, technical solutions (Ovako, n.d.), and financial support. The project also received funding from the grant provider *Energimyndigheten* through the program called Industriklivet (40% of the planned investment cost). These partnerships and financial support were essential in the establishment of the hydrogen plant – which is today the largest electrolyzer in Sweden (20 MW and 3,880 cubic meters of hydrogen per hour) and the first low-carbon hydrogen used in steel heating in the world (Ovako, n.d). Currently, *Ovako* is also investigating another potential electrolyzer project in Smedjebacken in the southern region of Dalarna.

Network 3 - Gävle Harbor

Gävle Harbor acts as a logistical center, which is an important facilitator for the hydrogen development in the region. The interviewee from *Gävle Harbor* described that their role in the hydrogen development in the region is to bring actors together, offering land and assisting in permit processes. Network 3 is a collaboration between several actors connected to *Gävle Harbor*. Adjacent to the harbor, *Svea Vind Offshore* plans to establish a wind turbine farm to produce electricity that could be used to produce hydrogen in cooperation with the harbor, but this project has been delayed due to a rejected permit application. The haulier *MaserFrakt*, who regularly use the harbor to transport goods, has shown great interest in a partnership with *Svea Vind Offshore*, and have signed an agreement where they will buy hydrogen that will be used in their trucks (Cision, 2022).

Network 4 - Baltic Hydrogen Collector

The Baltic Hydrogen Collector is a cross-border project to create an offshore hydrogen pipeline infrastructure in the Baltic Sea. *Nordion Energi* and *Gasgrid Finland Oy* are initiating the project in collaboration with the wind power developers *OX2* and *Copenhagen Infrastructure Partners*. Furthermore, the municipalities of the islands of Gotland, Åland and Bornholm have signed a letter of intent to become collaborators in the projects, since their beneficial geographical location is making them important nodes in the pipeline. Besides providing the Baltic Sea countries with better and quicker access to green hydrogen, the infrastructure will also enable balancing of the power grid in the region. Moreover, the project was on November 28, 2023, announced to be a "project of common interest" by the European Commission (BHC, n.d.). The Baltic Hydrogen Collector project identifies mid-Sweden as a demand center, and plans to have a node there in the future (Baltic Hydrogen Collector, n.d.) – thereby creating an important infrastructure connection between MSHV and other European countries.

Network 5 - SoutH2Port

Network 5 is a collaboration between *Skyborn Renewables*, *Lhyfe* and *ABB* that aims to build one of Europe's largest hydrogen plants in Söderhamn – a project called SoutH2Port. The hydrogen plant will be powered by electricity from *Skyborn Renewable's* planned 1 GW Storgrundet offshore wind turbine farm and is expected to produce 240 tons of hydrogen per day, 88.000 tons annually (Lhyfe, 2023). *Lhyfe* produces systems for low-carbon hydrogen production and will together with *Skyborn Renewables* operate the plant (Lhyfe, 2023). Furthermore, *ABB* brings technical expertise for optimizing the integration of hydrogen and electricity production (ABB, 2023).

Network 6 – Steel producer collaboration

Network 6 is a tenant agreement between *Green Iron* and *Alleima* in Sandviken's industrial park. *Green Iron* got their environmental permit for its production granted on March 28, and is about to commercialize their production later this year. The permit enables *Green Iron* to process 30 000 tonnes of low-carbon iron by using hydrogen, which could reduce the CO_2 emission with 42 000 tonnes per year compared to fossil-based metal production (GreenIron, 2024). Since *Green Iron* will have its production on *Alleima's* land, their iron could potentially be used as input material for *Alleima*, which would enable them to become low-carbon in the future.

Network 7 - Hydrogen production collaborations

The gas producer *Linde Gas* owns an electrolyzer that transports low-carbon hydrogen to several actors in MSHV. One of the buyers is the hydrogen fueling station owners. Another buyer of this hydrogen is the steel producer *Alleima*, who use it as shielding gas in their steel-heating processes, which is transported in pipelines from *Linde Gas*' electrolyzer to *Alleima*'s production. They currently use relatively small volumes, but in the future, they plan to use hydrogen to reduce their CO_2 footprint for their entire steel production, which will require significantly more hydrogen – around 6,000 tons of low-carbon hydrogen per year. Currently, the electrolyzer at *Linde Gas* has a relatively small capacity, which means that more hydrogen production is needed in the region to meet the future demands of *Alleima* and other hydrogen users. One actor who can potentially fill this gap is *Plagazi*, which will have a production facility in Köping operational in 2025/2026 which will be capable of producing

12,000 tons of low-carbon hydrogen each year. However, *Plagazi* mentions that their permit process for their production has been delayed.

Network 8 - OEM contributions

Network 8 is an example of how OEMs contribute to hydrogen development through different collaborations. *Volvo* has a collaboration with *Ovako*, where they supported and invested in their electrolyzer production in Hofors. In turn, *Ovako* will provide *Volvo* with surplus hydrogen that will be used in their upcoming fuel cell trucks, which will drive between Hofors and Gothenburg. In addition to gaining access to low-carbon hydrogen, *Volvo* also sees this collaboration as a way to learn more about the technology.

Other collaborations that were mentioned in the interview with *Volvo* include ZEFES, *Cellcentric*, and Hydrogen Accelerate Trucks. ZEFES is initiated and funded by the European Union, and is a collaboration project between *Volvo* and 39 other companies aiming to reduce their carbon footprint for long-distance heavy-duty transports (ZEFES, n.d.). *Volvo's* hydrogen trucks going from Gothenburg to *Ovako* in Hofors are a part of this project. Furthermore, *Cellcentric* is a joint venture between *Volvo* and their competitor *Daimler Trucks*, where Volvo invested 0.6 billion euro (Volvo Group, 2024), which will produce hydrogen fuel cells for the vehicles of the respective companies in the future. Finally, Hydrogen Accelerate Trucks is another initiative from the European Union, which includes participants such as *Volvo*, *Daimler Trucks*, and *Iveco Group*, who together will develop 150 hydrogen fuel cell trucks between 2025 and 2030. By collaborating and sharing knowledge, this initiative aims to remove some of the first-mover barriers that currently exist and move the market into a more mature state (IRU, n.d.). Even though these initiatives are not directly tied to MSHV, they still have possibilities to influence the region in significant ways.

4.1.3 Institutions

In the context of MSHV, the most relevant institutional components that have been identified are the national hydrogen strategy and regulations as formal institutions, and the culture of the MSHV collaboration platform as informal institutions.

Hydrogen Strategy

Energimyndigheten had in 2021 been responsible for creating a national hydrogen strategy for the Swedish government. However, this strategy was set aside once the new government was appointed in 2022, which means that Sweden has no official hydrogen strategy at the time of writing. This has been a source of concern by several of the interviewees, who emphasize the need for authorities to reach a consensus in questions related to hydrogen development. For example, many interviewees attested that some municipal actors were taking initiatives that impede the regional hydrogen development by sub-optimizing for their own municipality. The sidelined national hydrogen strategy could be one of the reasons why municipal actors sometimes not act in a way that fits the needs of MSHV actors.

Regulations

Another common concern among the interviewees was that current regulations are not well aligned with hydrogens current applications, which could impede the development of hydrogen infrastructure. According to Wickström et al. (2022), who has studied the development of hydrogen infrastructure in Northern Sweden and Finland, existing regulations cannot be directly applied to hydrogen infrastructure. One potential solution is to include hydrogen in the Natural Gas Act or to create a new Hydrogen Act. Additionally, the study highlighted that hydrogen activities are not listed in the Environmental Assessment Regulation, which leads to uncertainty for the operators regarding the required permit process. Adapting current legislation to include a clear permit obligation for hydrogen activities could address this issue. Furthermore, the permit process was a recurring theme in discussions about regulation during the interviews. Actors such as *Nordion Energi*, *Hydri*, and *Dalavind*, described that the lead times for permit processes are very long. The coordinator of MSHV suggested that working on permit processes simultaneously at the municipal and state levels could shorten lead times, thereby accelerating hydrogen development.

Moreover, Wickström et al. (2022) argue that new regulations should consider sector coupling, which is expected to become increasingly prevalent in the hydrogen expansion. A close collaboration between authorities and actors will therefore be required. Furthermore, the definition of "renewable hydrogen" used in the regulations will have a large impact on the development of hydrogen and should therefore carefully be discussed before setting the definition. For instance, hydrogen from water electrolysis and biomass is considered renewable while hydrogen produced from fossil fuels with CCS is considered low-carbon but not renewable (European Parliament, 2023). How these concepts are addressed in regulations could therefore affect the expansion of different production techniques.

Furthermore, *Powercell* described that the economy is one of the most important factors that hampers hydrogen development. The interviewee suggested that governments need to gradually increase taxes and prohibitions for the use of fossil fuels in order to speed up the development of greener alternatives, including hydrogen. In conclusion, the regulatory framework is currently not fully adapted to the emerging hydrogen economy. However, as Suurs (2009) argues, this is expected for a TIS in the formative phase, but it is nonetheless important that the regulations align as the hydrogen economy continues to evolve.

Culture

According to the MSHV coordinator, the culture of MSHV is based on mutual trust and a give-and-take mentality. To ensure effective collaboration, freeriding has to be avoided and all actors need to contribute in some way. However, one interesting finding from the interviews was that several of the interviewees, even though they had senior sustainability roles at companies who were formal members of MSHV, did not have much insight about MSHV and did not personally attend the get-togethers. Instead, it was described that 1-2 other employees who "had some free time" were sent to the get-togethers. This could indicate that some members do not take the membership as seriously as others.

4.1.4 Infrastructure

Despite the fact that the majority of all hydrogen produced today in Sweden is consumed on site, there is still a need for hydrogen infrastructure to meet future demand (Energimyndigheten, 2024). According to *Naturvårdsverket*, there is an interest in building infrastructure both from new and established actors. Furthermore, local and regional hydrogen valleys will play an important role in accelerating the expansion of hydrogen infrastructure (Strand, n.d.). In the following section, the most important infrastructure types in hydrogen development will be examined, including fueling stations, pipelines and renewable electricity parks.

Fueling stations

In order for the heavy transport industry to reduce its carbon footprint by 70% by 2030 (compared with 2010), and ultimately achieve climate neutrality by 2045 like all other sectors in Sweden, there should eventually be a hydrogen fueling station every 200 kilometers on main roads, as outlined by the EU commission (Energimyndigheten, 2024). At the moment of writing, there are five active hydrogen fueling stations in Sweden. But according to *Naturvårdsverket*, more than 50 new fueling stations are planned to be operational within five years. These fueling stations can receive relatively large support from *Naturvårdsverket* through *Klimatklivet*, which can cover up to 40-70% of total investment costs. For example, the actor *Hydri* is currently building 24 hydrogen fueling stations, in part funded by a 355 million SEK grant from *Naturvårdsverket*. *Masterfrakt* owns one hydrogen fueling station, and could see themselves investing in more as a means to power their vehicle fleet in the future. Even though the grants can cover a significant portion of the investment cost, the economic viability of the hydrogen fueling stations are not guaranteed, as *Dalavind* had to discontinue their pilot hydrogen fueling station in Malung because of poor economics.

Pipelines

If hydrogen valleys and regional clusters should improve economies of scale on a national level and not just on a regional level where the hydrogen valley is located, there needs to be a distribution network that can transport the hydrogen to other regions (Energimyndigheten, 2024). Sweden's existing pipeline infrastructure is very limited compared to other European countries, which means that the option of transporting hydrogen in the existing pipelines is not as relevant in Sweden. Additionally, most of the current natural gas pipelines in Sweden that are used to distribute methane cannot be used for hydrogen, since many customers depend on the carbon from the methane in their processes. On the local mid-Sweden level, some pipelines exist, e.g. from the hydrogen producer *Linde Gas* and the steel producer *Alleima*, but these kinds of pipelines are limited. Currently, there is demand for hydrogen in the region, but due to the lack of pipelines, some actors need to import hydrogen from distant locations by truck. One of the actors that has shown interest in building hydrogen pipelines is *Nordion Energi*, who have initiated some public projects, including Baltic Hydrogen Collector being the closest to the region. Moreover, one hydrogen producer mentioned that the challenges of building pipeline infrastructure is that close cooperation is required, which could only happen once there are clearly defined hydrogen producers and buyers. As it stands, this is far from reality, and the actor speculates that it will take about ten years before pipeline infrastructure could be built profitably.

Renewable energy parks and seasonal storage

Since electrolyzers require large amounts of renewable energy, there will be an increased need for establishing corresponding infrastructure, e.g. wind turbine farms and transmission lines, as the electrolyzer production starts ramping up. The quantity of renewable energy was a prevalent concern for nearly all major actors along the hydrogen value chain, and projections from some of the actors indicate that the quantity for renewable energy in Sweden has to more than double to support the future electrolyzer capacity. Actors like *Skyborn Renewables* aim to address this demand by establishing wind turbine farms adjacent to electrolyzers. However, they acknowledge that the wind turbine-to-electrolyzer infrastructure is about ten years away, and that it will require initiatives from both the private and the public sector to be implemented. One of these initiatives could for example be the storage provider *Nitiu*, who mention that their unique storage solution could be used for seasonal storage (i.e. to balance the fluctuations in wind speeds) adjacent to wind turbine farms and electrolyzers in the future, which would be an important infrastructure component in the future ecosystem.

4.1.5 Further structural considerations

As previously mentioned, it is important to also put the structural mapping into context, as suggested by Bergek et al. (2015). This includes adding four structural considerations: (1) interaction between a focal TIS and other TISs, (2) interaction between a focal TIS and relevant sectors, (3) TIS development in geographical context structures, and (4) interaction between a focal TIS and the political context.

These considerations are not intended to be analyzed in depth, as that task would justify a study of its own. The purpose is instead to shed light on the fact that the TIS does not exist in isolation, to acknowledge the largest external influences on the TIS, and also to highlight potential areas where further research can be conducted. The information provided below originates from the interviews but has been contextualized with the four structural considerations outlined by Bergek et al. (2015).

Interaction between a focal TIS and other TISs

There are other technologies with which the focal TIS interacts with, which can be either competitive or supportive (Bergek et al., 2015). The most prominent competitive relationship in our findings is with the battery TIS, e.g. by competing for political support and funding. The most prominent supportive TISs are OEMs technologies (e.g. fuel cell TIS and the heavy-duty transport TIS) and low-carbon energy production (e.g. wind turbine TIS, hydropower TIS, and solar panel TIS). The development of these TISs could have drastic implications for the focal TIS, as they provide inputs and components that are paramount for the focal TIS to function. Even though some of these interactions are explored in this thesis (e.g. the importance of renewable energy for hydrogen production), it is left for future research to determine the true magnitude of the interactions between these TISs.

Interaction between a focal TIS and relevant sectors

A sector is an overarching system which includes many TISs of similar structural elements that are necessary to fulfill a certain objective (Bergek et al., 2015). The primary sector for the focal TIS is the energy sector, as the focal TIS contributes to the objective of energy provision. Being aware of the overarching sector could be important, since norms and values on the sectoral level will impact the individual TISs. For example, being aware of what technologies for power generation (e.g. nuclear, solar, or wind) the energy sector regards as legitimate will have a drastic impact on the focal TIS. Adjacent sectors, e.g. the transport and steel sector, could also affect the focal TIS in significant ways, and therefore also be important to be aware of.

TIS development in geographical context structures

Unsurprisingly, the structural components of a TIS are bound spatially, and the premise of the TIS therefore varies depending on the geographical context. As our data collection and corresponding analysis is based on the mid-Sweden region, the findings are partly unique to this geography. For example, the geographical region of mid-Sweden will have structurally unique characteristics, e.g. in terms of culture, that will be inherently different from the TIS of other hydrogen valleys on a more global level. This contextuality implies that the findings have to be compared to other geographies in order to draw conclusions about hydrogen valleys on a more global scale – something that further research should address.

Interaction between a focal TIS and the political context

Similarly to the geographical context, the political context also influences the premise of the TIS. The political context largely influences the structural component *institutions*, e.g. in terms of culture, beliefs, and regulations (Bergek et al., 2015). This materializes in, for example, the degree of access to financial capital and legitimacy that exists for the TIS. The unique political context of Sweden, e.g. characterized by ambitious national sustainability goals and extensive permit processes, entails conditions that will likely not be applicable to the hydrogen valleys on a global scale. As noted earlier, the limitations in scope of this thesis will not allow us to explore the political context of other geographies – this is something that further research should investigate.

4.2 Functional analysis

The functional analysis is made to determine how the TIS works and how well it is performing, which is conceptualized through seven key functions – all of which need to be fulfilled in order for the TIS to be considered well-performing. A summary of these seven functions, and their performance appraisal, is presented in *Table 6*. As described by Bergek et al. (2008a), a well-performing TIS should ideally have all functions fulfilled at a satisfactory level – therefore, the TIS of MSVH could be labeled as relatively well-performing. Below the table, each function is analyzed in more detail.

Functions	Performance	Summary
Knowledge development and diffusion	Intermediate performance	Strong in general in MSHV, but lacking in some authorities, end-users, and the public.
Influence on the direction of search	Strong performance	Pressure from regulations creates strong incentives to join MSHV. Grant providers and early adopters steer the direction of search.
Entrepreneurial experimentation	Intermediate performance	While some experimentation in MSHV exists, but a general lack suggest opportunities for improvement.
Market formation	Intermediate performance	MSHV is in a formative phase and the market is underdeveloped. The chicken-and-egg problem is hindering its development.
Legitimation	Strong performance	The social acceptance for hydrogen is strong within MSHV, but lacks to some degree in the public.
Resource mobilization	Intermediate performance	Financial capital can be acquired relatively easily but the application processes are cumbersome.
Development of positive externalities	Intermediate performance	Both positive and negative externalities exists.

Table 6. Summary of the functional analysis and performance appraisal.

4.2.1 Knowledge development and diffusion

While fossil-based hydrogen has been used for a long time in the industry, including chemical, petrochemical and refineries (Vätgas Sverige, n.d.), the evolving landscape of applications, business models, production methods, and value chains, requires continuous research and exploration. The current level of knowledge development and diffusion appears ambiguous, with varied perspectives between the interviewees. Nevertheless, a consensus emerges among the majority that both MSHV and Sweden on a national level would benefit significantly from advancements in knowledge and research. In the following sections, three perceived knowledge gaps will be discussed, followed by a discussion with a more optimistic perspective and a performance appraisal.

Knowledge gap in general

Overall, there is a consensus among the majority of the interviewees that the knowledge about hydrogen in the industry and in public needs to increase in order to enable scaling of the technology. The interviewees mentioned the necessity of enhancing knowledge across various sectors, including private entities, municipalities, government authorities, academic institutions and society in large. A hydrogen researcher at *Luleå University* described that when they worked to develop the hydrogen strategy for *Energimyndigheten*, everyone pointed to a lack of knowledge. Some examples of general knowledge gaps discussed in the interviews were related to handling and safety of hydrogen, and the integration between the power grid and hydrogen production.

One factor that could hinder knowledge development is related to the dynamics of innovation in competitive markets, in which actors might be reluctant to share information about their R&D processes. Furthermore, the polarization that puts different energy sources against each other instead of seeing them as complements (commonly mentioned in the interviews), is another factor that could slow the knowledge development. Finally, another factor that could hinder knowledge development is the lack of competition between technologies in the TIS, which was identified as a major factor for knowledge development in another TIS analysis (Bach et al., 2020). As mentioned earlier, a lot of focus has been given to electrolyzers as compared with other production methods, which therefore could affect the function negatively.

Knowledge gap at the customer side

The interviews revealed a notable knowledge gap among the end users of hydrogen, particularly among the users who are currently relying on alternative techniques and energy sources. One interviewee mentioned that while a construction site has experience in operating and maintaining a diesel generator, they lack the requisite knowledge in utilizing and maintaining a fuel-cell generator. This suggests a greater need for education and support tailored to specific use-cases.

Knowledge gap within authorities

Moreover, the interviews also highlighted that there is a critical knowledge gap within municipalities and authorities. One interviewee argued that the municipalities have a key role in enabling the low-carbon hydrogen transformation, citing examples such as: attract qualified people to the region, shifting public transport, and establish low-temperature district heating networks (facilitating the utilization of excess heat from electrolysis, thus improving the business case of hydrogen production). Additionally, the MSHV coordinator highlighted the EU's pressure to accelerate transformation and proposed that increased hydrogen comprehension among decision-makers could shorten policymaking lead times. Furthermore, as Suurs (2009) argues, it is important for technology developers to communicate their needs to policymakers – but this is not something that has been identified from the interviews. Since most knowledge sharing in MSHV is on a regional level, the national authorities might not be informed about recent developments in the region. This limited contact with policymakers could therefore contribute to the knowledge gap in authorities.

Positive knowledge developments

While there is certainly room for enhancing the understanding of hydrogen and its applications, the interviews also revealed a more optimistic outlook regarding knowledge development. *Energimyndigheten* highlighted extensive research conducted on several universities in Sweden, covering various aspects such as production (electrolysis, bioCCS), fuel cells, storage and transport, safety considerations, market and applications. Additionally, there is major research on system analysis, aiming to understand how the hydrogen expansion would impact the electricity grid. Hence, a lot of knowledge development is based on "learning-by-searching" coming from facilitators, as described by Suurs (2009). When it comes to actors that currently are involved in projects related to hydrogen, the grant provider *Klimatklivet* noted that the applicants have demonstrated substantial knowledge, as it is a prerequisite for securing grants. The steel industry, which is prominent in MSHV, has also used hydrogen for a long time and has the most experience of using it in their processes. Furthermore, a grant provider also mentioned that there is ongoing knowledge development within certain authorities.

MSHV was often brought up as an important initiative for increasing the knowledge about hydrogen in the region. The conferences result in a good knowledge exchange according to the majority of the members who were interviewed. One interesting point made by *Sandbacka Science Park* was that members in MSHV have access to a lot of knowledge, which other actors cannot access since they do not know it exists. Furthermore, one interviewee was a course leader at Ny Teknik Education, and explained that there are currently several educations related to hydrogen, and an interest among actors to learn more about the technology. Moreover, one actor has been part of creating a vocational education for hydrogen operators.

Performance appraisal - Intermediate performance

The knowledge development and diffusion seem to be solid within the members in MSHV but lacking in some authorities, end users and the public. Another TIS analysis, which studied the use of hydrogen in the maritime transportation sector in Norway, concluded that the knowledge development was very limited (Bach et al., 2020). Even though it was limited, the function's performance was concluded to be of intermediate strength, since there had been many projects and collaborative partnerships that indicated that knowledge development would increase in the future. Similarly, as MSHV is in a formative phase, some knowledge development will naturally be lacking, which is why the more important question instead is if the knowledge development has the potential to improve in the following years. The MSHV-platform and the various hydrogen educations are two factors that could impact this potential in a positive way. Actors throughout the value chain, OEMs, and facilitators involved in MSHV, have the opportunity to gain and share knowledge at the get-togethers. The amount of knowledge exchanged depends on each actor's willingness to share their knowledge and listen to other members. According to the interviewees, the current knowledge exchange at the conferences is solid. However, to speed up the knowledge development and diffusion, more hands-on projects are wanted by the members, which could be seen as a possible improvement point in MSHV. It is also a bit uncertain how the knowledge diffusion would target state-level authorities and the public that are not part of the get-togethers. In conclusion, the function is assessed to have intermediate performance.

4.2.2 Influence on the direction of search

The development of MSHV requires incentives for actors to join, while simultaneously ensuring a selection of technological options for further investments. Pressure from governmental sustainability goals seems to be the strongest incentive for actors to join MSHV. Expectations of valuable collaborations and increased revenue are two other incentives. Moreover, the interviews revealed that grant providers and early adopters have an important influence on the direction of search. These factors will be elaborated on in the following sections, and concluded with a performance appraisal.

Legal requirements on reducing carbon footprint

The majority of companies acting within the industry today are facing a large transformation due to the pressure on reducing their environmental footprint in order to stay relevant in the future. Climate neutrality is according to most actors the strongest incentive for actors to enter the hydrogen economy. Hence, one important factor affecting the direction of search is the regulations and laws regarding climate, for example the EU climate goal to reach climate neutrality by 2050. Hydrogen has the possibility to substitute fossil fuels in a myriad of applications, and creates an inherent incentive for actors to explore different hydrogen use-cases. One significant example is the iron and steel industry, where hydrogen could replace existing use of fossil fuels in several applications.

Visions and expectations of a hydrogen valley

The majority of the interviewed members in MSHV had some sort of vision of how the platform could result in valuable relations and networks. The majority of the interviewees expressed interest in connecting with other actors to foster potential collaborations. One interviewee argued that the more members there are from each actor group in MSHV, the better chances are for finding partners that could match their needs. Three interviewees also described that they through MSHV hope to get more support and engagement from grant providers, permit granting authorities, and local politicians. For example, if a group of actors together express their visions, this could create awareness for decision-makers. Other expectations mentioned was sharing risk, collectively applying for permits, and a better understanding of the demand and supply – thereby reducing uncertainty.

Hydrogen as a new source of revenue

Using sustainable energy sources, like hydrogen, could also lead to increased revenues for companies. More specifically, the interviews indicated three different types of economic incentives for investing in hydrogen. Firstly, companies specializing in hydrogen techniques (e.g. storage/production) see the opportunity to get their product out on the market. Secondly, both energy providers and potential hydrogen producers pointed out that hydrogen could diversify their current product portfolio and increase revenue. For example, companies that today are producing electricity from wind parks could use hydrogen as a second revenue source. One interviewee argued that the electricity prices are very low in some parts of Sweden, and hydrogen could therefore compensate by increasing the revenue for the company. Thirdly, end users like steel producers, that are competing on quality and sustainability, could see green hydrogen as an enabler of producing fossil-free steel. This could in turn increase their sustainable brand image and attract more customers that value sustainability.

Grant providers influence

While grant providers support the development of hydrogen value chains, the interviews also revealed that it steers some of the research by providing grants to specific areas. One example is that *Klimatklivet*, from the EU's directive, currently is providing specific grants for fueling stations along the Trans-European Transport Network (TEN-T). Another example, based on the definition of renewable hydrogen, the water electrolysis seems to be included in more grants compared to other production methods.

Early adopters influence

Besides grant providers influencing the direction of search, members in MSHV that already have initiated hydrogen projects might influence other members. A common project that has received a lot of attention is Ovako’s electrolysis in Hofors – a project that has been referred to a lot in the interviews and in the marketing of MSHV. Since the project is one of the first in the region to prove that hydrogen usage in the steel industry is viable, the uncertainty around adoption may have been reduced, and more actors might be interested in exploring the opportunities with electrolysis. As described by Hekkert et al. (2007) successful projects, like Ovako’s electrolyzer, can have a notable impact on the *influence on the direction of search*. Moreover, during the MSHV conferences, some members are usually having presentations on their recent projects and developments within hydrogen, which also might affect the function positively.

Performance appraisal - Strong performance

There are strong incentives to invest in hydrogen technology in terms of pressure from regulations on the national and EU-level to become fossil-free. Some actors also mentioned profit-seeking incentives, but compared to the regulation-incentives, these seem to be quite small due to the uncertain gains of the investments. Since the TIS is in an formative phase, it is not reasonable that profit incentives will play a significant role. To compensate for this, it is favorable that grant providers provide incentives instead – these are somewhat solid incentives as seen from the interviews. These types of incentives are similar to the ones commonly mentioned in the TIS literature (e.g. by Bergek et al., 2008a; Hekkert et al., 2007). However, these grant providers also affect the direction of search in significant ways by influencing what technologies will get support and funding. For example by providing more support directed to electrolyzers than other techniques, and more support to larger projects than smaller ones. Hence, the grants do not provide incentives for a *wide direction of search*, since they are biased towards certain kinds of technologies, which could be hindering other technologies that might have other benefits. Finally, the majority of the interviewees argued that they joined MSHV with the vision to create collaborations and partnerships that could help them in the development of hydrogen and reduce uncertainty, e.g. by sharing risk. In sum, this function is assessed to have <u>strong performance</u>.

4.2.3. Entrepreneurial experimentation

Development of a TIS requires testing of technologies, applications and networks. Experimenting is therefore fundamental for a hydrogen valley to evolve, since it could both reduce uncertainty and create a learning process. In the following sections, the actual degree of experimenting within technologies, applications and networks will be discussed, followed by some examples of how experimentation is lacking and a performance appraisal.

Experiments with hydrogen technologies

Regarding the experiments of technologies within MSHV, the interviews suggest a limited range of technologies for producing hydrogen, primarily focusing on electrolysis and waste gasification. Water electrolysis stands out as the most prominent method, and while the method is quite well developed, there are still opportunities to optimize its high electricity usage and high investment costs. However, within MSHV, there are no companies focusing on electrolyzer development, leading to a lack of experimentation in this area. Another emerging method that is getting more attention is waste gasification, a technique that *Plagazi* develops. According to our interviewee, *Plagazi* has developed a functional technique for waste gasification but remains committed to ongoing improvements and pursues new patents in this field.

Experiments within applications

The majority of experimentation within MSHV focuses on practical applications. A noteworthy example is *Ovako*, who have installed an electrolyzer at their facility in Hofors, where they produce hydrogen which is then used in their steel heating process. Furthermore, *MaserFrakt* has purchased a few hydrogen trucks and built a fueling station, currently exploring the feasibility of using hydrogen in their transports. According to the interviewee, investing in this early stage would lead to first-mover advantages and at the same time increase demand by showing that it actually works. Meanwhile, Sandviken municipality has bought a few hydrogen buses, but encountered some challenges with fueling infrastructure which has caused delays (Kristensson, 2024). Moreover, *Dalavind* described that they have been part of several pilot studies – both theoretical and practical. A few actors have also initiated a hydrogen operator education in order to educate operators, as previously mentioned. From the interviews, it is evident that there is significant uncertainty surrounding the commercial aspects of hydrogen and its applications.

OEMs experimenting

According to the coordinator of MSHV, there is also a lot of experimentation regarding storage and distribution. One company that develops a technique for storage is *Nitiu*. The interviewee described that most of their work is spent on improving their material structure regarding weight and strength. They also have collaborations with some labs around Sweden. Furthermore, the interviewee from *Powercell* described that about half of the company work within research and development on their fuel cells. *Volvo* is another company who focuses greatly on research to develop technologies and capabilities required to become climate neutral in the future. They currently invest heavily in exploratory projects and partnerships related to hydrogen and fuel cells.

Examples of lacking experimentation

The interviews revealed that the development of MSHV requires more experimenting with new business models. The use of hydrogen differs from existing fossil fuels, with its less developed value chain, forcing actors to work in symbiosis with other actors to a larger degree. Actors within the industry need to see opportunities in collaborations with other actors, and also find new ways to compete on the market. Furthermore, to make the electrolysis production process more profitable, it is important to make use of both the excess heat and oxygen that comes from production. Here, the municipal energy companies should see the value in low-temperature waste heat for district heating and build infrastructure to support this, which could provide new business models for hydrogen producers.

One of the most common critiques of MSHV from the interviews was that the collaboration resulted in few practical projects – indicating a lack of experimentation, at least in terms of projects emerging from the collaboration itself. Some members even perceived MSHV as “only a discussion club”. Most members, however, see great value in that the collaboration platform is limited to knowledge development, even though practical projects are lacking, by reasoning that knowledge development is the first step in the early developments of MSHV.

Performance appraisal - Intermediate performance

Although there is some experimentation within MSHV, many interviewees contend that there's a general deficiency in hydrogen-related experimentation. One cited reason is that larger companies encounter challenges in exploring areas beyond their core business, prioritizing profit generation instead. Additional factors mentioned include general uncertainty in the hydrogen market, a tendency to wait for other actors to take action, low prioritization, and significant investment requirements. However, one interesting finding is that all but three actors could be labeled *incumbent companies aiming to diversify their current business* (as described by Hekkert et al., 2007; Suurs, 2009), rather than being new and smaller actors – potentially indicating a lack of experimentation in the form of new actors entering the TIS. Furthermore, several actors explain that there exists a bias towards certain kinds of technologies that indirectly inhibit experimentation of other alternatives. For example, on a national and strategic level, electrolyzers are portrayed as the most legitimate method for producing low-carbon hydrogen, which indirectly limits the support of other methods by impairing their financing opportunities, as testified by *Plagazi*. However, many companies have started investing heavily in hydrogen related experiments, with particular notable experiments taking place within steel companies and OEMs. In conclusion, this function is assessed to have intermediate performance.

4.2.4 Market formation

Below, findings from the current hydrogen market are presented. Thereafter, expectations on future market developments and some inconsistencies from the interviews are presented, followed by a performance appraisal.

Current market

All the actors testified that the market for low-carbon hydrogen is in a very early stage, since most projects are in an ideation phase and the use-cases are much more expensive than fossil-based alternatives. However, as shown by Jacobsson and Johnson (2000), poor price/performance ratio is expected for new technologies, as they have inherent weaknesses compared existing ones. Many actors believe that the market will remain small in the upcoming years. For example, one grant provider does not believe that investments in hydrogen fueling stations will be profitable on their own within the next five years and that actors in MSHV will continue to rely upon their grants to make investments. Another example is that a hydrogen producer estimates that it will take around ten years before a sufficiently mature market will exist that would justify building the necessary infrastructure. A common reason found in the interviews for why the market formation is slow can be attributed to the paradoxical “chicken-and-egg” problem, i.e. if supply or demand should come first – which have also been found in other TIS analysis such as Mäkitie et al. (2021). For example, there is little incentive to invest in manufacturing hydrogen trucks if there are no fueling stations on the roads, and similarly, there is little incentive to invest in fueling stations if there are no trucks that need to be fueled. This dilemma indicates that the hydrogen market is currently only in a formative phase (Mäkitie et al., 2021). Many actors believe that the subsidies, especially the relatively generous grants, provide a possible solution to the chicken-and-egg problem. For example, the actor *Hydri* has started building 24 new hydrogen fueling stations with support from grant providers, even though the demand currently does not exist.

Expectations on future market

All interviewed actors believe that hydrogen will play a significant role in the future energy ecosystem. However, there are varying opinions regarding what use-cases hydrogen will have. Some actors argue that hydrogen will substitute electricity more broadly, e.g. by being used as many kinds of vehicle fuels (cars, boats, airplanes etc.), industrial processes, and household energy. The majority of actors take a more cautious approach, stating that hydrogen will be used more specifically, with the most common beliefs being heavy duty transports, industrial processes, and other types of vehicles which cannot charge with electricity easily. As it stands, the most important driver for hydrogen market formation is the regulatory demands for industry to be carbon neutral in Sweden by 2045.

Demand for hydrogen

There was an interesting inconsistency regarding hydrogen demand that was identified from the interviews. Many actors said that the demand for low-carbon hydrogen solutions is considerable, e.g. for green steel and hydrogen trucks. For example, one renewable energy provider gets contacted several times each quarter and asked if they have any low-carbon hydrogen to sell. Still, very little low-carbon hydrogen is available on the market, since no actor is willing to invest in its production. The only exceptions in the region being through *Ovako*'s electrolyzer (currently only for internal use) and *Linde Gas* (small volumes). This is the reason why some hydrogen users in the region have to buy hydrogen from outside the region and transport it by truck. This represents an interesting contradiction: even though demand and a supposed willingness to pay exists, there is a great reluctance for actors to invest in low-carbon hydrogen production. This contradiction is rooted in two blocking mechanisms (nr. 1 and nr. 2), which is identified and elaborated further in section *4.5 Identifying inducement and blocking mechanisms*.

Appraisal of performance - Intermediate performance

As mentioned, the TIS is in a formative phase. This is not a problem in itself – however, it is important that the TIS can move smoothly into a growth phase in order for this function to rank highly. As noted, many interviewees believe that the market will take a long time to develop, which indicates that certain blocking mechanisms exist that will prohibit the TIS from transitioning into a mature phase smoothly and rapidly. However, certain actors like steel producers, hauliers, and fuel station providers have all shown ambitious goals to utilize hydrogen relatively soon. For example, the 24 new hydrogen fueling stations that are planned to be operational next year is a solid indicator that market formation may be accelerated. In sum, the function is assessed as having intermediate performance.

4.2.5 Legitimation

Firstly, the legitimation in industry and the public is presented, followed by the legitimation in authorities and a performance appraisal.

Industry's and the public's perception of hydrogen

According to the MSHV coordinator, there exists an acceptance towards hydrogen in the region, partly since hydrogen has been used in the steel industry for a very long time. For example, the steel industry in the municipality of Sandviken has a hydrogen pipeline running straight through the city, and there is generally a belief amongst citizens that hydrogen developments provide local employment opportunities and contribute to sustainable development. From a more broad and national perspective, a common theme in the interviews was that the legitimation in industry was solid, which can be attributed to for example extensive safety precautions taken by the companies and a strong belief in future growth opportunities. However, some interviewees had observed some skepticism from the public. This skepticism was based on either safety concerns or opinions about overspending, which had been expressed by the public in some instances.

Relatively rigid view on hydrogen by authorities

A common perception from the interviewees was that policymakers, and to a certain degree the public, had a very rigid view of hydrogen as an energy carrier. They felt that the discussion about hydrogen tended to be polarized, with people either being positive or entirely against it, which results in an unproductive discussion, since some people regard hydrogen as illegitimate. All the interviewees agree that society will need both hydrogen and direct use of electricity in the future, even though beliefs of the exact proportions and use-cases varied between interviewees. A common theme was that policymakers should not focus entirely on one alternative over the other when designing policies and see them as complements rather than substitutes. A similar theme could be found in the context of renewable energy types, where many actors believe that policymakers have a too rigid view of the different renewable energy sources. According to the interviewees, all renewable energy sources will be needed, as the future hydrogen economy will have high energy requirements, which politicians should take into account when proposing policies.

Appraisal of performance - Strong performance

There is a solid understanding in industry when it comes to hydrogen and a long history of using (gray) hydrogen in varying applications. Other TIS analyses of hydrogen ecosystems have found that regulatory frameworks with ambitious goals to reach carbon neutrality is another important factor that increases legitimacy of the TIS (Bach et al., 2020), which is also the case for the TIS of MSHV. However, some unawareness exists amongst the public which may lead to biases towards the legitimacy of hydrogen. Also, political stances usually favor either electricity (batteries) or hydrogen rather than seeing them as complements, which create polarization. However, these negatives are not seen as that significant by the interviewees. Altogether, the function is assessed as having strong performance.

4.2.6 Resource mobilization

This function is divided into mobilization of financial capital and human capital, which are presented below, followed by an appraisal of the performance. Bergek et al. (2008a) describe that another kind of resource is complementary assets, but the mobalization of this resource was not identified to be of significance from the interviews.

Financial capital

Many hydrogen projects within MSHV have been provided with financial capital, mostly from grant providers. For example, grant provider *Klimatklivet* provides aid for investments in hydrogen fueling stations, by covering around 40% of the investment cost. In particular, the infrastructure provider *Hydri* has received 355 million SEK from *Klimatklivet* for the establishment of their 24 new hydrogen fueling stations. These types of grant initiatives, which are made on behalf of the Swedish government, are seen as very positive by actors in MSHV, since they can help overcome the obstacles in the early stages until the technology becomes self-sufficient. Another actor who received significant financial support was *Ovako*, who received 40% of the investment cost by the grant provider *Energimyndigheten*, while also being supported through a co-ownership by *Volvo*, *Hitachi*, *H2 Green Steel*, and *Nel Hydrogen*. Funds from the state and EU-level also help to finance other types of initiatives, such as the incubator *Sandbacka Science Park*, which in turn aids in the hydrogen development in the region, e.g. by connecting industrial actors with risk capital firms such as *Almi Invest*.

One problem that most interviewees described was that the application period for grants was very long and ineffective. For example, a renewable energy company explained that you almost need one full-time employee to handle the application processes, which makes it burdensome for smaller companies to apply since they do not have the available resources. It was also noted that projects with larger budgets and more stakeholders had an easier time getting funding, which made grant applications for smaller pilot projects more cumbersome. However, according to the MSHV coordinator, the MSHV collaboration makes the processes easier, since you can cooperate with other actors in the region by applying for grants together, but it was unclear if this happens in practice. Some interviewees expressed the application processes as less burdensome, but these were often larger actors with more resources. In sum, the belief amongst most interviewees is that the availability of financial resources and grants are plentiful, but that the application processes are cumbersome.

Human capital

Opinions about the relative ease of acquiring human capital have been inconsistent. Some actors explain that the recruitment of talented and knowledgeable personnel is among the greatest challenges for their business. Other actors believe that they already have all the talent they need. *MaserFrakt* for example, who previously had no experience with hydrogen, had within four years completed their own hydrogen fueling station and hydrogen trucks, only through in-house experience and competence development. Although it may be difficult to assert the true cause for this discrepancy, the findings indicate that smaller companies were generally more concerned about human capital, while larger companies thought of it as adequate.

Appraisal of performance - Intermediate performance

In sum, financial capital for hydrogen projects could be acquired relatively easily, with the only downside being that the application process is relatively time-consuming. There was also an inconsistency in the availability of human capital, where some interviewees said that it was a problem while others did not. An analysis of a battery electric (BE) TIS with similar characteristics to our TIS concluded that performance was strong even though interviewees in that TIS also considered grant application processes cumbersome (Bach et al., 2020). However, one contradiction was that it has been noted that some actors see human capital as a critical obstacle in our TIS, which was not the case for the BE TIS. Therefore, this function is assessed as having intermediate performance.

4.2.7 Development of positive externalities

Positive externalities exist if a strength in one function creates a virtuous cycle that reinforces itself or another function. The identified externalities are not exhaustive, since most functions influence each other in either indirect or modest ways. In this thesis, the externalities which are presented are: (1) partly unique to MSHV as opposed to generic for all TISs, (2) considered a direct externality as opposed to indirect, and (3) significant for the TIS. In addition to the positive externalities, some negative externalities have also been found. These externalities are presented below, and are concluded with a performance appraisal.

Positive externalities

One positive externality is between the *resource mobilization* function and the *entrepreneurial experimentation* and *direction of search* function. In practical terms, since grants are available for many types of hydrogen projects, this allows actors to make larger investments, which gives actors more incentive to join MSHV as well as to participate in experimental projects and collaborations. Another positive externality is within the *entrepreneurial experimentation* function itself. This is reinforced by actors who are taking the initiative in terms of innovation, e.g. by showing actors that the technology works. Therefore, risk is reduced for other actors to experiment, and the cycle continues as more and more actors start to participate. Another positive externality that was found was between the *entrepreneurial experimentation* and *market formation* functions, since experimental projects are believed to be amongst the most crucial steps before a self-sustaining hydrogen market can be formed.

Negative externalities

However, some negative externalities could also be identified. One such example is the reluctance for actors to take action and participate in actual projects, which creates the perception that nobody is taking action – which in turn has caused frustration for some actors that have caused them to distance themselves from MSHV. This distancing then leads to even less collaborations and projects, which perpetuates the cycle. This creates a negative externality in the function *entrepreneurial experimentation*. Additionally, another negative externality exists between *entrepreneurial experimentation* and *market formation*, since lacking experimentation, e.g. in terms of practical projects in the region, risks leading to a slower market formation.

Appraisal of performance - Intermediate performance

Currently, some positive externalities exist, i.e. within and from the *entrepreneurial experimentation* function and from the *resource mobilization* function. However, within and from *entrepreneurial experimentation*, negative externalities also exists. Positive and negative externalities can exist for the same functions, since the interviews indicate that both are true at the same time. In other words, MSHV currently stand at a crossroad – relatively many projects are in the planning phase, and depending on the outcome of these projects, the externalities could go in either the positive or negative direction. Earlier projects have commonly been delayed or canceled, and if the same were to happen with these projects, there is a risk that actors will be afraid to act in the future – thereby creating a negative externality. However, if the projects succeed, it will showcase to the other actors that the low-carbon hydrogen market is starting to transition into a growth phase – creating a positive externality in the process. In sum, the function is assessed as having <u>intermediate performance</u>.

4.3 Identifying inducement and blocking mechanisms

The fifth step of the Bergek et al. (2008a) framework relates to finding inducement and blocking mechanisms (i.e. opportunities and challenges) in the TIS. These mechanisms were mostly derived from the functional analysis, by analyzing the reasons behind the performance of the functions. However, some of these mechanisms were derived directly from thematic analysis and coding and not directly connected to a function, but which could be connected to a function in retrospect. Note that many of the mechanisms identified are similar to those found in the literature on renewable energy technologies (Johnson & Jacobsson, 2001). However, the mechanisms identified in this study are more specifically adapted to the hydrogen market and MSHV. The two inducement mechanisms and six blocking mechanisms, are presented below.

Inducement mechanism 1 - Geographical proximity

As was showcased in the interviews, the degree of collaboration in MSHV is mostly limited to knowledge sharing and get-togethers, with few practical projects taking place. An example is that some hydrogen users in MSHV buy hydrogen from distant regions even though many possible collaboration possibilities exist locally. This inability to initiate collaborative projects locally presents an important opportunity going forward. If the actors along the entire hydrogen value chain would realize that there are many other local actors willing to cooperate, and commit to partnerships and practical projects, this could lead to the development of a localized hydrogen value chain – including energy production, hydrogen production, distribution, and utilization networks. This would in turn reduce the dependency on distant sources and promote self-sufficiency in MSHV. However, these types of collaborations require that all participants benefit, which can be difficult to achieve in practice due to varying risk/return for each participant.

The geographical placement of MSHV, where a myriad of actors exist who can populate the hydrogen value chain, is a unique opportunity to strengthen some of the functions in the TIS. If more local collaborations are initiated, knowledge development would strengthen as more actors share knowledge with each other. Entrepreneurial experimentation will also increase in the region if more local collaborations occur. Finally, the mobilization of financial resources will strengthen, since actors can jointly apply for grants, which increases the chances of getting approval (as grants currently favor larger projects) and also reduces the financial risks for the individual actors.

Inducement mechanism 2 - Sustainability pressure

Another critical inducement mechanism is the pressure on companies to become more sustainable. A part of this pressure comes from regulatory frameworks, which stipulates that companies will have to become carbon neutral. This pressure from regulatory frameworks is a common inducement mechanism found within the renewable energy technologies field (Johnson & Jacobsson, 2001). Addressing these demands is not something that companies can postpone to a distant future, as the required investments have long time horizons and therefore have to be made as soon as possible. Since hydrogen could be an important substitute for many use-cases utilizing fossil fuels, this pressure creates an opportunity for the hydrogen market to grow in the near future. For example, refineries, heavy transports, industrial heating, and steel manufacturing are some of the many industries that our interviewees identified that could use hydrogen as a substitute.

Another part of the sustainability pressure is social, i.e. that consumers put more and more emphasis on sustainability when choosing to associate themselves with a brand. The general concern for the environment is a common factor that stimulates market formation in the literature (Johnson & Jacobsson, 2001). This could be either when buying a company's product/service or when choosing which jobs to apply for. According to our interviewees, a sustainable brand image is a prerequisite to attract talented employees. This social pressure, together with the pressure from regulatory frameworks, are important drivers and opportunities for the hydrogen market development going forward. The sustainability pressure has for example led *Volvo* to invest substantial resources in projects and collaborations related to hydrogen as a means to decarbonize their product portfolio. The magnitude of these investments can have a noticeable impact on the market development for hydrogen, and therefore, the continued sustainability pressure provides an important opportunity as more and more actors are likely to increase their investments.

In sum, this sustainability pressure leads to an increased willingness for companies to experiment with new business areas and partnerships, an increased social acceptance, and improved availability of financial capital (e.g. from grants and venture capitalists). Accordingly, the functions that are positively affected by the sustainability pressure are *entrepreneurial experimentation*, *market formation*, *legitimation*, and *mobilization of resources*.

Blocking mechanism 1 - Sequential and temporal dependency

The first blocking mechanism is the sequential and temporal dependency that characterizes the hydrogen value chain. The sequential dependency refers to that each step, from energy provision to end users, are to a large degree dependent on the other steps, see *Figure 6*. A functioning value chain therefore requires actor types from each group to be contributing, and with the same capacity – otherwise a bottleneck will be created. For example, if there exists a shortage of electricity, this will directly limit the amount of hydrogen that could be produced if the hydrogen production capacity is above the electricity capacity. Furthermore, a temporal dependency also exists, which refers to that timing is required between each actor group. For example, if a hydrogen producer has made an agreement with an infrastructure provider to deliver hydrogen through pipelines to their customers, and the infrastructure gets delayed due some requirement in the permit process – the hydrogen producer will have no revenue from their investment until the infrastructure is completed. Relating this to the current lack of hydrogen infrastructure in both MSHV and across Sweden nationally, it is clear that these dependencies hinder the diffusion of hydrogen. Similar dependencies exist between every actor group in the value chain. Some of the main causes for delays were described by the interviewees as: availability of material, financial resources, and permit processes. These uncertainties, together with the dependencies, leads to a market with very high risk.

Because of these dependencies and associated risks, the market creation is very slow and only a few actors who are willing to take the risk are currently forming the market. Therefore, this blocking mechanism critically affects the *entrepreneurial experimentation* and *market formation* function.

Blocking mechanism 2 - High costs

The second blocking mechanism is the comparably high costs of low-carbon hydrogen. Firstly, the equipment required for producing hydrogen, e.g. an electrolyzer, is a large investment for actors. Some interviewees argued that they would only be willing to invest in an electrolyzer in collaboration with other actors, as a means to divide the high investment costs and to spread the risks. Secondly, the electrolyzer is using a lot of renewable electricity, which increases the price of producing hydrogen further. Thirdly, the production of fuel cells and hydrogen trucks are also considerably more expensive than their fossil counterparts. The estimates of the cost difference varied between the interviewees, but typically ranged from 3-4 times more than when using fossil fuels in multiple use-cases. Even though end users may have ambitious intentions to reduce their carbon footprint, the interviewees' experiences seems to suggest that they are currently not willing to pay such a large premium. However, some interviewees mentioned an important nuance – this 3-4 increase in cost will not be transferred to the end users, since hydrogen is only one component of the end-product. The production of fossil-free steel has other large costs, e.g. material, logistics, and refining processes, which makes hydrogen a much smaller percentage of the total cost and the premium much less significant. For exampe, empirical findings from Emanuelsson & Johnsson (2023) show that the cost increases for end-users are only 1-3%.

Nonetheless, the comparably higher costs of hydrogen use-cases is arguably a notable challenge in the hydrogen development. The functions which are most prominently affected by this blocking mechanism are *entrepreneurial experimentation* and *market formation*.

Blocking mechanism 3 - Premature technology lock-in

Another blocking mechanism that hinders low-carbon hydrogen diffusion is a lock-in on certain technologies and energy sources. An example is that electrolyzers have received a lot of attention and support, while other more experimental technologies have not received close to the same attention. *Plagazi's* method for waste gasification is one alternative to the electrolyzer that has been excluded from many grants and subsidies due to not being labeled renewable, even though the method has a very low carbon footprint. This labeling of what is renewable or not therefore creates a bias towards certain technologies, even though other technologies might have similar positive effects on the environment.

Similar kinds of lock-ins have been expressed by the interviewees to exist within other areas as well. One of these is the electrification-vs-hydrogen debate, which some policymakers see as an either-or decision, e.g. leading to policies that favors battery development over hydrogen. Another lock-in exists within the renewable energy alternatives, as some individuals lobby for one energy alternative as the only potent solution. Nearly all of our interviewees expressed that batteries and hydrogen will be used for different use-cases, and will be complementing each other in the future, and that all renewable energy alternatives will be needed to meet the future energy demands. Therefore, labeling one alternative as the most legitimate could lead to challenges for the TIS, since it will be important to have a mix of technologies.

These types of biases negatively affect the functions of *knowledge development and diffusion*, *direction of search*, *entrepreneurial experimentation*, *legitimation*, and *resource mobilization*.

Blocking mechanism 4 - Electricity capacity

The high electricity consumption for producing hydrogen demands availability of renewable electricity. The electricity demand is likely to increase in the future, with estimates ranging from 80% to 150% by 2050 (Svenska Kraftnät, 2024), which places high demands on the expansion of the electricity grid. The use of off-shore wind power to produce electricity is a method which is expected to play a important role in the development according to the interviews. The problem, however, is that off-shore wind power takes a long time to establish, and therefore needs to be planned in advance. Reasons for the long development times could be attributed to extensive construction projects, uncertain permit processes, and conflicting interests of local actors (e.g. municipalities with veto power). If connected to the sequential and temporal dependency discussed in *blocking mechanism 1,* it becomes evident that sufficient electricity capacity needs to be built to be able to expand the hydrogen production. Even if the energy provision is currently available for production of low volumes of hydrogen, it risks becoming a bottle-neck later when the demand and production of hydrogen increases. An inefficient expansion of the energy production would therefore postpone the hydrogen diffusion or lead to market stagnation. Accordingly, this blocking mechanism negatively affects the *market formation* function.

Blocking mechanism 5 – Unclear national hydrogen goals

The fifth blocking mechanism is related to that Sweden currently has no national hydrogen strategy. The facilitator actor group is especially affected by these kinds of national directives, and without them, it is hard for these actors to act in a systematic and consistent way, as decisions are taken based on individual judgement. Many interviewees attested to that the lack of national directives create large obstacles for actors within MSHV. For example, because there are no guidelines, interviewees described how policymakers from different municipalities sometime make decisions that impede on the regional hydrogen development by sub-optimizing for their own municipality. This blocking mechanism primarily impacts the *influence on the direction of search* and *resource mobilization* function negatively. The lack of a hydrogen strategy reduces the incentives for actors to join the TIS and hinders the ability of facilitators (e.g., grant providers and municipalities) to support the TIS effectively.

Blocking mechanism 6 - Inefficient application processes

The final blocking mechanism is inefficient application processes, which refers to the long and uncertain processes when applying for both grants and permits. These application processes were commonly brought up as problems in the interviews, with several motivations. One of the motivations is linked to the sequential and temporal dependency in *blocking mechanism 1*, since lengthy and uncertain application processes lead to significant difficulties when planning and collaborating. Four specific examples were given in the interviews where projects had become majorly delayed by permit processes. One example was a hydrogen producer waiting for a permit from an environmental agency investigating the risks for bird life at the facility's location – which delayed everything, as all other processes were already complete. Another example is a hydrogen infrastructure provider who had completed all of their construction and engineering, who were only waiting for the permit approval to start building. Such delays significantly complicate collaboration and forecasting efforts.

Another motivation that was brought up in the interviews were specifically about grants, since the process required a lot of time from the actors who had applied. This resulted in employees having to work close to full-time specifically with this task. As one interviewee explained, this creates a reluctancy for smaller companies, with smaller budgets and fewer employees, to apply for grants. These motivations showcase that the inefficiencies that exist in application processes risks negatively affecting the functions of *market formation* and *resource allocation.*

4.4 Specifying key policy and managerial recommendations

The last step of the TIS analysis is to make recommendations for policymakers and managers. These recommendations have the purpose of alleviating the blocking mechanisms and in turn strengthen the functions of the TIS. These recommendations are presented in *Figure 7* below, along with the results from all other steps of the TIS analysis. The recommendations are presented in more detail further below the figure.

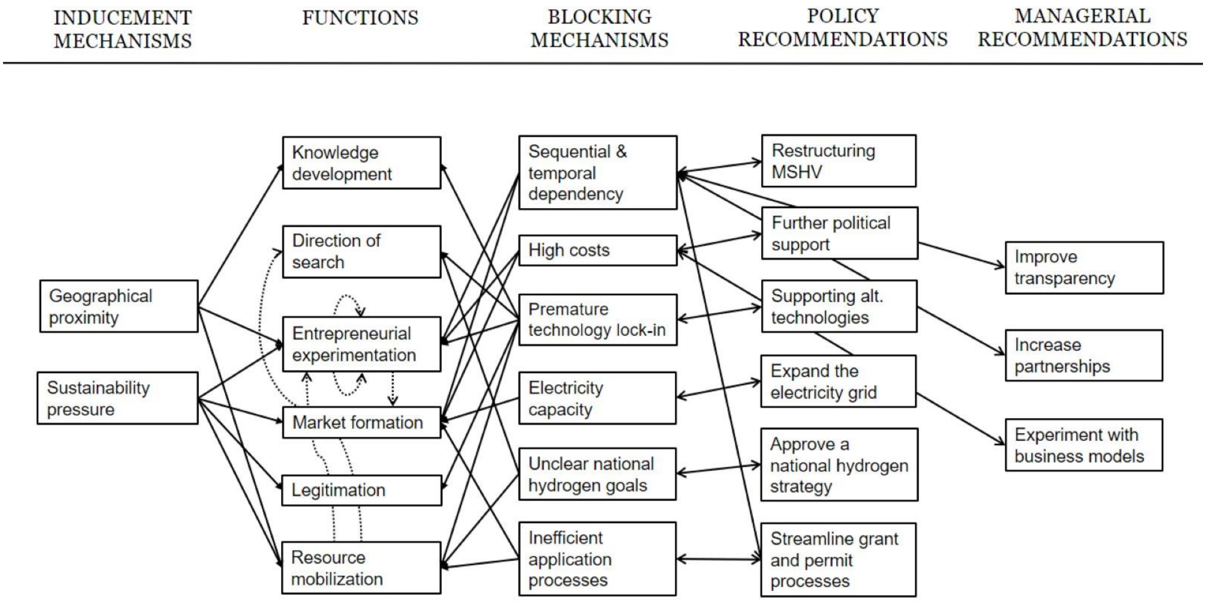

Figure 7. Results from the TIS analysis with corresponding recommendations for policymakers and managers. The function of positive externalities is indicated by the dotted lines between the other functions.

Recommendation for policymakers 1 - Restructuring MSHV

The first recommendation is for the decision makers of MSHV to restructure the hydrogen valley, to better incentivize the actors in MSHV to collaborate on more practical projects – which could in turn alleviate blocking mechanism 1. As it currently is designed, MSHV is regarded as a knowledge sharing platform between the members, with no commitments required. Some members have expressed frustration that MSHV feels like a “discussion club”, with very little action being taken outside of the get-togethers. A way to combat this supposed disadvantage could be to become a legal entity, similar to the hydrogen valley in Rotterdam, which according to the interviewees have the power to allocate funds and initiate projects centrally.

Another type of structure that MSHV could utilize is one which is currently used by Klimatledande Processindustri (Klimatledande Processindustri, 2024). This is a collaboration platform with members from the materials- and chemicals industries of Western Sweden, and from research institutes and universities. Klimatledande Processindustri aims to make the Swedish region of Västra Götaland fossil-free (Klimatledande Processindustri, n.d.-b). Similarly to MSHV, it arranges meetings and seminars, but also has the possibility fund collaborative projects, under the condition that at least two members from industry and one research organization participates. The funded projects involve research organizations receiving financial support to lead the studies, while industry members contribute by dedicating a certain amount of in-kind time to the project. This approach effectively encourages collaboration between the research and industry members (Klimatledande Processindustri, n.d.-a).

Other less drastic forms of restructuring could also be made, e.g. to have more conferences and to increase marketing for the collaborations and get-togethers. Some conferences could be in the form of workshops where actors from different actor groups could discuss the development and the regional challenges. Compared to traditional conferences, the workshops might lead to even more interactions, which could result in more partnerships. These initiatives could create a positive pressure on actors to participate, since it will showcase that many other actors are participating and seeing positive results. It will also lower the risk of actors leaving, since actors who are only looking to share knowledge (and not participate in many projects) are still welcomed. This approach, or a combination of the two approaches, could be a favorable resolution, since many actors from the interviews appreciated the less demanding approach taken today. The goal of these recommendations is to improve coordination and communication between the actors, thereby reducing uncertainty and risks in the value chain, and ultimately increase entrepreneurial experimentation and market formation.

Recommendation for policymakers 2 - Increased economic incentives

As mentioned previously (theory chapter), there are two distinct types of policies that could promote the development of hydrogen: the first stimulates the use of hydrogen, and the second impedes the use of other energy sources, such as fossil fuels. One major policy, of the former type, that was mentioned in the interview with the MSHV coordinator was the US Inflation Reduction Act. This policy, in part, aims to reduce the price of low-carbon hydrogen by 80% to $1/kg within a decade, e.g. by subsidizing US hydrogen valleys, electrolyzers, and other hydrogen production methods (The White House, 2023). This projected price level is considered to be very competitive by the coordinator of MSHV, and the policy could be an important opportunity to overcome many of the economic challenges associated with low-carbon hydrogen. This policy is especially prominent, as it is initiated by the government of the leading world economy, which therefore has large potency to influence other countries. The coordinator believes that if a similar initiative would be taken in Sweden, the outcome of such a policy could revolutionize the energy landscape and significantly accelerate the transition to a sustainable hydrogen-based economy in MSHV. However, it is important to highlight that these price reductions are not sustainable in the long run, since financial resources are taken from other parts of the society. Instead, these policies should be seen as a temporary solution with the aim to establish a functioning value chain and a self-sustaining hydrogen market.

Another example of the first type of policy is the EU's funding program, which includes the goal of scaling up and commercializing the hydrogen market within the EU (European Commission, 2024a). This is done through an auction, which implies that project developers bid for a subsidy for a specific activity or product (see *Appendix B* for step-to-step process). The first auction was launched on 23 November 2023 to support production of renewable hydrogen and out of 132 bids from 17 countries, 7 projects received an Innovation Fund Grant (see *Appendix C*). The next auction is planned to be launched before the end of 2024. The advantages with using an auction as a financing instrument includes: (1) cost-efficient support (2) shifting the risk onto project developers, as payments are based on delivered volumes (3) transparency in revealing costs and setting valuable and comparable price points, which can help in starting a European hydrogen market and, (4) easier applications with shorter evaluation times (European Commission, 2024a). Besides informing actors of hydrogen auctions from the EU, Swedish policymakers should evaluate the opportunities with having similar auctions on a national level. Perhaps, these auctions could support in expanding the hydrogen market in Sweden.

The second type of policies are the ones that impede the use of other energy sources, which could be an effective way to make end users switch from fossil fuels to more sustainable alternatives. In Sweden there are for example various energy and carbon taxes on fossil fuels (Skatteverket, 2024) and taxes on vehicles with high emissions called Malus (Transportstyrelsen, 2023). Increasing these taxes could speed up the diffusion of hydrogen and other sustainable energy sources, since the economic incentives to switch increases. However, to avoid the risk of affecting companies' and citizens' economies too negatively, the taxes should increase gradually and to a reasonable level. Furthermore, an alternative is that the revenues generated from the Malus system could be used as a bonus for the use of hydrogen in heavy transports, which would stimulate the use of hydrogen. Moreover, on a EU level, the EU Emissions Trading System (EU ETS) sets a limit on the CO_2eq emissions from major emitters (European Commission, 2024b). In short, this system implies that polluters pay for their greenhouse gas emissions, which besides leading to lower emissions also generates revenues that are used in financing the EU's green transition.

Arguably, policies could be an effective tool in creating a hydrogen market, since they have the ability to bridge the current cost barriers while also stimulating the use of hydrogen, e.g. by reducing production investments and end user costs. Therefore, this would alleviate *blocking mechanism 2 - High costs*, which in turn strengthens the functions of *entrepreneurial experimentation* and *market formation.*

Recommendation for policymakers 3 - Support alternative technologies

Since the interviews revealed a difficulty in securing grants for some technologies, policymakers should ideally support a broader range of technologies, as opposed to being limited mostly to electrolyzers. This could for example materialize in a wider definition of what is considered sustainable hydrogen, e.g. by looking at total carbon footprint rather than a narrow definition, thereby broadening the threshold for political support. As a means to alleviate blocking mechanism 3, the recommendation is therefore to widen the definition of what should be considered renewable hydrogen, by using a definition that encompasses all production methods that have a close-to-zero negative impact on the environment, i.e. by striving for technological neutrality. This could enable multiple technologies to emerge, hopefully complementing each other's weaknesses. For example, alternative technologies could be used to partially off-set some of the demand on the electricity grid, by using methods that require less electric energy. In addition, the future demand for electrolyzers could potentially be much higher than the capacity for producing them, making other production methods an important way to diversify risk. However, these alternative methods will most likely have drawbacks of their own, which is why a mix of complementary hydrogen technologies are most favorable. The suggestion has many positive effects on the functions of the TIS, see *Figure 7*. However, one potential risk with the recommendation is that the direction of search and entrepreneurial experimentation could become less focused, which in turn could lead to reduced economies of scale and knowledge development for the technologies with less focus.

Recommendation for policymakers 4 - Expand the electricity grid

As the society electrifies, the electricity consumption in Sweden will increase significantly. Svenska Kraftnät (2024) predicts 80-150% increase in demand in the next 25 years. The demand for low-carbon hydrogen, which is expected to skyrocket within the upcoming decades, will require vast amounts of electricity, especially if the hydrogen is produced by electrolysis. Since renewable energy infrastructure takes many years to build, it is important to take action now to avoid becoming a bottleneck in future. Hence, policymakers should incentivize renewable energy production and set goals that reflect the predicted increase in demand. From the interviews, an issue that was continuously brought up was that it is difficult and takes a long time to obtain permits. This indicates that policies that simplify and speed up the permit processes could have a positive impact on the electricity supply. Furthermore, the interviews also showed that it is beneficial if the electricity production is located close to the hydrogen production facilities, which is also something that policymakers should keep in mind when planning the expansion of electricity production, for example by providing specific grants to some regions.

Recommendation for policymakers 5 - Approve a national hydrogen strategy

To alleviate *blocking mechanism* 5, it is essential to approve a national hydrogen strategy. Specifically, the grant provider *Energimyndigheten* should be appointed to this task, given their experience in creating a national hydrogen strategy in 2021 (which was not approved when the new government was appointed). Establishing a national hydrogen strategy would result in more consensus between actors in the TIS, as all actors will operate towards the same goals and with the same guidelines. Consequently, this would lead to better support in MSHV from facilitators and improved mobilization of resources.

Recommendation for policymakers 6 - Streamline grant and permit processes

As the grant and permit application processes have been labeled cumbersome by the majority of the interviewees, the final recommendation for policymakers is to revise the long processes that exist today. As it is seen as a major obstacle for actors in MSHV, policymakers should allocate more resources to the agencies that control these processes. Further suggestions have been given by some of the interviewees, which includes making the processes work in parallel when there are multiple steps, and better prioritizing. This would prevent ineffective situations from occurring, such as a hydrogen producer having to wait for approval from an environmental agency who wanted to investigate the bird life, or an infrastructure provider with all material and planning completed having to wait for long processes in building permits. Consequently, this recommendation would alleviate *blocking mechanism 6 - inefficient application processes*, and also *blocking mechanism 1 - sequential and temporal dependency*. Alleviating blocking mechanism 1 is made through reducing uncertainty and improving the ability to collaborate in a predictable way, which in turn improve *entrepreneurial experimentation* and *market formation*. However, it is important to be aware that ensuring proper due diligence in these grant and permit processes is continually essential. Therefore, any efforts to streamline these processes must be balanced with maintaining thoroughness.

Recommendations for managers 1 - Improve transparency

As described earlier, there exists a blocking mechanism in MSHV in terms of a sequential and temporal dependency between the actors in the value chain. To avoid creating a bottleneck in the value chain, actors will need to match the capacity of other actors groups at the same time. A recommendation to alleviate this blocking mechanism is for managers to increase transparency about capacity and readiness level. For example, a hydrogen producer should ideally be public about their investments to produce a certain amount of hydrogen, which would make the rest of the value chain able to adapt. The same type of transparency regarding projects and planning time-horizons should ideally be taken by all actor groups.

It is important to consider that companies might be reluctant to share information about their hydrogen projects. However, the give-and-take culture of MHSV may help in alleviating this fear and helping companies open up to other actors in MSHV. In other words, if companies want to know about the capacity and plans of other actors in the value chain, they too have to reveal this type of information. If more companies trust each other and increase their transparency with each other, this could help alleviate blocking mechanism 1 and in turn improve *entrepreneurial experimentation* and *market formation*. The “chicken-and-egg” problem that was mentioned earlier could potentially also be alleviated.

Recommendations for managers 2 - Increase partnerships

As mentioned, the hydrogen value chain is complex, with many different actors that are dependent on each other. In addition to improving transparency, managers should also look to enter into more partnerships with actors along the value chain. Finding partners to share risks and investment costs is essential. For example, hydrogen producers need to collaborate with energy companies to secure electricity supply, and identify customers willing to purchase their hydrogen, unless they intend to use it themselves. The complexity of the hydrogen value chain extends to managing by-products like excess heat and oxygen, which requires partnerships with actors that can utilize these resources. For example, district heating infrastructure in the mid-Sweden region is currently being expanded (Wickström, 2024), which can open up many collaboration possibilities. Similarly, in the context of waste gasification, it is crucial to partner with waste suppliers. Establishing connections through organizations like MSHV can facilitate these partnerships. Moreover, engaging with current partners about their sustainability transitions can uncover new opportunities for collaboration in the hydrogen sector. Having closer relationships with other actors, as opposed to short-term contracts, is ultimately beneficial for alleviating blocking mechanism 1 and improving the hydrogen market formation.

Recommendations for managers 3 - Experiment with new business models

The final recommendation for managers is to experiment with new business models to enhance profitability and sustainability within the hydrogen value chain. Exploring alternative revenue streams is a critical step in this direction. For instance, the residual heat generated from electrolysers presents a valuable opportunity. By selling this excess heat to nearby industries or residential areas, hydrogen producers can create an additional income source that helps offset initial investment costs – however, the excess heat has to be connected to a low-temperature infrastructure, which are currently limited. If this can be accomplished, this approach not only maximizes resource utilization and increases revenue, but also promotes a more circular economy. Managers should actively seek and develop such innovative business models, leveraging by-products and optimizing the entire production process for financial and environmental benefits.

Other types of business models could include co-ownership of hydrogen investments, such as electrolyzers. This ownership structure will result in lower investment costs, with revenues or utilization of the electrolyzer being shared among the partners according to the agreement. Therefore, if managers want to reduce the high investment costs and risks associated with hydrogen investments, it is recommended that they explore different partnerships involving co-ownership. For instance, they could create joint ventures with companies that have similar needs and operational contexts. These recommendations for exploring novel business models have the potential to reduce blocking mechanism 2, by providing additional revenue sources, cutting costs, or reducing risks.

5. Conclusion

By using a TIS framework, this thesis set out to address three primary research questions related to the development of hydrogen valleys, using Mid Sweden Hydrogen Valley (MSHV) as a case study. To conclude, each research question is answered below, followed by a discussion of the theoretical contribution of this study, and finally suggestions for further research.

RQ1: What are the structural components, i.e., actors, networks, institutions, and infrastructure, in a hydrogen valley, and how are they interconnected?

Our research identified the key structural components of MSHV, which include several actor groups along the hydrogen value chain (i.e. renewable energy providers, hydrogen producers, storage/distribution providers, and hydrogen users), as well as supporting actor groups such as facilitators (i.e. grant providers, incubators and research institutes, and authorities) and OEMs. The largest network is the MSHV collaboration platform which include over 30 actors. In addition, seven smaller networks in the form of partnerships were identified. Further, the institutions within MSHV are characterized by mutual trust and a collaborative mindset, but also affected by the lack of a national hydrogen strategy and appropriate regulations. The necessary infrastructure in MSHV includes fueling stations, pipelines, and renewable energy parks.

RQ2: How do the functional dynamics affect the development and performance of a hydrogen valley?

The analysis revealed that the development and performance of a hydrogen valley is greatly affected by the seven functions of the TIS framework, where some functions also affect each other, leading to positive or negative reinforcing mechanisms. MSHV performs relatively well in the performance appraisal of its seven functions, where each function is labeled as either intermediate or strong. For example, MSHV works well as a platform for increasing knowledge development, grant providers ensure financial resource mobilization for various hydrogen projects, regulatory frameworks provide strong incentives for actors to become more sustainable and explore hydrogen use-cases, and some early adopters are taking the initiative through ambitious hydrogen projects and collaborations. However, findings also indicate that there is room for improvement within some functions. For example, many actors are not taking action due to the high uncertainty that exists in the hydrogen market, leading to slow commercialization. The uncertainty seems to be one of the fundamental dilemmas in the hydrogen development. Entrepreneurial experimentation, which are currently low in many aspects of MSHV, have an essential role in forming the hydrogen market and reducing uncertainty. Therefore, these weaknesses need to be addressed before the hydrogen market can move smoothly from a formative phase into a growth phase.

RQ3: Which inducement and blocking mechanisms are present in a hydrogen valley, and how do they impact the valley's development?

The inducement mechanisms found in this study are (1) geographical proximity and (2) sustainability pressure. Geographical proximity is addressing the potential of utilizing the regional area to a larger degree, e.g. in terms of collaboration between relevant actors, knowledge exchange and infrastructure establishment. This inducement mechanism could result in more knowledge sharing and more experimentation. Furthermore, the sustainability pressure from regulatory frameworks leads to an increased willingness for experimentation, an improved social acceptance, and increased availability of financial capital.

Moreover, the blocking mechanisms that were found are (1) sequential and temporal dependency, (2) high costs, (3) premature technology lock-in, (4) electricity capacity, (5) unclear national hydrogen goals, and (6) inefficient application processes. The sequential and temporal dependency, the high costs, and the inefficient application processes, are slowing down the hydrogen market formation. The premature technology lock-in instead affects the influence on the direction of search negatively, as it reduces the variety and willingness to experiment. The unclear national hydrogen strategy reduces the support that the hydrogen valley receives from facilitators such as grant providers and municipalities. Lastly, the electricity capacity could be a potential bottleneck, hindering the market development in the future hydrogen expansion.

Theoretical contributions

Apart from answering the research questions, this study makes several contributions to theory. Firstly, to the best of our knowledge, this study represents the first TIS analysis, or similar socio-technical analysis, to investigate hydrogen valleys, suggesting that the findings provide novel and potentially fruitful insights to the currently limited body of literature on hydrogen valleys. Secondly, the study contributes to the TIS literature by combining theoretical components from several frameworks, such as including infrastructure as a fourth structural component and acknowledging four additional structural considerations. In doing so, we have created an expanded analytical framework that could potentially be used by future analysts wishing to conduct a more exhaustive TIS analysis. Thirdly, the methodology of the performance appraisal has been described in more detail compared to previous TIS analyses. Due to the arbitrary nature of performance appraisal methodologies, the expanded explanations in this study could potentially aid future TIS analysts. Finally, the study highlights how a TIS framework could have a more managerial focus, as previous TIS analyses have primarily focused on policymakers.

Limitations and suggestions for further research

A major limitation of this study is the lack of generalizability when investigating a single case like MSHV. To enhance our knowledge of hydrogen valleys, further research should therefore examine the structural context and functions of other hydrogen valleys to determine if similar findings exist on a more general level. Even though qualitative methods is arguably a strenght of this study, e.g. by being able to explore the context of hydrogen valleys in a deeper and more nuanced way – the qualitative nature can sometimes lead to subjective presuppositions, e.g. when appraising the functions' performance. This limitation is likely difficult to mitigate, as the explorative nature of hydrogen valleys makes it almost impossible to find definitive answers that are not nuanced or multifaceted. However, future research should favorably investigate many of the findings and recommendations of this study more in depth, preferably in terms of their practical implementation or perhaps using quantitative methods. For example, some recommendations for policymakers and managers may have secondary consequences that were not identified in this study, thereby justifying further research to ensure comprehensive understanding and effective application of the findings.

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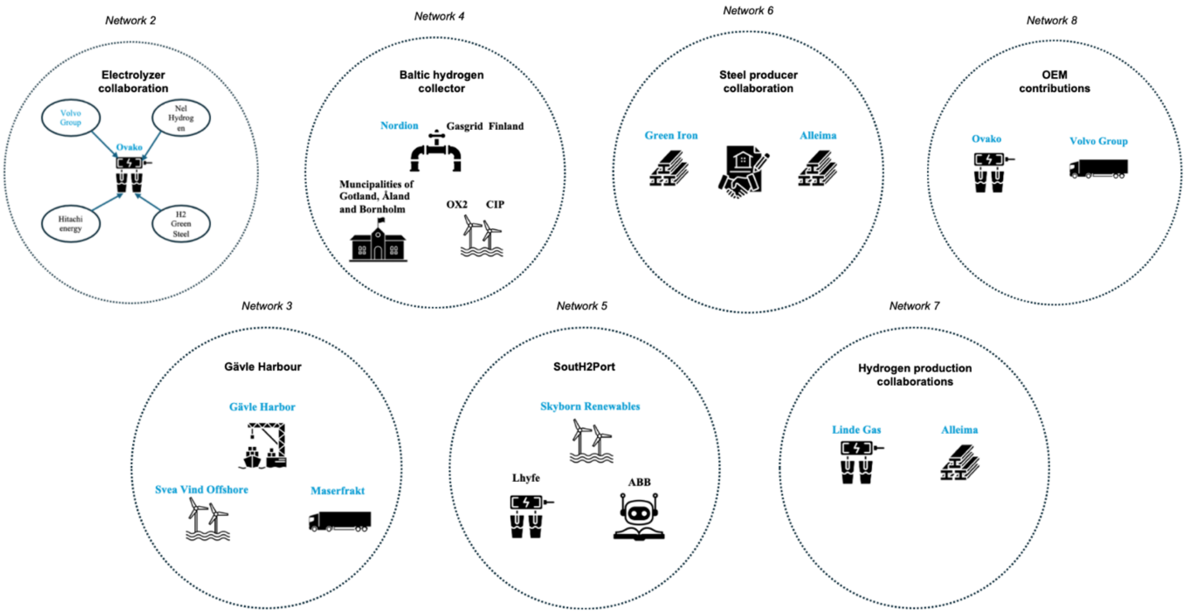
Appendix A

A visual illustration of the identified networks in MSHV. Network 1 is not included.



Appendix B

Step-by-step process of the European Commission's auction (European Commission, 2024a).

Appendix C

Overview of the projects that received funding from the auction launched on 23 November 2023 (European Commission, 2024a).

Project	Coordinator	Country	Bid volume (kt_H_2 / 10 yrs)	Bid capacity (MWe - megawatts electricity)	Expected GHG avoidance (kt_CO_2 / 10 yrs)	Bid price (EUR/kg)
eNRG Lahti	Nordic Ren-Gas Oy	Finland	122	90	836	0.37
El Alamillo H_2	Benbros Energy S.L.	Spain	65	60	443	0.38
Grey2Green-II	Petrogal S.A.	Portugal	216	200	1477	0.39
HYSENCIA	Angus	Spain	17	35	115	0.48
SKIGA	Skiga	Norway	169	117	1159	0.48
Catalina	Renato Ptx Holdco	Spain	480	500	3284	0.48
MP2X	Madoquapower 2x	Portugal	511	500	3494	0.48

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