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Implementing a hydrogen system into the power grid

Business models for hydrogen energy storage applications in the Swedish grid

Master’s thesis in Management and Economics of Innovation

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se
Report No. E2023:054

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Printed by Chalmers Reproservice
Gothenburg, Sweden 2023

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Abstract

The power grid is more than essential in today's society, and it needs to remain stable to operate. Today there is a transition from fossil fuels to renewable energy and the power grid needs to be modified stay stable. The increased amount of renewable energy makes the power grid less plannable due to the energy sources being dependent on the weather itself. This creates potential discrepancies in the grid between consumption and production. To create a power grid that can handle the volatility it is important to store energy. Hydrogen is a storage medium that has recently gained an increased focus. Using a hydrogen system consisting of an electrolyzer, a storage tank, and a fuel cell, creates a whole solution for energy storage that can be implemented in the power grid. The report focuses on innovation management and tries to explain patterns in the transition to renewable energy sources. It also focuses on the economic feasibility of implementing a hydrogen system in the power grid in two different scenarios. Firstly it investigates the potential for using a hydrogen system for electricity arbitrage, and secondly, a hydrogen system which helps mitigate fluctuations in frequency through the ancillary services. The model forecasts future prices of electricity and ancillary services based on historical data to help estimate the potential profitability of these two scenarios. The analysis is based on a discounted cash flow model which estimates cash flows during a 10-year investment in the form of a net present value. While the first scenario, i.e., electricity arbitrage is far from profitable, ancillary services appear to be a profitable application of a hydrogen system today.

Keywords: Ancillary services, Electricity arbitrage, Electricity spot price, Electrolyzer, Fuel cell, Hydrogen system, Innovation management, Power grid.

Acknowledgements

We want to thank everyone at PowerCell Group, and especially our supervisor and contact person Dr. Andreas Bodén, for the contribution to the report and throughout the entire process. It has been a valuable experience in a growing industry and organization. We would also like to thank Prof. Hans Löfsten, our supervisor and examiner at Chalmers, for all the valuable help during the process. Lastly, we would like to thank all respondents for taking the time to participate in our interviews and providing us with important data.

Victor Koch, Gothenburg, May 2023
Jacob Svensson, Gothenburg, May 2023

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Introduction

The report will start with an introduction to the topic through necessary background information to understand present and future challenges relating to climate change and what is presently done. The focus is on electrification and hydrogen technologies. Thereafter, a section on the implications of renewable energy on the Swedish power grid will follow, which will end up with a section defining the problem statement, helping to identify and narrow down the problem at hand with a set of research questions. Lastly, the research aim and demarcations are presented.

1.1 The effects of mitigating climate change

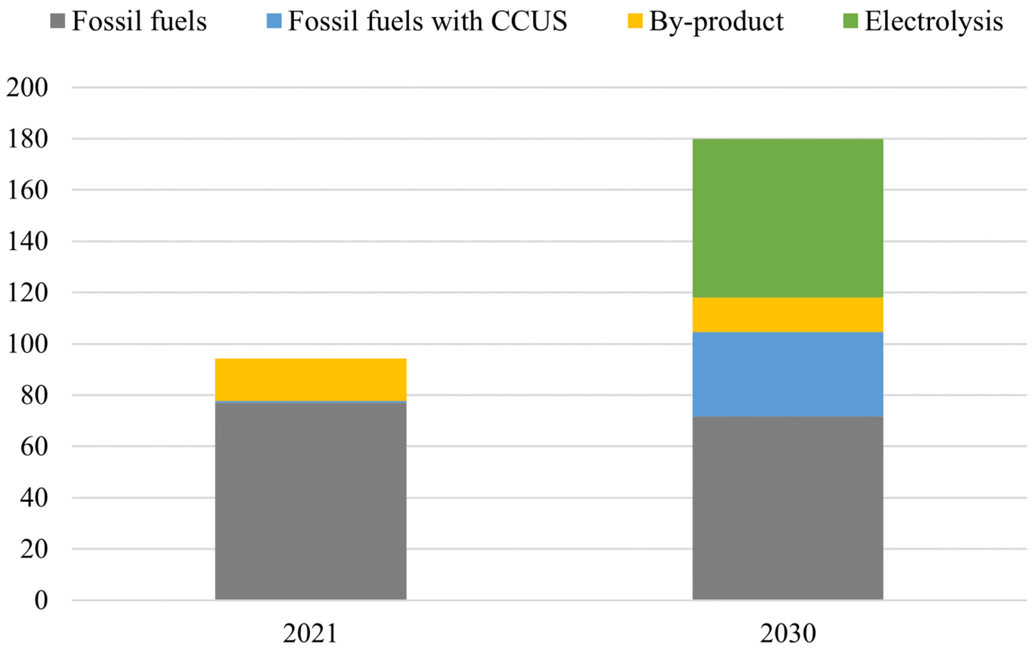
The climate change debate is high on every agenda, from rising sea levels to more extreme weather, the climate effects are changing human behaviour globally. Responsibility has been split among governments, companies, and individuals, however, progress has been slow. Governments have introduced goals, both locally and globally to affect companies and consumers. Most countries in the world have signed the Paris Accord, and thus agreed on Agenda 2030, aiming for a maximum rise in temperature of 1,5 °C (UN, n.d.). A global shift away from fossil fuels is needed to meet the global climate change targets set by Agenda 2030 (UN, n.d.). To achieve this, governments have introduced regulations and taxes on pollution to nudge society towards alternative fuels.

New technologies and solutions are needed to replace fossil fuels. A big part of the transition is electrification, a change which is already underway, and accelerating through governmental nudging which incentivizes companies and consumers through this path. The automotive industry, for example, is shifting away from internal combustion engines (ICE) to electric vehicles (EVs). After 2035, in the European Union (EU), combustion engines in new cars will be banned (European Council, 2022). Because electrification is so widespread, the global shift will lead to large increases in electricity demand. In Sweden, electricity demand is expected to double by 2045 (IVA, 2022). However, all processes cannot be electrified, but many can be altered in other ways to become climate neutral. One example is replacing fossil fuels with hydrogen, which in steel production can be used instead of coal to drastically reduce its carbon emissions (IEA, 2022d). The global demand for all types of hydrogen amounted to 94 Mt in 2020 but is expected to double in 2030 as innovation shifts processes from fossil fuels to using hydrogen (International Energy Agency [IEA], 2022c).

While hydrogen is the most abundant element in the universe it is rarely found in its pure form (Amaroli and Balzani, 2011). Instead, it is often found together with oxygen making up water, or with carbon to form molecules called hydrocarbons, some of which make up fossil fuels. Consequently, these are the two main options for extracting hydrogen. In 2021, 62 % of the global supply of hydrogen came directly from natural gas as seen in Figure 1.1. However, this leads to large emissions of carbon dioxide (CO2) (IEA, 2023) and is therefore not a viable climate-neutral solution. If hydrogen is to become a replacement for fossil fuels, it needs to come from water.

The share of low-emission hydrogen, meaning hydrogen created through water electrolysis or from natural gas equipped with carbon capture, utilization, and storage (CCUS) systems that minimizes CO2 emissions, was in 2021 less than 1 % of the global hydrogen supply (IEA, 2023), meaning less than 1 Mt. However, IEA (2023) expects the demand for low-emission hydrogen to surpass 100 Mt in 2030 and 450 Mt in 2050, which will substantially increase the electricity demand, needing 700 GW of renewable energy in 2030, assuming 70 % comes from electrolysis.

Figure 1.1: A comparison of hydrogen sources in 2021 and 2030 (IEA, 2023).



To meet the increasing demands for renewable energy, from electric cars to hydrogen production, alternatives like solar panels and wind turbines are needed to replace the fossil energy sources such as coal, oil, and natural gas (IEA, 2022b; Kungliga IngenjörsVetenskapsAkademien [IVA], 2022). However, these new sources lead to an entirely different playing field, where energy production is heavily weather-dependent (IVA, 2022). Therefore, there is a risk that the electricity supply cannot meet sudden high demands, leading to a volatile energy price, necessitating solutions to ensure a stable affordable supply of electricity.

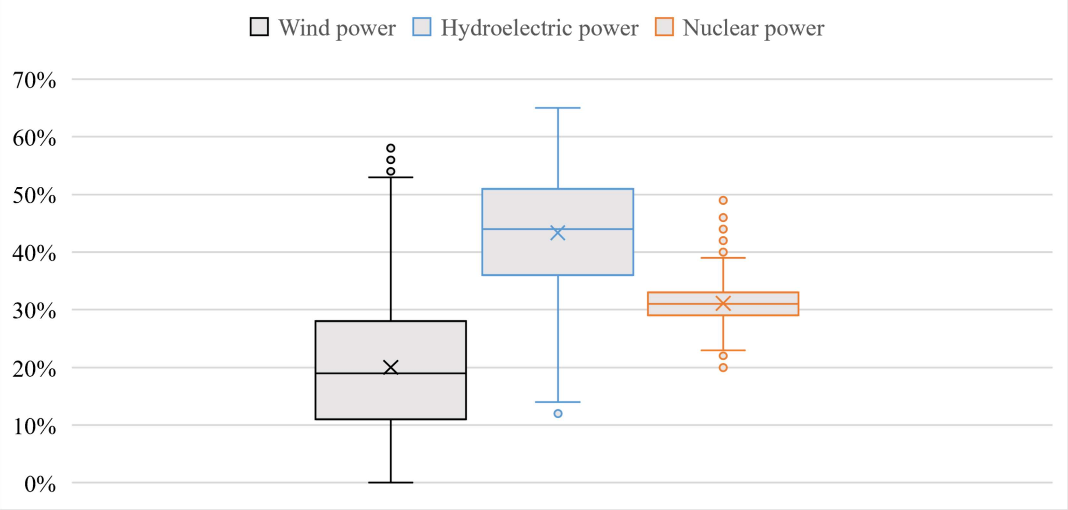
1.2 The impacts of renewable energy on the Swedish power grid

The Swedish power grid was deregulated in 1996 and is now run by multiple actors in a competitive market (Svenska Kraftnät [SVK], 2021). SVK is a department of the Swedish government responsible for developing and maintaining the national high-voltage transmission lines, while regional and local distribution lines are owned and run by private power companies (SVK, 2022b). The market is free, and the electricity prices are generally determined by supply and demand. However, constraints in transmission lines cause discrepancies in pricing under heavy loads due to the geographical imbalance in the production and consumption of electricity (SVK, 2022b). While the demand fluctuates depending on the time of day, season, and weather, it is rather predictable, and supply can therefore be planned accordingly, which is done through day-ahead auctions. Small mismatches, however, are expected, and in Sweden, it is the responsibility of SVK to stabilize the power grid through balancing power reserves and regulation power, denoted as ancillary services (SVK, 2022b). The frequency of the power grid is set to 50 Hz, but small fluctuations are expected to happen due to mismatches in production and consumption (SVK, 2022b). The power reserves are energy sources that can start up rapidly to meet high demand when the regulation power is not sufficient.

The total electricity consumption in Sweden amounted in 2020 to 134,9 TWh, a number which is expected to rise as electrification speeds up (IVA, 2022). They project the demand to reach somewhere between 157 and 162 TWh in 2030, depending on the level of electrification. Wind power is currently one of the most attractive sources of renewable electricity since it is highly profitable compared to others, and IVA (2022) expects the majority of the rise in demand to be met by wind because of its competitive price. Wind power is predicted to produce on average between 26 % and 30 % of electricity in 2030, thus passing nuclear power and becoming the second largest energy source (IVA, 2022).

Today's fossil-based energy sources are plannable and are therefore well suited to meet fluctuations in demand. However, because renewable energy sources are weather dependent, the supply is becoming less plannable. There are, simply put, two options to mitigate this, either invest in a large overcapacity or bridge the discrepancies with energy storage solutions. Today, energy for regulation power is often stored in spinning flywheels, and the output of hydroelectric dams is regulated to balance the load (IVA, 2022). The hourly production from wind power fluctuated in 2022 between 75 MWh and 10 763 MWh, a difference of 10,7 GWh (SVK, n.d.-a). As seen in Figure 1.2, this large variance means that wind power contributes close to 60 % of the total power production in rare circumstances, however, it can also produce nothing in times of low wind. Hydroelectric power can be scaled between 3 and 13 GWh according to IVA (2022), meaning that it is sufficient for now, but the limits are being reached. The issue is further compounded by the correlation between cold temperatures and slow winds which severely impacts the price of electricity due to the regulation power not being sufficient in extreme cases, which will only be more prevalent in a future scenario of a substantially higher share of renewable energy production as predicted by the IVA (2022).

Figure 1.2: Share of total power production from top three sources 2022 (SVK, n.d.-a)



Microgrids are often proposed as part of a solution, where energy production and storage are decentralized and localized close to the demand (Hatziargyriou et al., 2007). Enabling grid-wide storage systems can help renewable energy sources such as wind and solar to operate near their maximum capacity more often. When conditions are favourable, such as high winds and clear skies, the excess electricity is stored for when demand is high and conditions are unfavourable. Such a solution for storing energy can be built upon a hydrogen system. The system produce hydrogen, through an electrolyzer, stores the hydrogen in a tank and then later consumes it to produce electricity via a fuel cell.

1.3 Problem statement and research questions

As the electrification increases globally, so does the need for sustainable sources of energy. Renewable sources such as wind and solar are however weather dependent, as discussed earlier, and thus require a storage medium to balance supply and demand and ensure a stable and affordable price of electricity (Ghirardi et al., 2023). Not only does renewable sources require energy storage, they affect the grid in unpredictable ways, increasing the chances of frequency deviations. An increased share of renewable energy therefor necessitates new solutions for frequency balancing, also called ancillary services. Hydrogen can be used for both of these applications, but the solution is not entirely clear-cut. The Swedish energy mix is already relatively fossil-free, with its main sources in hydro, nuclear, and wind power, which makes it a suitable market for producing low-emission hydrogen.

Batteries are without a doubt currently the most common way to store energy. It is often seen as the key to the electrification trends which aim to mitigate climate change. There are ongoing projects for using batteries for peak shaving and keeping flexibility in the power grid by storing energy from wind power and solar energy (Vattenfall, n.d.). One newly built renewable energy park in the Netherlands aims to stabilize the power grid through a combination of batteries, wind, and solar power into a hybrid park. There is also a project in Uppsala with uses a large-scale battery backup (Vattenfall, n.d.). However, Today's battery technologies can be insufficient in terms of cost and scale, as well as sustainability due to the production of its components and sourcing of rare metals (Borah et al., 2020). Therefore there is a need for other technologies of storing energy.

Whether it is better or not than a hydrogen system is difficult to determine, with varying opinions from experts. One study from Ghana suggested an optimal solution concerning energy generation capacity, emissions, and costs from wind power (Acakpovi et al., 2020). They concluded that batteries have a clear economic advantage, but also have a higher environmental footprint compared to hydrogen fuel cells. This highlights the importance of considering all parameters when comparing the two technologies. Acakpovi et al. (2020) argues that the world needs to pay more attention to hydrogen when exploring new sustainable means of storing energy. In an off-grid application, i.e., an island, Singla et al. (2021) concluded that hydrogen fuel cells were both more suitable and cost-effective when the energy source came from wind and solar power. Belmonte et al. (2016), on the other hand, concluded that, for an off-grid application in Turin with a 3kW peak power, it was more cost-effective to use a battery system. Rodrigueza et al. (2022) conclude the opposite, showing that a hydrogen system would be cheaper.

Using hydrogen as a part of the grid is uncharted territory, and the technology's maturity compared to other technologies such as batteries and established means of producing energy such as burning fossil fuels is low. In Sweden, Naturvårdsverket (2022) is investing in low-emission technologies through its initiative Klimatklivet, such as a 50 MSEK electrolyzer investment in Strandmöller AB for green hydrogen. While Sweden is uniquely invested in hydrogen technology, such as leading fuel cell developments by PowerCell Group, it is often difficult for investors to commit to emerging technologies without incentives from governmental actors, thus limiting their technological development and diffusion. To mitigate this, the EU has announced heavy investments in green energy, including hydrogen, to decarbonize the region cost-effectively. In 2020, the EU adopted its vision for a European hydrogen ecosystem, which included research, innovation drivers and scale-up investments for production and infrastructure (European Commission, n.d.), which will help incentivize additional investments from commercial actors. Other European efforts include the Hydrogen Energy Network, which an informal group of energy ministers from its members to share knowledge, good practices, and developments (European Commission, n.d.). The EU has also launched the European Clean Hydrogen Alliance to support its hydrogen strategy and is aimed to bring the industry together, including both national and local actors, the public, and other stakeholders (European Commission, n.d.; Naturvårdsverket, 2022).

The transition to renewable energy will affect the energy market, leading to opportunities for new entrants and exits from failing firms. Firms that earlier were successful in terms of products and knowledge need to adapt, which requires new types of knowledge (Anderson & Tushman, 1990). However, innovation does not always succeed and cannot always compete with established ones (Geels, 2004). In this case, a change in the behaviour of the market and nudging from governments can be necessary to create opportunities for innovations within the energy sector.

Incumbent firms that cannot break up from path dependencies and lock-in effects often end up in a difficult situation. Historically, There are many well-known examples of innovations that dramatically replaced the old, and the leaders of the incumbent technology were not able to handle the transition. One example is the Swedish company Facit which was a manufacturer of mechanical calculators (Sandström, 2013). Facit dominated the market for a long time, but when the electronic calculators came, they went bankrupt only a few years later (Sandström, 2013) The electronic calculators were more user-friendly and had a better performance compared to mechanical ones. The knowledge of constructing intricate mechanical parts was no longer relevant to the new technology, meaning that much of Facit was rendered obsolete.

Though there are lots of both national and international efforts to develop hydrogen technologies, it is still emerging and there are many uninvestigated opportunities, especially using hydrogen as an energy storage medium. By exploring some of these implementations, and investigating their future potential, this study will be a piece of a much grander puzzle. It will focus on the potential profitability as a measure of potential within two scenarios, or use cases, of a hydrogen energy storage system in grid applications from an investor's perspective. The transition and development towards renewable energy also make it interesting to focus on innovation management and how different innovations are emerging alongside other technologies. Breaking down the introduction and problem statement leads to the following set of research questions:

- *Which of the following scenarios of implementing a hydrogen storage system into the power grid is profitable?*
  1. *Scenario 1: Using the hydrogen system for electricity arbitrage.*
  2. *Scenario 2: Using the hydrogen system for ancillary service to balance the frequency.*

- *How can the patterns of innovation, such as life-cycles, market dynamics and socio-technical transitions help explain the shift towards renewable energy?*

1.4 Research aim

The purpose of the report is to understand recent and future developments in the power grid through innovation management and the potential roles for hydrogen systems. To achieve this, the report aims to determine the potential profitability of implementing hydrogen as a storage medium in areas where the waste heat can be captured to maximize the system's efficiency. The system, as calculated, will be integrated into the Swedish power grid to mitigate the mismatch between the supply and demand of electricity by offering different solutions.

1.5 Demarcations

The report will focus on the potential of implementing hydrogen for electricity arbitrage and ancillary services in the Swedish power grid to handle the mismatch between the supply and demand of electricity. The reason behind this is that every country is different in terms of regulations and preconditions for the power grid and its supply, making it difficult to generalize any findings to other countries. For electricity arbitrage and ancillary services, the PEM technology is most suitable. The industry believes in the PEM technology and there is a great focus on developing it further because it has a great potential to reach a higher efficiency. The technology will be examined and compared with others in Chapter 2. However, the hydrogen system can be used for other purposes such as back-up power.

The system consists of an electrolyzer, storage, and a fuel cell. While the initial investment in hydrogen storage includes peripheral components, e.g., compressors, the fuel cell and electrolyzer do not. They require other peripheral components, such as a management control system or inverters. These expenditures are low compared to the whole investment and are therefore neglected. Furthermore, the discounted cash flow model does not consider taxes. The amount of taxes is dependent on which region, SE1, SE2, SE3, or SE4, the system is placed because it is a surcharge. In SE1, the electricity price is cheaper compared with SE4, resulting in a lower amount of tax, but with the same percent surcharge. It is also important to consider the book value of the company, meaning if the result is negative from other operations, the taxes will be substantially lower.

2

Technical background

Storing energy can be done in many ways, one of which is hydrogen. Hydrogen can be used in areas where other types of storing are difficult or inefficient, often in bigger applications (IEA, 2023). A hydrogen system consists of an electrolyzer, a storage medium, and a fuel cell. The electrolyzer converts electricity to hydrogen and the fuel cell converts hydrogen to electricity. The process is shown in Figure 2.1.

Figure 2.1: Schematic overview of a hydrogen energy storage system.

The following sections will introduce a basic understanding of the technologies behind hydrogen electrolyzers and fuel cells. Then there will be an introduction to ancillary services, and the last section will be an overview of the district heating network, which the hydrogen system is connected to. The hydrogen system will create heat and to keep a high efficiency it must be captured and utilized.

2.1 Hydrogen electrolyzer technologies

There are many electrolyzer technologies currently available on the market and the technology chosen is often dependent on the application area. The production of renewable hydrogen today costs around \$ 5 per kilogram and the goal is to reach \$ 2 in 2025 and further down to \$ 1 by 2030, which requires new technologies with higher efficiency (U.S. Department of Energy, n.d.). Rise (2022) concluded that three main technologies can be useful in the power grid. These are Alkaline water Electrolyzer Cell (AEC), Proton Exchange Membrane Electrolyzer Cell (PEMEC) and Solid Oxide Electrolyzer Cell (SOEC). Today, the AEC technology is the most common, most developed and has the lowest costs. It is, however, difficult to develop the technology further in terms of cost and efficiency (RISE, 2021a). The AEC has a slow start-up time and a slow response to frequency changes in the power grid compared with PEMEC. This makes it difficult for using together with a renewable source which tends to have more frequency deviations (Zhang et al., 2022). The PEMEC, on the other hand, has greater potential with higher technological possibilities compared to AEC. For example, PEMEC can operate under a lower cell voltage, has higher current densities, can be reversible, is less caustic, highly pure, and works on higher pressure and temperature leading to higher potential efficiencies (Falaco & Pinto, 2020). It also has the best cost reduction potential, soon becoming cheaper than AEC and dominating the market in the future (RISE, 2021a). However, PEMEC contains expensive and rare raw materials in its membrane and electrolyte (RISE, 2021a). The SOEC technology, on the other hand, is relatively new and is in the early stage of development (Zhang et al., 2022). To produce hydrogen, the SOEC requires both a high temperature and pressure, which makes it difficult to use in scenarios relevant for this report. Zhang et al. (2022) concluded that the PEMEC technology is most attractive to use in a renewable energy system. This report will therefore focus on PEM electrolyzers.

The electrolyzers work mainly in reverse relative to a fuel cell, and they have many components in common. All electrolyzers uses water and electricity to split the molecules into hydrogen and oxygen gases (RISE, 2021). Water is supplied to the anode of the cell where it reacts and creates oxygen and free protons. The protons are then transported through the membrane to the cathode where it creates hydrogen. PEMEC has a working temperature between around 20-80°C, where a cooling system is necessary to keep the temperature within the range and ensure a stable process and not damage the electrolyzer (RISE, 2021a). A commonly used cooling system is air or water with a radiator. A PEMEC can theoretically reach an electrical efficiency of 80 - 90 % (Zhang et al., 2022). However, the efficiencies are currently around 59 – 70 %, with efforts to increase this (RISE, 2021a). PEMEC are often installed in larger production facilities due to economies of scale, with estimated lifetimes of around 50 000 hours, equivalent to 5 to 6 years of continuous production (RISE, 2021a).

2.2 Hydrogen fuel cell technologies

Fuel cells are a collection of technologies for converting fuel and air into electricity through a reaction and in this case, the fuel is hydrogen (Research Institutes of Sweden [RISE] 2021b). Some technologies are currently capable of an electric efficiency exceeding 60 % (U.S. Department of Energy, n.d.), with the rest of the energy mainly transformed into heat. If the solution can capture and utilize heat energy, the total efficiency will rise to nearly 100 % and the efficiency is substantially higher compared to a combustion engine. Hydrogen fuel cells only emit water vapour and are therefore not a source of pollution, affecting the climate or the society, both in terms of materials and air pollution. The fuel cell is also silent and has few moving parts, which makes them applicable versatile and relatively durable. Other solutions than stationary power, as this report is aimed for, are transportation, like marine and road vehicles, and portable power such as handheld electronics and portable generators (U.S. Department of Energy, n.d.).

Like electrolyzer, there are multiple different fuel cell technologies, which are often categorized by the kind of electrolyte used (U.S. Department of Energy, n.d.). For example, there are different electrochemical reactions in the cell, operating temperatures, and catalysts requirement. The different classifications have their own advantages, efficiencies, and limitations which make them suitable for different applications. Many of these technologies are under development and some technologies are more used than others due to their expected potential (U.S. Department of Energy, n.d.). The five most common technologies for a hydrogen fuel cell are Proton Exchange Membrane Fuel Cell (PEMFC), Alkaline Fuel Cell (AFC), Phosphoric Acid (PAFC), Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC) (U.S. Department of Energy, n.d.). From these five technologies, there will be one technology that will be in focus and used for the fuel cell.

The three more promising technologies are PEMFC, AFC and SOFC, which have the highest electrical efficiency (U.S. Department of Energy, n.d.). PEMFC and AFC are similar, however, SOFC needs a higher operating temperature and has a long start-up time. Tan et al. (2021) investigated the application of SOFC in energy systems for buildings. The SOFC can be used in the energy system but there will be a long time of pre-heating to reach full efficiency and not damage the fuel cell stacks. Therefore, the SOFC is inefficient as a backup power or power regulation in the power grid because of the requirements of a fast activation time and because the system is only activated for a short period of time (SVK, 2022b).

However, there are still two types of technologies left with the highest electrical efficiencies, PEMFC and AFC. Among the two, the AFC technology has lost development due to the technical instability caused by the fuel cell's sensitivity to carbon dioxide (CO2) which can accumulate and poison the cell (Wang et al., 2017). AFC is also more expensive compared to PEMFC which also has the highest potential in terms of efficiencies and cost-cutting leading to the industry centring around PEMFC (Wang et al., 2017). RISE (2021b) similarly conclude that the PEMFC technology is the most applicable type in the Swedish power grid because of the lower investment costs and better energy density compared to other solutions. However, they also note that the catalyst used in PEMFC for separating the molecules uses precious metals, and there is a need to increase the working temperature to better fit more applications (RISE, 2021b). The report will focus on what the hydrogen community believes is the most promising fuel cell technology, i.e. the PEMFC technology.

As mentioned before, The fuel cell works simplified in reverse relative to an electrolyzer, and they have many components in common. All fuel cells consist of an anode, which is the negative electrode, and a cathode, which is the positive electrode. They are squeezed together around an electrolyte which facilitates the transfer of electrons between the electrodes. Hydrogen is fed to the anode where a catalyst is working to separate the molecules into electrons and protons (RISE, 2021b). The electrons and protons take different paths to the cathode. The electrons flow through an external circuit creating electricity, while the protons will pass through the electrolyte membrane to the cathode where it reunite with electrons and oxygen to produce heat and water (U.S. Department of Energy, n.d.). A single fuel cell creates a voltage of 1,16 V (U.S. Department of Energy, n.d.). The single fuel cell is combined into a series of fuel cells, the so-called fuel cell stack, to get a higher more useable voltage. There can be hundreds of fuel cells in a stack, which is often constructed according to the specific application area.

2.3 Ancillary services

For the power grid to function and operate predictably it requires a stable frequency, which in Europe is set to 50 Hz (SVK, 2022b). The frequency will naturally fluctuate depending on the current load on the system, which is affected by the supply and demand of electricity. This is because power generators will slow down in relation to an increased resistance, i.e., load, or vice versa. Small deviations in frequency are common. During the period of 2015-2020, the frequency was higher than 50,1 Hz on an average of 37 500 times and under 49,9 Hz on an average of 33 000 with 45 % of the occurrences lasting less than one second (RISE, 2022). This is also shown in Table 2.1. Very small and short-term fluctuations are generally not a problem, but larger or longer ones are. Therefore, to keep the frequency stable under varying circumstances SVK procures different types of regulation power, so called ancillary services, that help keep and restore the grid frequency to 50 Hz (SVK, 2022b). These work in two directions, some of which increase the system load by drawing power or decreasing production, thus pushing the frequency down, while others generate additional power or reduce the load which helps raise the frequency. The three main type of services are FFR, FCR and FRR and an overview can be found in Table 2.2 (SVK, 2022b).

Table 2.1: Percentage of time within each frequency interval between 2015 to 2020 (RISE, 2022).

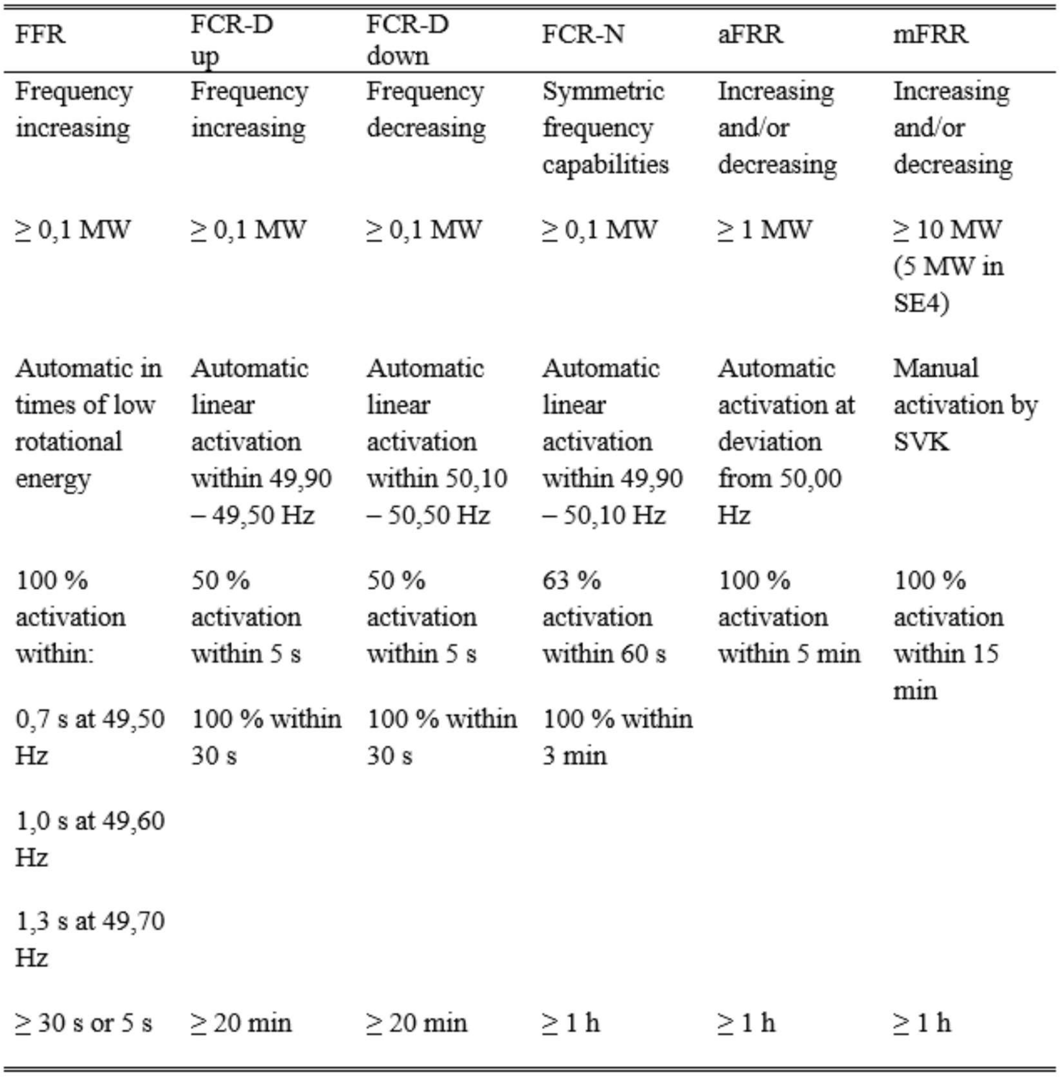
Year	< 49,8 Hz	< 49,9 Hz	49,9 - 50,1 Hz	> 50,1 Hz	50,2 Hz
2015	0,002	0,98	97,91	1,11	0,003
2016	0,004	1,25	97,31	1,44	0,003
2017	0,002	1,12	97,70	1,18	0,002
2018	0,004	1,09	97,70	1,20	0,006
2019	0,001	1,21	97,46	1,33	0,004
2020	0,003	0,85	98,13	1,02	0,001

Fast Frequency Reserve (FFR) is the first measures to act and are automatically activated by quick and substantial drops in frequency. This is often accomplished through batteries or in some cases flexible loads which can quickly reduce their power draw. However, these measures are not a long-term solution and can only endure in the order of seconds but provide a buffer for larger slower measures to activate (SVK, 2023b). FFR was introduced in 2020 because of wind turbines. As the share of wind power increases the total rotational mass, or inertia, of the system decreases, especially in times of low energy demand. This is a physical limitation of wind turbines because they cannot have the same rotating fly wheels or massive turbines as, for example, hydroelectric or nuclear power plants, which help mitigate frequency fluctuations solely due to their rotational energy.

Frequency Containment Reserve (FCR) are a set of reserves that quickly restores and stabilize fluctuations in the frequency. There are two types, FCR-N (Normal) which is active when the frequency is relatively stable and is within +- 0,1 Hz and FCR-D (Disturbance) which is activated when the frequency deviates outside the normal range (SVK, 2023b).

Frequency Restoration Reserve (FRR) is activated to relieve the FCR and FFR services and bridge the discrepancy between energy supply and demand. They are activated linearly to the frequency deviation and are typically hydroelectric power (SVK, 2023b).

Figure 2.2: Requirements for ancillary services (SVK, 2023b).



FFR	FCR-D up	FCR-D down	FCR-N	aFRR	mFRR
Frequency increasing	Frequency increasing	Frequency decreasing	Symmetric frequency capabilities	Increasing and/or decreasing	Increasing and/or decreasing
≥ 0,1 MW	≥ 0,1 MW	≥ 0,1 MW	≥ 0,1 MW	≥ 1 MW	≥ 10 MW (5 MW in SE4)
Automatic in times of low rotational energy	Automatic linear activation within 49,90 – 49,50 Hz	Automatic linear activation within 50,10 – 50,50 Hz	Automatic linear activation within 49,90 – 50,10 Hz	Automatic activation at deviation from 50,00 Hz	Manual activation by SVK
100 % activation within:	50 % activation within 5 s	50 % activation within 5 s	63 % activation within 60 s	100 % activation within 5 min	100 % activation within 15 min
0,7 s at 49,50 Hz	100 % within 30 s	100 % within 30 s	100 % within 3 min		
1,0 s at 49,60 Hz					
1,3 s at 49,70 Hz					
≥ 30 s or 5 s	≥ 20 min	≥ 20 min	≥ 1 h	≥ 1 h	≥ 1 h

The services have somewhat varying procurement methods. All but mFRR, is procured on a capacity market, meaning that they are compensated independently on whether they are activated or not. SVK will soon change the process for mFRR so that all services are procured on a capacity basis (M. Isaksson, Personal Communication, March 7, 2023). FCR-N and aFRR are also compensated based on energy activation according to current regulation prices at Nord Pool (SVK, 2023a). The pricing for all measures, except FCR, are determined by the marginal price model, meaning that all providers are paid equally at the price set by the most expensive source procured. FCR is instead procured through a traditional bidding process but will change to the marginal pricing model in 2024 (M. Isaksson, Personal Communication, March 7, 2023).

2.4 The district heating system

The fuel cell has an electrical efficiency of 50 - 60 % (RISE, 2021b) and the electrolyzer 65 - 85 % (RISE, 2021a) which is dependent on among other factors, the environment and technology used. To raise the total efficiency the heat generated needs to be captured. Since the components are typically cooled with water it is relatively easy to use the heat for other industrial processes or heating purposes, such as a district heating network (Energimyndigheten, 2022). It is important to be close to the application to reduce heat loss (Böhm et al., 2021).

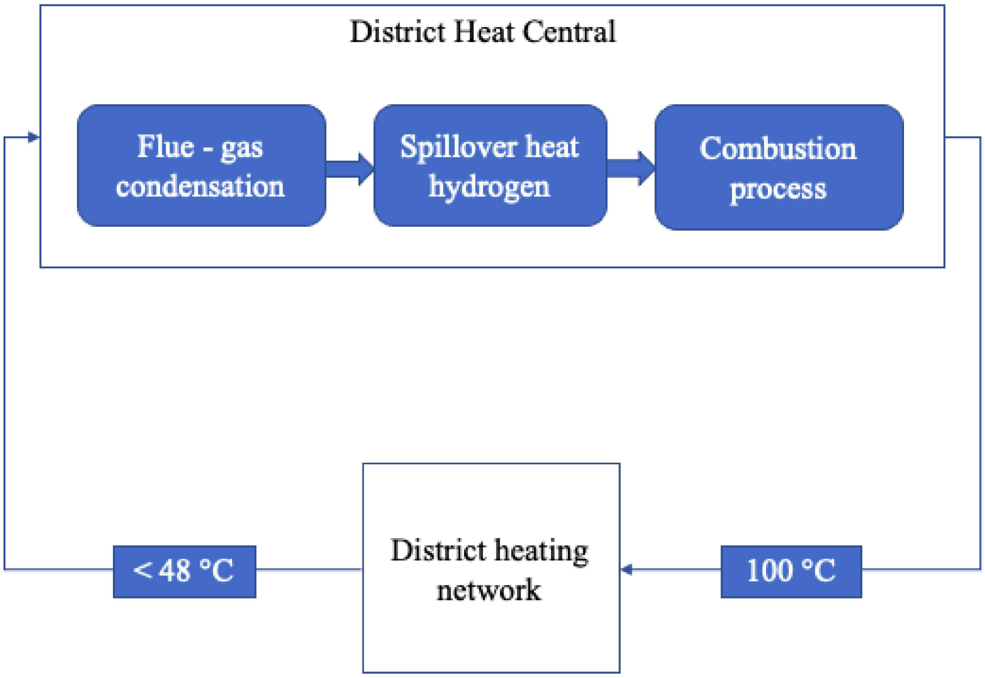
RISE (2021b) has studied the potential of connecting a hydrogen system to the district heating network, and there are ongoing pilot projects in Sweden to test the implementation (RISE, n.d.). RISE (2021b) concluded that there are opportunities for such an interconnect in Sweden because much of the infrastructure, both in the power grid and the widespread district heating network, is already there. The Swedish energy system is therefore a great opportunity to create synergies in terms of heat and electricity with a high energy efficiency and revenues. A similar system is already in place in parts of Austria, where Böhm et al. (2021) estimate that 12 % of the heat energy in the district heating system will in 2030 come from electrolyzers.

Around 90 % of all residential buildings in Sweden were connected to a district heating network in 2014 (Fjärrvärme, 2014). The Swedish district heating networks mainly use biofuels to generate energy, approximately 46 %, and garbage generating an additional 21 % (Rydegran, 2022). The heat from a hydrogen system can be used to lower the need to burn biofuels. Biofuel plays a crucial role in the changeover to a fossil-free environment and the demand is believed to increase in the future (IEA, 2022a). A higher demand often leads to higher prices and a shortage of biofuels in processes where there is no substitute.

The basic principle of a district heating system is that water is heated in a central location and then distributed throughout the network. The water is either heated in a heating plant, where fuel is burned purely for heating the distribution network, or in a cogeneration plant, where both electricity and heat are generated, much like a fuel cell system but at a much larger scale (Rydegran, 2017). The heated water is then transported to facilities through the network where it is used for heating. The cold water is then returned to the plant through the network, creating a closed system, ready to be heated again.

District heating networks in Sweden are standardized across the industry (Fjärrvärme, 2014). The water temperature at the heating plant needs to reach at least 100 °C and be pressurized (Fjärrvärme, 2014). The return temperature is dependent on the system load but is often lower than 48 °C (Fjärrvärme, 2014). The return water is often reheated through flue gas condensation, but this is only possible when the return temperature is below 50 - 55 °C (Naturvårdsverket, 2005). The water is then heated through different means, e.g., burning biofuels or waste, to above 100 °C to meet the industry standards (Rydegran, 2022). The heat from a hydrogen system, with either electrolyzers, fuel cells, or both, could be inserted between the flue gas condensation and the final heating to reduce the amount of fuel burned. The temperature of the hydrogen system doesn't matter, but the higher it is the more energy it will contribute to the heating (R. Hagberg, Personal communication, February 22, 2023). For typical electrolyzers and fuel cells, this temperature is around 80 °C (RISE, n.d.). A simplified overview of the process is illustrated in Figure 2.3.

Figure 2.3: A simple district heating network with an integrated hydrogen system



3

Literature

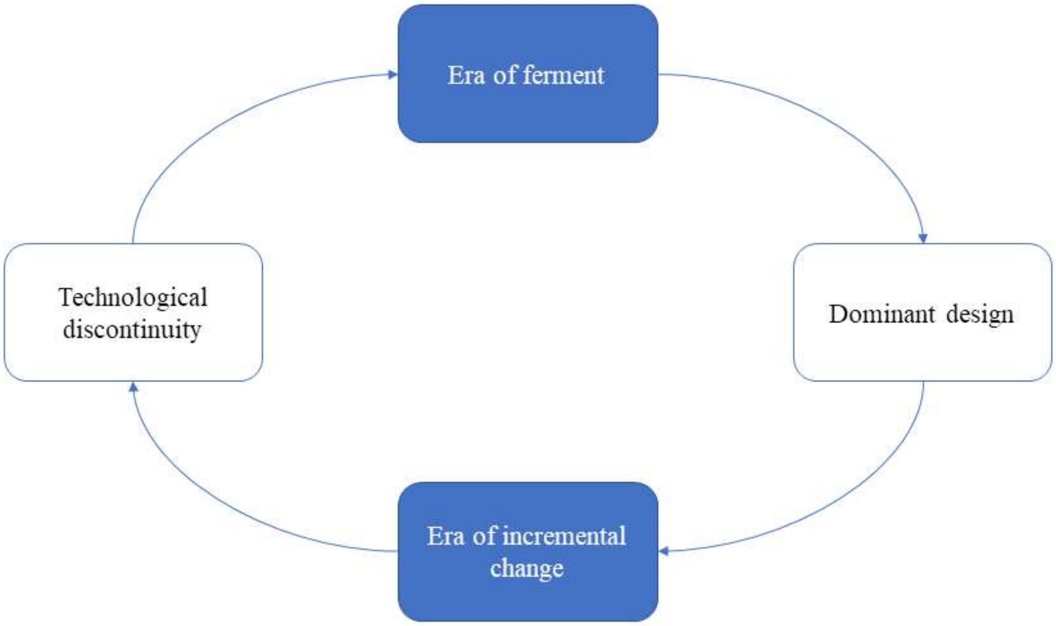
The literature review will dive into the innovation management literature to help explain patterns and changes in an unstable and changing industry. Innovations and changing customer behaviour typically threaten otherwise stable products and industries. The chapter will start with the technology life cycle, exploring how innovations changes over time, followed by patterns in market dynamics and how it affects diffusion, and then a section on how innovations emerge and affect the socio-technical transitions. Finally, the chapter will end with a summary bringing the sections together.

3.1 The technology life cycle

Historically, there has been much research on radical innovations because incumbent firms often find it difficult to maintain their market share. A new life cycle starts with a technological discontinuity (Anderson & Tushman, 1990), which is an innovation that breaks current norms and standards, requiring new skills, processing abilities and a different level of market understanding (McDermott & O'Connor, 2002). This is what established, incumbent, firms find difficult to manage and survive because of their investment in the old knowledge. Schumpeter calls this period a Mark I industry, coining the term creative destruction for the process of successful companies and technologies falling in favour of radical innovations (Caballero, 2008).

The technology life cycles describe how innovation occurs, the technology development that follows, and the dynamics of the firms involved. It helps describe why firms enter and exit the industry, and how the technological evolution changes over time in distinct phases. Anderson and Tushman (1990) designed a model to illustrate and characterize the life cycle in two distinct phases and two important events, seen in Figure 3.1. The first phase, the era of ferment, starts with a technological discontinuity, an innovation, which is eventually followed by an emergence of a dominant design, which enables the second phase, the era of incremental change. Each era is characterized by a distinct pattern in terms of quality, enter or exit of firms, performance, cost and focus (Anderson & Tushman, 1990).

Figure 3.1: The technological life cycle model (Anderson & Tushman, 1990).



The following sections will explain the life cycle model, and its phases and event. How long the cycle is depends on the characteristics of the technological discontinuity, meaning how much of the current knowledge is made obsolete. A completely new technology tends to have a relatively long life cycle compared to when the technological areas are known (Anderson & Tushman, 1990).

3.1.1 Era of ferment

The technological breakthrough, or technological discontinuity, initiates the era of ferment. The period is characterized by high technological uncertainty, which creates possibilities for many actors to provide their solutions. However, many of them will fail (Anderson & Tushman, 1990). The new technology is not yet ready to become mainstream and it is most relevant, or competitive, in smaller niches where it better meets customer needs. Therefore, the new technology and the old one are existing in parallel, creating different multiple regimes, due to the heavy diversity and experimentation of the new technology (Breschi et al., 2000). The performance and characteristics of the product are not yet set until a dominant design has evolved, whereby it all changes rapidly, leading to products fast becoming old. The production volumes are low and there are many competing designs, which inhibits a clear pattern of economies of scale (Anderson and Tushman, 1990; Suarez and Utterback, 1993).

Looking at the industry level, there is a wide diversity of firms entering and exiting the market (Anderson & Tushman, 1990). Companies are focusing on rapid innovation to try and gain first-mover advantages against their competitors (Breschi et al., 2000). It can be new firms, like start-ups, or firms from other markets, which can use their knowledge from other fields to create advantages (Breschi et al., 2000). If the innovation activities succeed it can provide future benefits, for example, influencing the dominant design and gaining important market shares (Lieberman and Montgomery, 1988; Anderson and Tushman, 1990). On the other hand, there is often only one path leading to a successful dominant design and if the chosen technological regime fails, it can be very costly for the firms involved (Lieberman and Montgomery, 1988; Anderson and Tushman, 1990). Suarez and Utterback (1995) conclude that there is a higher probability of success if a company enters the market in this era compared to later. They argue that companies, if they can afford the risk, can buy time to experiment with the product while the demand is changing rapidly, leading to future competitive advantages.

While innovation activities are high, there are also ongoing imitations among firms, where companies look at each other's designs and solutions (Anderson & Tushman, 1990). Companies can reduce development costs and shorten the time for innovation activities, gaining so-called free-rider effects, by imitating (Lieberman & Montgomery, 1988). This form of imitation can lead to best practices and standardization in the industry, thus laying the foundations for a dominant design to emerge.

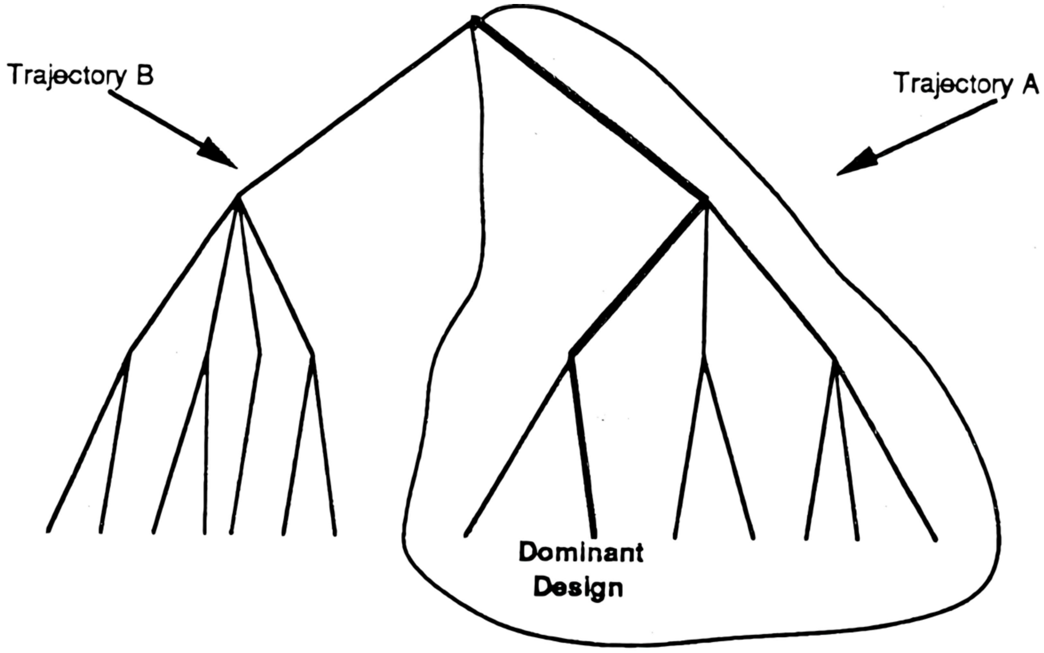
Technology development is dependent on complementary products and requires a successful co-devolvement in creating a regime and achieving a greater diffusion (Teece, 1986). Grubler (1996) mention technological clusters that are cross-enhancing by building families of technological innovations which are dependent on each other. For example, the innovation of cars required innovations on roads, fuels, and much more, which do not work independently of each other (Grubler, 1996).

3.1.2 Dominant design

A dominant design is based on a series of technical decisions, which creates a standard on the market. The technical decisions create a technological trajectory, leading to a single architecture that eventually becomes dominant in its product class (Utterback & Suárez, 1993). Political, social, and organizational dynamics are selecting the dominant design through different technological opportunities and trajectories (Anderson & Tushman, 1990). As seen in Figure 3.2 there is a development of different paths depending on different decisions made in certain points in time, and only one of these paths typically lead to the dominant design.

All decisions cannot lead to a dominant design which explains why some companies succeed and others do not. It will be hard to commercialize products that are not based on the dominant technology since the demand and complementary assets are focused on products based on the dominant design (Utterback & Suárez, 1993). It takes time for the dominant design to set and it is difficult to conclude when the technology becomes dominant, but it is rarely the best-performing technology at the time it becomes standard (Anderson & Tushman, 1990). Anderson and Tushman (1990) define the emergence of a dominant design when the technology reaches 50

Figure 3.2: Different trajectories and the emergence of the dominant design (Utterback & Suárez, 1993).



% of the industry sales. After the dominant design is set, companies start to focus on incremental changes instead of drastically changing the architecture (Anderson & Tushman, 1990). They also conclude that the initial technological discontinuity never becomes the dominant design. Firms that successfully develop the technology becoming the dominant design, have a competitive advantage against others (Utterback & Suárez, 1993). They will often grow in volume, gain market shares, and economies of scope, and be able to create complementary assets. Therefore, there is more likely that these firms become industry leaders.

The dominant design is often influenced by the degree of appropriateness of the technology, which is the degree to which companies can defend and make the technology proprietary (Srinivasan et al., 2006). If there is a low level of appropriability, a single dominant design will often occur because it is easier to imitate each other and vice versa (Anderson & Tushman, 1990). Other authors also conclude that a dominant design is more likely to occur if there are weak network effects, low production radicalness and high research identity (Srinivasan et al., 2006).

The number of firms in the market often peaks when the dominant design occurs, and after that, it will decline, and the so-called shake-out period is initiated (Anderson and Tushman, 1990 Suarez and Utterback, 1995). Suarez and Utterback (1995) explain the pattern as being easier to enter the market before a dominant design has emerged due to lower barriers of entry. The time just before the dominant design emerges is often called a window of opportunity to enter a market because many of the uncertainties have been ironed out (Suarez et al., 2013). Markides and Geroski (2004) however, discuss the term fast seconds, which is right after the emergence of the dominant design. They suggest that this time is instead the most beneficial time to enter the market. Firms can potentially cut development costs and minimize the risk of jumping on a failing path, gaining the free-rider effects discussed by Lieberman and Montgomery (1988).

3.1.3 Era of incremental change

Firms' efforts and focus on the technological architecture set by the dominant design are mainly on profitability and performance in the era of incremental change (Anderson & Tushman, 1990). Improvements are made in the manufacturing processes and the variety of products is minimized through product standardization. It is difficult to introduce dramatic changes as these do not fit within the dominant design (Suarez & Utterback, 1995). While the architecture is set by the dominant path, the overall design is not, leading to companies focusing on developing the design to differentiate (Anderson & Tushman, 1990). The patterns during the era of incremental change are in line with what Schumpeter describes as a Mark II industry. It is characterized by a stable technology and a calm environment for the firms, with no drastic changes (Caballero, 2008).

The beginning of the era of ferment, right after the dominant design emerges, is characterized by many firms leaving the market (Anderson & Tushman, 1990). The reason is twofold, some firms have focused on the wrong technological trajectories, creating a lack of knowledge of the dominant technology. While others are simply outcompeted when trying to scale up their production. Firms within the market tend to grow bigger and split market shares between each other until it reaches saturation (Anderson & Tushman, 1990). Firms chose different segments to compete within, often based on price, performance, exclusivity, and quality. There are also firms that are focusing on niches for specific customer demands.

Suarez and Utterback (1995) argue that there is a high risk of failure for firms that are entering a time after the dominant design has emerged. Firms that mastered the dominant design have accumulated complementary assets to the product, exploited economies of scale, and created entry and mobility barriers for the industry (Suarez & Utterback, 1995). Also, the case of patents can create high barriers. Firms that enter later often do so through acquisitions of firms that are already in the market, thus gaining the necessary knowledge to compete (Anderson & Tushman, 1990). Firms are often evaluated on the attractiveness of the industry and the competitive position the specific company has (Hopkins, 1987).

The period ends with a new technological discontinuity that starts a new technology life cycle, meaning an innovation starts to compete with the old ones. After a while, when the innovation, the new regime, showing, for instance, a higher density of performance, the old technology is replaced and the life cycle keeps going (Anderson & Tushman, 1990).

3.2 Market dynamics

Market dynamics help explain the diffusion of technology and why different customers adopt a product at different times. The diffusion is dependent on behaviours of multiple factors, for example, willingness to accept risk, price and where the information about a product comes from (Rogers, 2003). Tornatzky and Klein (1982) also explain the relationship between the implementation of an innovation and diffusion. They conclude that there are many things affecting the adoption rate, for instance, the amount of time saved, cost, complexity, social approval, and reliability. The adoption rate is also affected by how the market itself works. There are two common types of market strategies for companies: push and pull (Brocato, 2010). A push strategy is when companies actively push their goods to the customer, while a pull strategy means that customers themselves are searching for information on products to satisfy a need.

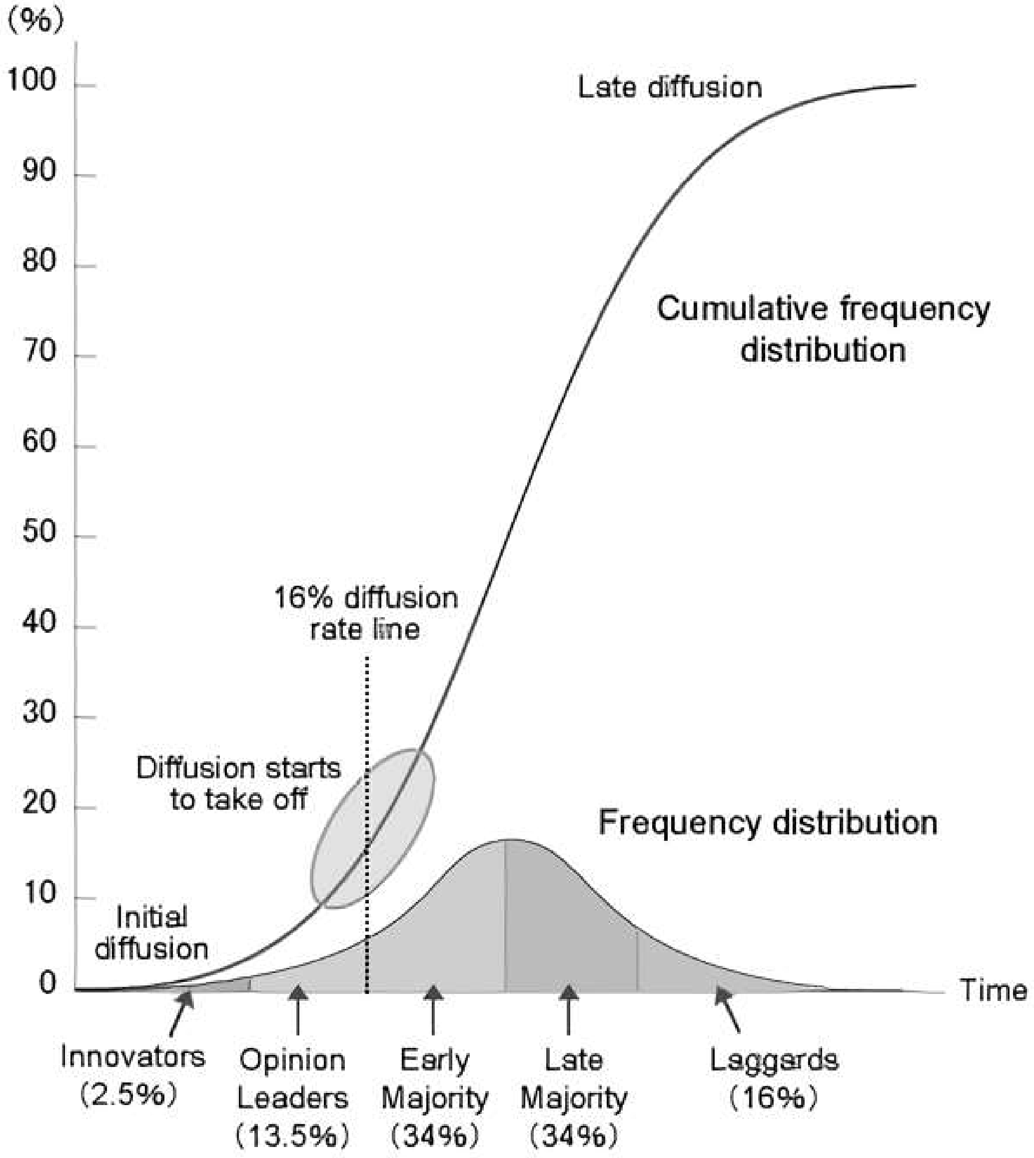
Rogers (2003) takes a sociological perspective on explaining the diffusion rate. He explains five different groups of adopters and categorizes them by the time of adoption and how the groups affect each other. Companies cannot manage all groups in the same manner and therefore need to consider them separately because of their distinct characteristics. For example, reaching the first adopters requires a different focus compared to when the product has reached the mass market. The method of categorizing adopters is common in diffusion research to explain patterns of behaviours (Rogers, 2003).

The cumulative number of adopters will typically follow an s-shape curve (Rogers, 2003). The reason behind this curve is that human behaviour is generally normally distributed and follows the same pattern as the learning curve (Rogers, 2003). The learning curve of industries comes from the process of learning by doing, increasing the output with the same amount of input (Spence, 1981). For adoption, the curve means that the adoption rate will increase in speed, and the derivative is positive until half of the population has adopted it. Then the speed will decrease until it reaches a level of saturation and levelling out.

Grubler (1996) also focuses on the innovation studies perspective, by analyzing diffusion patterns. For example, railways, roads, and telecommunication show the pattern of an s-shaped diffusion curve as described by Rogers (2003). Grubler (1996), compared with Rogers (2003), takes a different perspective and argues that diffusion is dependent on time and space. He concludes that not all industries will follow a typical s-shaped diffusion process. The difference lies in the social network. The speed of diffusion is often dependent on the importance of network effects and network externalities (Grubler, 1996) where people communicate and extract information from each other in the network (Katz & Shapiro, 1994). The later a region adopts, the faster the diffusion speed will be, but the saturation level of a product will be lower (Grubler, 1996). He also argues that diffusion does not occur by itself and is dependent on other innovations, creating clusters of innovation families, working as a cross-enhancing mechanism.

Looking at Figure 3.3, the s-shaped curve, which is the cumulative adopters, can be translated into a frequency distribution, resulting in a bell-shaped curve with the number of mean adopters per year. It is in essence, a normal distributed curve, enabling a grouping of customers representing the different types of adopters in the population (Rogers, 2003).

Figure 3.3: Cumulative s-shaped adoption (Tanahashi, 2008).



The model is not as symmetrical as it seems, with three adopter categories to the left and two to the right. The laggards can be split into two types of groups, but it will be many characteristics in common and therefore appear homogenous (Rogers, 2003). One difficulty with the model appears when there is not a complete adoption, meaning that the entire population does not adopt, which makes it hard to fill all categories (Rogers, 2003). A solution to the problem can be to make a composite innovativeness scale by combining a series of innovations (Rogers, 2003). The next section will explain the different characteristics of different adoption categories described by Rogers (2003).

3.2.1 The adopter categories

Innovators: Venturesome
The innovators are the first group to adopt a innovation (Rogers, 2003). They are close to the system's boundaries, bringing new ideas into the system from the outside, and thus having a gatekeeping role. They are often curious and obsessive over innovations and have also the ability to understand complex technologies. Their interests together with others lead them to a local circle of peer network with a cosmopolitan social relationship and are often scattered all over the world (Rogers, 2003). They are often financially strong, which is necessary due to uncertainties and the high risk of losses with immature innovative technologies (Rogers, 2003).

Early adopters: Respect
Compared to innovators, early adopters are more integrated into the local social system. The early adopters help to reduce the uncertainty of technologies by making a subjective evaluation of the technology and sharing it with its closest peers. Instead of cosmopolitan, early adopters are more like localities (Rogers, 2003). They have the most respect in the system making their opinion highly valuable. They are often associated with successfully adopting innovations and have a crucial role in the social network leading other potential adopters (Rogers, 2003).

Early majority: Deliberate
The early majority is, as the name suggests, one of the biggest categories. They often interact with their peers and have a unique position between the very early adopters and the relatively late adopters, leading to an important link in the network for a greater diffusion (Rogers, 2003). It will take time for them to adopt due to their decision period being longer than the first two categories. The early majority tend to think "Be not the first by which the new is tried, nor the last to lay the old aside" (Rogers, 2003, p.284).

Late majority: Sceptical
This group adopt innovations only due to peer pressure after the average individual has adopted. They want to avoid risk as much as possible, thus being generally sceptical of new innovations (Rogers, 2003). Their resources are often scarce, thus not being able to handle as much risk as earlier types of adopters and requiring tried and tested solutions to feel safe with adopting.

Laggards: Traditional
Laggards have the longest decision-making process and are consequently the last category to adopt. They have little to no leadership or opinion and are the most localized of all adopters. They tend to be isolated from the system's social networks, and they primarily interact with people sharing the same values. Their reference to technology often comes from the past and the decision is based upon what has been previously done (Rogers, 2003). Therefore, they tend to be suspicious and resist new technology that changes their lifestyle. Their resources are often scarce, and they are the adopters least likely to take risks.

3.3 Socio-technical transitions

Technological developments do not happen in a vacuum, but rather in collaboration with society which are defined by Geels (2004) as socio-technical systems. There are three dimensions of analysis which interact with each other. Geels (2004) emphasizes the important interaction between socio-technical systems, the human actors and social groups, and the rules i.e., regime, which they operate within. This trifecta can be compared to a game, in which the rules define the boundaries in which actors play and react to each other and consequently alters the socio-technical systems (Geels, 2004). What is important, however, is that it is omnidirectional, meaning that e.g., while actors influence the socio-technical systems they also act within the context of that system, and rules change over time as actors move strategically.

3.3.1 Path-dependency and lock-in

Due to its nature, socio-technical systems will prove stable over time, which is caused by the effects of path-dependencies and lock-in and can be understood through three underlying aspects: rules and regimes, actors and organizations, and the artefacts and material networks (Geels, 2004). Looking deeper at these we see that Geels (2004) categorize the rules into three distinct types. Cognitive rules describe subconscious ways of working where actors do what they usually do because of sunk costs in old competencies and the effort needed to acquire new breakthrough knowledge. Normative rules on the other hand are caused by underlying mutual perceptions and expectations within relationships. Finally, are the formal rules, which are legally binding e.g., due to contracts or standards. Parallels can be drawn in the description of the actors and organizations and the cognitive and normative rules. These are structured through a deep web of interdependent networks and dependencies among the actors where business is carried out as usual and the large systems built cause organizational inertia. Finally, the artefacts and material networks are described as hard to change. This can be caused by investments in production plants, and dependencies between components in a product, but also due to society's investment in the artefacts causing network externalities. Together the rules and regimes, actors and organizations, and artefacts and material networks cause path-dependencies in socio-technical systems, leading to distinct paths and trajectories which cause incremental innovation and barriers to new radical innovations (Geels, 2004).

3.3.2 Protective spaces

Radical innovations, which are described by Henderson and Clark (1990) as establishing a new dominant design through a new set of core concepts in a new architecture, are not compatible with existing socio-technical systems. This is due to the path dependencies and lock-in effects discussed previously. A form of protection from the established systems is therefore necessary, which is why successful radical innovations are developed in what Geels (2004) describes as niches. These niches are what Smith and Raven (2012) describe as protective spaces, where innovations that break established paths are protected through means of shielding, nurturing and empowering.

Smith and Raven (2012) describe sustainable innovations, that are path-breaking, as structurally weak compared to established socio-technical systems. They need to be shielded from the selection environment and existing structures developed through the process of establishing and reinforcing the dominant design. There are two types of shielding: passive and active (Smith & Raven, 2012), where the latter is of more interest to potential actors willing to strategically influence the niche. A passive type of shielding is exemplified by solar cell firms focusing on actors on the outskirts of the incumbent regime such as rural farmers who wish to diversify their revenue or lower their electricity spending. While a more active approach could be by specifically incentivizing research and development of technologies related to solar cells.

When a shielded, either active or passive, space emerges, it needs to be developed and nurtured. There are three key processes to nurturing a niche: helping learning processes, formulating expectations, and supporting network-forming processes (Smith & Raven, 2012). For a niche to grow and be path-breaking to the socio-technical system, it needs to develop the internal structures necessary to survive in the long term. There are two distinct stages to nurturing, the formative and the growth stage (Smith & Raven, 2012). They describe the former stage as having relatively long development periods, low volumes, and high uncertainty, while the latter stage focuses on system expansion and large-scale diffusion of technology.

Empowering niches come in two distinct forms, fit, and conform, and stretch and transform, which differ in the way they help build the subsequent socio-technical system (Smith & Raven, 2012). Empowering a niche to fit and conform will help the innovation become compatible with an unchanged selection environment of existing markets and regimes, according to Smith and Raven (2012). A stretch and transform approach will on the other hand more heavily affect the external regime and society to transform the selection environment to one that is compatible with the innovation. Smith and Raven (2012) further discuss a key part of empowerment which are the narratives. They are described as broader patterns in empowerment and typically consist of three parts: forming positive expectations surrounding the niche, proposing the niche as helping solve larger social, environmental, and economic challenges, and assumptions about the current regimes are rephrased. Depending on the environmental conditions surrounding society, one type of narrative might be more suitable than another. Smith and Raven (2012) exemplify this with solar cells, arguing that a narrative that empowers the regime to stretch and transform might be more suitable in an urban setting to decentralize the energy grid, while in rural areas, large solar cell parks could gain economies of scale and be price competitive to incumbent sources, thus better empowered through a fit and conform narrative.

Smith and Raven (2012) finally emphasize that the means of shielding, nurturing and empowerment neither happen in isolation nor in a linear way. It is rather an iterative process of interconnected actions between the trifecta described by Geels (2004): the socio-technical systems, the human actors and social groups, and the rules and regimes that govern.

3.3.3 The multi-layer perspective

Geels (2005) describes a technological transition through a multi-layer perspective, integrating three different levels which Markard and Truffer (2008) elaborate on. The highest level is the landscape (Macro-level), which is an abstract level including both internal and external factors which influence innovation and transitions. The landscape is stable over a long period of time, but it can change due to destabilizing effects such as discussed by Geels (2004) in Section 3.3.1. In cases of a changing landscape, pressures will be exerted on the regime, which is the framework's middle or Meso-level (Markard & Truffer, 2008). They describe socio-technical regimes as a broader term than the socio-technical system described by Geels (2004). While Geels (2004) makes a distinction between the system, the actors, and the rules, these are instead integrated into the socio-technical regime of Markard and Truffer (2008). The concept is however similar, and Geels (2004) could be interpreted as a deep-dive into the Meso-level dynamics of Markard and Truffer (2008). The final part of the framework is the Micro-level, or the niche, which was elaborated in the previous section.

Markard and Truffer (2008) and Geels (2005) emphasize the interplay between the different levels, and how they can lead to niches by breaking through a weakened regime. This process does not happen instantaneously, instead, it is generally a long-term process where changes in the landscape destabilize established socio-technical regimes which then leaves them vulnerable to developing niches to break through and establish new regimes (Geels, 2005). This is exemplified by the transition from horse carriages to cars in the 19th and 20th centuries, where landscape changes such as industrialization and urbanization destabilized the urban transport regime through a higher need for transport. Innovation around horse-drawn buses and trams was developed in middle- and high-class niches finally leading to the diffusion and domination of cars (Geels, 2005).

3.4 Literature summary

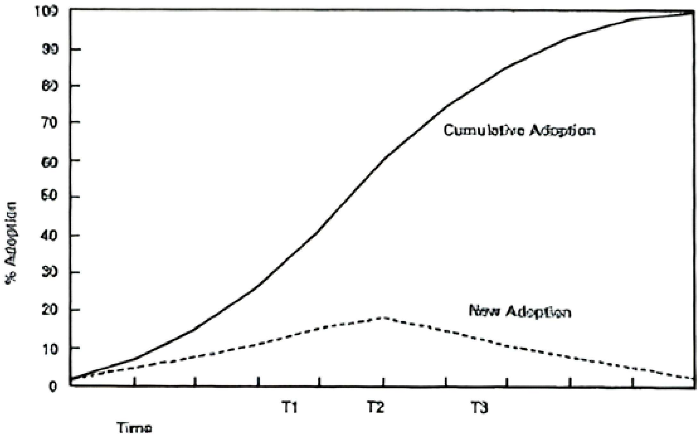
The life cycle model and market dynamics are closely related to each other. The pattern of market dynamics is essential when developing technologies because there is a need for customers willing to adopt a certain innovation. Upon how far the innovation activities have become, it is important to focus on different customers depending on the specific time and phase to create a great diffusion.

The lock-in effects and path dependencies are important to consider to reach mass diffusion and technology development, including customers and firms (Geels, 2004). If the lock-in effects and path dependencies into the regime are too strong, the technological discontinuity will not have space to emerge and the life cycle will not start over. This hampers the development of society and welfare. However, there can still be innovations, but they are not protected, as described by Smith and Raven (2012), meaning that they cannot compete with the old ones. These innovations can probably reach the first adopter category, innovators, but then it will not continue to the next adopter category.

Most of the potential adopters will wait until the emergence of a dominant design has occurred (Anderson & Tushman, 1990). The dominant design creates conditions for mass adoption, because of the reduced uncertainty. Therefore, the sales will peak sometime after the emergence of the dominant design. When a new dominant design emerges, the protective spaces have succeeded, and the former lock-in effects have been erased from both incumbents and the market. The earlier to adopt a certain innovation, the more advantages can be reached to not fall behind.

It is difficult to conclude when the dominant design occurs and in which adoption category it will happen due to the uncertain diffusion time (Mahajan et al., 1990). Rogers (2003) argues that the early adopter triggers the critical mass and Anderson and Tushman (1990) argues that the dominant design will be set before the majority has adopted it. T2 in Figure 3.4 shows where the sales would peak and the dominant design will be set nearby the point T1 (Anderson & Tushman, 1990). Looking at the adopter categories, the sales will peak between the early majority and late majority, in the middle of the S-shape curve, T2 in Figure 3.4. These arguments from Anderson and Tushman (1990) and Rogers (2003) can be understood as the dominant design is somewhere between the early adopters and the early majority. The dominant design on the other hand splits the era of ferment and the era of incremental changes.

Figure 3.4: The relation between market diffusion and dominant design (Anderson & Tushman, 1990).



4

Method

This report aimed to calculate a business case of the profitability of using a hydrogen system in the power grid. Therefore took a quantitative perspective, using numerical data to evaluate properties (Eriksson & Wiedersheim-Paul, 2008). The quantitative perspective takes a positivistic point of view, meaning that there is more focus on hard data, such as numbers (Bell et al., 2022). The report therefore attempted to describe, analyze, and evaluate correlations and relationships through numerical reasoning. It is important that the numbers are equally bounded and isolated so they can be compared (Eriksson & Wiedersheim-Paul, 2008). The underlying data is of high importance to get a valid result, which required a sufficient quantity and good input data. It is easier to understand data if it is standardized, measurable and delimited. The data, in a quantitative study, often comes from surveys, different measurements, and databases.

However, qualitative studies, on the other hand, are more about analyzing, making assumptions, and understanding the causation of a problem (Eriksson & Wiedersheim-Paul, 2008). It is more difficult to compare with other studies and is often used as a complement when it is hard to do a strict experiment (Wallén, 1996). The unbiased view is important, which often is easier in quantitative research compared with qualitative research (Eriksson & Wiedersheim-Paul, 2008).

This study used a deductive approach, meaning that it started with a theory and then formulated a hypothesis to come up with a conclusion, which often is used when doing a quantitative study (Bell et al., 2022). An inductive study, on the other hand, is often blurrier because the conclusion usually ends in a theory based on an analytical process (Bell et al., 2022). The inductive process is more iterative compared to the deductive.

The following sections will go through how the method is structured. First, it starts with the literature review, followed by the interviews. Then comes a section discussing the validity and reliability of the interviews and the literature review. The chapter ends with a brief introduction to the building blocks of the model which is further described in detail in Chapter 5.

4.1 Literature review

The study started with a review and summary of previous literature on the topic of hydrogen from a technical and societal perspective. This laid the foundation for the research aim and questions. The literature review was based on the subject of innovation management. It tried to explain patterns such as the life cycle and diffusion of technology and why some innovations succeed and some do not from a socio-technical perspective, and examine path dependencies and lock-in effects. The relevance and selection of the literature were done through an overview of the title, keywords, and abstract. The date of publication was also important to consider, due to the changing nature of the early technology and the rapidly increasing shift to renewable energy. There was a risk that the numbers and information found are outdated. Therefore, the main focus has been to find literature that was published in the last three years. Whenever relevant recent literature was difficult to find, older sources were used but reviewed carefully.

According to Wallén (1996), it is important to create an opinion about the source and its content by comparing it with similar sources. A framework from Umeå Universitet (2013) was used for this purpose. The first step was to start with a review of the goals and aim to determine the study's focus. The next step was to delve into the methodology, results, and conclusions. By doing so, an evaluation of the validity and reliability was also done. After finishing the overview, the literature was sorted and categorized based on relevance and topic, i.e., diffusion, industry life cycle and socio-technical systems.

The literature was mainly found in research databases. The most commonly used were Google Scholar and Scopus. Published information from governments and companies has been useful to evaluate the political impact on the energy system and technical solutions for products on the market. Commonly used keyword for searching in databases has been hydrogen, electrolysis, fuel cell, district heat, power grid, energy storage, diffusion, technological life cycle, socio-technical systems, lock-in, trajectories and path dependencies in different combinations.

4.2 Interviews

The study conducted a set of interviews to complement the literature review. The interviews were aimed to answer questions that were hard to find in the literature, i.e., information regarding the power grid, the electricity market, and ancillary services. These types of information gaps were essential to fill to create a complete and correct model. Otherwise, the model would have become poor, and simplifications would have been necessary which compromise its reliability and validity.

The respondents were chosen through purposive and snowball sampling. Purposive sampling is often used to get improved knowledge from experts that were otherwise difficult to find (Lundén, 2020). Snowball sampling was used if the purposive respondent cannot answer the question directly or if other respondents are recommended during the interview (Lundén, 2020). The respondents were evaluated on how well they can provide the necessary information and if they would have any conflicting self-interests. This could be due to respondents having connections to companies, which creates an unbiased view of the answers.

The interviews were conducted physically, by video call, or by phone. The video and physical interviews were detailly planned with templates of topics and guiding questions were sent before in preparation to the respondent. The physical and video call interviews were always conducted by both authors. One was responsible for leading the interview and the other for taking notes. On the other hand, the telephone interviews were in order to gain specific knowledge relatively fast. The questions and topics were not sent beforehand, meaning that they were not prepared.

The interviews are held in a semi-structured way, where some questions or topics are predetermined, and some are not. The semi-structured approach can lead to a more open-ended interview and make it more conversational compared to a strictly structured way (Bryman, 2008). However, the order and any additional questions will depend on where the interview leads and if there is something that is needed to be clarified (Bryman, 2008). Many questions were of an open-ended nature, and respondents were encouraged to answer them freely, but some questions were more of a closed or specific nature, where it was possible to answer either yes or no. The questions were constructed so that they minimized the risk of inducing presumptions in the respondents or was potentially leading. The interviews are summarized in Table 4.1, and the full contents are compiled in the Appendix A.

Table 4.1: Overview of interviews.

Company	Name	Date	Duration [min]	Type
PowerCell Group	Jan Thorsson	20/2 2023	60	In person
Kvänum Energi	Jonas Karlsson	22/2 2023	80	Video call
Skara Energi	Roger Hagberg	22/2 2023	10	Phone call
Svenska Kraftnät	Maja Isaksson	7/3 2023	30	Video call
Kvänum Energi	Jonas Karlsson	30/3 2023	40	Phone call

4.3 Method discussion

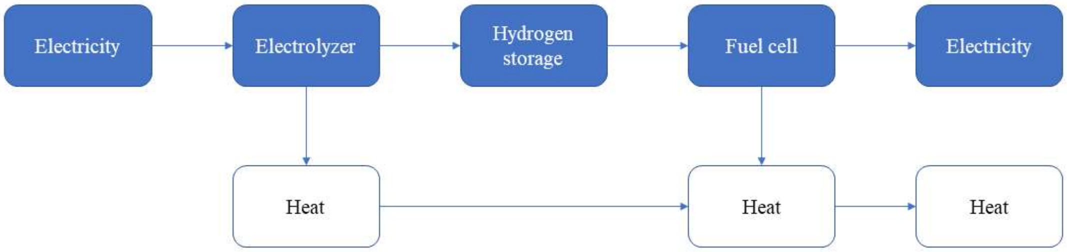
The hydrogen and energy sectors are rapidly changing, leading to an uncertain market influenced by political decisions and the fast development of different technologies. Therefore there was a need to consider whether the source was current or not. One example was the efficiency of fuel cells and electrolyzers, which have increased rapidly. Also, the future of storing hydrogen is relatively uncertain and there is research ongoing on how to reduce the costs. The path and the transition to a sustainable future without fossil fuels is relatively unclear, due to technological uncertainties and political actions. This could potentially hamper the reliability of the study, meaning that the results risk becoming outdated quickly. To deal with the problem as far as possible, the study aimed to use as much new information as possible, with the goal to use information from 2020 and newer for critical facts.

Another important thing that could hamper the reliability is that respondents were not anonymous. Respondents tend to be more honest and give more information about themselves, if it is sensitive, with a higher anonymity (Mühlenfeld, 2005). The aim of the interviews was to get expert knowledge in some areas, where there was a gap in the literature and therefore the questions were mainly concerning hard facts. The arrangement would look different if the questions were more qualitative, about feelings, which can conflict with other interests.

4.4 Calculation model

To determine the profitability of implementing a hydrogen energy storage system in a power grid application, a model was created to internalize relevant aspects. The model was used to evaluate two different scenarios for a hydrogen system; electricity arbitrage and ancillary services, to answer the first research question. The inputs for the model, which is a prediction of the future, were based on historical and forecasted data. By designing a model, it was possible to investigate several scenarios by varying a set of variables. It helped to understand the range of the system and where it could be optimized, as well as determined the potential risk with uncertain variables. A hydrogen system, as described in Chapter 2 consisted of an electrolyzer, a hydrogen storage, and a fuel cell stack, with the inputs being electricity and water. While the outputs were heat, electricity, and water. The electrolyzer consumed electricity to convert water into hydrogen and oxygen gas, while the fuel cell operated in reverse. Since the technologies are not perfect, they lost energy in the form of heat. The process is illustrated in Figure 4.1.

Figure 4.1: A schematic overview of a hydrogen system.



The constituent parts, electrolysis, hydrogen storage and fuel cell, were first examined in isolation and then combined into the discount cash flow model. In each part, the investment, revenues, and expenses were calculated. The variable revenues for the electrolysis is heat and for the fuel cell were heat and electricity. The variable expenses for the electrolyzer was electricity because the expense of water was negligible, and in a closed-loop system non-existent. Both the electrolyzer and the fuel cell needed maintenance expenses every year. However, the parameters included and estimated in the model are investigated and explained in detail in Chapter 5. A discussion follows about the different estimations, assumptions, and simplifications. In the end, there is an introduction to the two scenarios.

5

Calculation model

The chapter starts with an examination of the discount cash flow model and how it will be constructed. Next, an overview of the constituent parts of the model: the electrolyzer, the hydrogen storage, and the fuel cell, followed by their initial investment, revenues, and expenses relevant to the discounted cash flow model. Then a deeper analysis of the estimation will follow, by showing calculations, assumptions, and simplifications of each constituent part. Lastly, the two scenarios are be presented.

5.1 The discounted cash flow model (DCF)

The objective of a firm is generally to create value for its stakeholders, and therefore most management decisions are based on some type of business case to help facilitate the decision (Messner, 2013). It is important to base the decision on a valuation strategy that best reflects the value of the investment. One commonly used approach is the discounted cash flow model (DCF) for evaluating business decisions e.g., valuation of companies and investments in assets, and it can be a prerequisite for success in the market (Messner, 2013; Yao et al., 2005). The model has become popular (Lantz et al., 2018) because it is possible to capture all the elements that will affect the valuation of an investment. It is also easy to use and quite straightforward (Yao et al., 2005).

The future cash flows, both revenues and expenses are estimated and discounted with an interest rate to get the net present value (NPV) of an investment. This is because future cash flows are estimated, thus uncertain, and because future money is generally worth less due to the opportunity cost and inflation. Receiving \$ 100 today is better than receiving the same amount tomorrow because it could be invested and thus be worth more than \$ 100 tomorrow. What the discount rate is can vary a lot between actors (Cochrane, 2011) and the discount rate reflects two aspects. Firstly, it should reflect the timeframe under which the investor is seeking to tie up capital (Yao et al., 2005). Secondly, it must reflect the risk that the investor wants to be compensated for. A higher risk results in a higher risk premium which leads to a higher discount rate (Yao et al., 2005).

The DCF model also has some limitations. For example, it is hard to incorporate uncertain parameters such as the future cash flow, lifetime and the discount rate used (Yao et al., 2005). They argue that the parameters are treated as random variables and are estimated by historical data, which is often biased. On the other hand, the uncertainty in estimating the cash flow becomes greater further into the future and therefore the future estimated cash flow is weighed less (Lantz et al., 2018). This means that the model already deals with the uncertain parameters in time by giving them a less important share.

The DCF model is shown in Equation 5.1. If the sum of the discounted cash flow is positive, then an investment should be made (Messner, 2013). Of course, there are other parameters that are necessary to consider in the decision-making process, meaning that the DCF model is only a tool in the process and is not used in isolation.

$$NPV = \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \ldots + \frac{CF_n}{(1+r)^n} \tag{5.1}$$

where: CF = cash flow
r = discount rate
n = year

Fortum, one of the larger regional power companies in Sweden, uses a discount rate of 10 % for solar power in Nordic countries (Fortum, 2019). Taghizadeh-Hesary et al. (2021) studied a hydrogen project in China and concluded that the discount rate is between 6 – 10 % for renewable types of investment, where they used the average discount rate of 8 %. The report from the International Renewable Energy Agency (IRENA), also uses a discount rate of 8 % for future investment in hydrogen technology (IRENA, 2021).

To calculate the discount rate used in Equation 5.1, the Capital Asset Pricing Model or CAPM method is used and is shown in Equation 5.2. This is a common way of determining a discount rate because it not only takes into account the sensitivity to the systematic or market risk, but also the expected returns of the market and risk-free assets (Messner, 2013).

$$ER_i = R_f + \beta_i(ER_m - R_f). \tag{5.2}$$

where: ER_i = expected return on investment
R_f = risk free rate
β_i = beta value of the investment
$(ER_m - R_f)$ = market risk premium

The $(ER_m - R_f)$ is called the risk premium of the investment, and represents the additional risk caused by the investment over and an otherwise risk-free asset. A report from PwC has concluded that a long-term interest is around 2,7 % (PwC, 2022). The report also concluded, based on the surveys, that the average risk premium is 6,6 % (PwC, 2022). The average β-value for a company is 1. Together, these number results in an interest rate of 9,3 % which is in the interval discussed in 5.1, and is what will be used in the model.

The initial investment for the hydrogen system will happen in 2024, meaning the DCF model will start in 2024. The lifetime of the investment is also important to consider (Jennergren, 2008). A common lifetime of using DCF in the industry is 10 years (Skolnik, 1993). While he also questions why a 10-year lifetime is so common, he concludes that the cash flow prediction for a much longer time frame is too unpredictable, and the latter years are already weighed so little in comparison that they do not significantly contribute to the outcome. In other words, the DCF model reflects the future estimated cash flow with the investor's willingness to risk. In this case, the taxes are not considered in the DCF method. Taxes are more suitable when the initial investment is less capital intensive, which causes deductive depreciation throughout the lifetime of the investment. The DCF model will include the cash flow over a 10-year period, due to the large investment necessary, the lifetime of the hydrogen system, and because it is the most common lifetime used.

5.2 An overview of the estimated cash flow parameters

The constituent parts of the hydrogen system are the electrolyzer, hydrogen storage, and the fuel cell, which all affect the revenues and expenses, resulting in an estimated cash flow. The parts can further be divided into electricity, heat, initial investment, maintenance, and grid connection. This section will provide an overview of the relevant parts of the cash flow and how these are estimated. As of writing, the USD and EUR to SEK exchange rates are approximately 11, which is what is assumed in the model. Exchange rates are inherently difficult to predict, and there is therefore a risk that these will affect the calculation either positively and negatively.

Section 5.3 explains the estimation of the initial investment, CAPEX, and OPEX, e.g., maintenance, for a PEM-electrolyzer. Section 5.4 will describe hydrogen storage and its CAPEX. The OPEX expenditure for large storage tanks is not well documented and is therefore difficult to estimate. Furthermore, Section 5.5 describe the estimation of the CAPEX and OPEX of a PEM fuel cell.

Section 5.6 estimates the revenues from the heat created in the hydrogen system's processes. The electrolyzer and fuel cell create heat, as discussed earlier, and therefore become a source of revenue if the system is connected to a district heating network. The estimation of the revenue from the district heating network is based on the biofuel prices. The underlying assumption is that the district heating network will not pay more for the source of heat regardless of where it comes from, hydrogen system or biofuel. Therefore, the estimated future revenue from heat follows a regression in biofuel prices.

Section 5.7 estimate future electricity spot prices and is especially aimed for Scenario 1. The electrolyzer uses electricity for producing hydrogen, thus an expense. The fuel cell converts hydrogen to electricity, meaning it generates revenue. The price of buying electricity must be lower than the price it is sold at, otherwise, the sum will not result in a positive cash flow. The data is based on historical and future data from the NASDAQ Commodities market where it is possible to buy electricity futures up to 10 years in advance. The volatility of the price, during the estimated days, comes from historical data.

Section 5.8 estimates the revenue from ancillary services which is used in Scenario 2. A higher degree of renewable energy in the power grid requires more suppliers that can offer ancillary services. The estimation of ancillary services is based on historical data and future market predictions, creating a linear regression of how the price will develop. The regression model, based on historical numbers, gives an interpretation for each year until a saturation level is met. The hydrogen system can offer FCR-D up and down at the same time meaning that there are potential double revenue streams.

Section 5.9 investigates the expenditure of connecting a hydrogen system to the power grid, and Section 5.10 finally explains the different scenarios; electricity price arbitrage and ancillary services, which brings these estimations together. The scenarios will then be analyzed and discussed in Chapter 6.

5.3 The electrolyzer

The electrolyzer consists of two types of expenditures, an initial investment or capital expenditure, CAPEX, in technology and installation, and a variable operational expenditure, OPEX. The section will first determine the CAPEX followed by an estimation of the OPEX.

5.3.1 Estimating the electrolyzer CAPEX

Reksten et al. (2022) predict the CAPEX of future electrolyzers by considering plant size in kW and expected technology developments. The model is based on data from projects regarding investments in electrolyzers and calculates the average price per kilowatt in a specific year after 2020 (Reksten et al., 2022). Moreover, RISE (2021a) also predicts the CAPEX and concludes that the price should be reduced by 40 % by 2030, while the model by Reksten et al. (2022) calculates an approximate 50 % decrease in capital expenditure by 2030. Equation 5.3 shows economies of scale relative to the plant size, meaning that the greater the plant size, the smaller investment in dollars per kW (Reksten et al., 2022).

$$CAPEX_{AVG}(\frac{\$}{kW}) = (k_0 + \frac{k}{Q} * Q^{\alpha}) * (\frac{V}{V_0})^{\beta} \tag{5.3}$$

where: $\alpha = 0{,}622$
$\beta = 158{,}9$
$k_0 = 585{,}85$
$k = 9458{,}2$
$V_0 = 2020$
V = year
Q = plant capacity [kW]

5.3.2 Estimating the electrolyzer OPEX

The greatest expenditure of producing hydrogen from the electrolyzis is mostly attributed to the expenditure of electricity (RISE, 2021a). However, there are still maintenance expenditures and eventual stack replacements dependent on the usage. The stack degrades with the time used, resulting in lower efficiencies and thus higher electricity consumption (RISE, 2021a). The degradation is affected by multiple factors such as the working temperature and usage. RISE (2021a) has estimated the maintenance expenditure to range between 2 and 5 % of the initial investment each year, and around 20 – 40 % to replace the stack. The brands investigated in the report had a lifespan between 80 000 and 87 000 hours until needing replacement, which results in around 10 years of continuous operation (RISE, 2021a). A summary of the models assumptions is found in Table 5.1.

Table 5.1: A summary of the Electrolyzer OPEX assumed.

Maintenance cost	3,5 % of investment cost
Stack replacement	30 % of investment cost
Lifespan	80 000 hours

5.4 The hydrogen storage

The three most common storage mediums for hydrogen are pressurized tanks, metal-cased caverns and old salt mines (IVA, 2022). Davis et al. (2023) estimates prices of steel tank between \$ 135 and \$ 345 per kg H2 with prices of salt mines being orders of magnitude cheaper at approximately \$ 2 – 13 per kg H2. This report will focus on pressurized tanks because of their versatility and the lack of potential natural underground storage opportunities in Sweden (IVA, 2022). The Danish Energy Agency (2020) estimated the CAPEX of hydrogen storage in tanks to be around € 57 per kWh in 2020 and forecast a price of € 45 per kWh in 2030. Because the report investigates a near future hydrogen system, given the current year, prices are assumed to land somewhere in between, i.e., around € 50 per kWh. Converting € 50 per kWh to €/kg H2 nets approximately € 1 650 per kg H2, which is an order of magnitude larger than what Davis et al. (2023) estimate. The Danish estimation, however, also includes all other expenditures such as installation and the necessary compressor system (Danish Energy Agency, 2020). Such a comprehensive estimation is therefore more applicable to this model. The price in 2020 was € 57 and is estimated to reach € 27 by 2040 (Danish Energy Agency, 2020), meaning that it will decrease on average by € 1 per kWh annually. Danish Energy Agency (2020) further estimate the operational costs of a tank based hydrogen storage system to be around € 0,5 per kWh. An overview of the costs assumed in the model is found in Table 5.2.

Table 5.2: A summary of the Hydrogen storage expenses assumed.

CAPEX	€ 50 per kWh
OPEX	€ 0,5 per kWh

5.5 The fuel cell

There are, as previously discussed, multiple types of fuel cell technologies. Cigolotti and Genovese (2021) conducted a meta-analysis of scientific and academic literature, as well as technical papers and reports relating to fuel cell advancements. The CAPEX of PEMFC and solid-oxide technologies are investigated and forecasted for a range of stack sizes. Advancements in durability, maintenance and efficiency are also taken into consideration. The CAPEX for large-scale variants, meaning an output of more than 400 kW, currently lie between 2 000 and 3 500 €/kW but is expected to reach as low as 1 200 €/kW by 2030 (Cigolotti & Genovese, 2021). The mean value of an investment in a fuel cell in 2030 is 1 500 €/kW (Cigolotti & Genovese, 2021). However, the model assumes a price of 2000 €/kW, which is somewhere between 1 500 €/kW and the value calculated in 2021. The estimation is not linear, however, the assumption is that it is easier to make greater improvements in the near future than later.

The operational expenditures of large-scale fuel cells are not insignificant (J. Thorsson, Personal Communication, February 20, 2023) and are estimated to hover between 0,02 and 0,05 €/kW (Cigolotti & Genovese, 2021). This is on the same order of magnitude as the average Swedish electricity spot price, which over the last five years averaged 0,55 SEK/kWh (approx. 0,05 €/kWh). RISE (2021b), on the other hand, estimates the operational expenditures to approximately 120 SEK/kW, which is the figure used in the model. Cigolotti and Genovese (2021) further argues that the electrical and thermal efficiencies of solid-oxide fuel cells in real-world applications are on average 46 % and 37 % respectively, while lab results show a potential to reach 53 % and 43 % electrical and thermal efficiencies. PEMFC, however, do not show the same discrepancies between real-world and laboratory environments (Cigolotti & Genovese, 2021), which is a clear advantage. A summary is found in Table 5.3.

Table 5.3: A summary of the Fuel cell expenses assumed.

CAPEX	€ 1 500 per kW
Maintenance cost	120 SEK/kW
Lifespan	30 000 hours

5.6 The district heating network

As previously discussed, it is important to capture all energy from the system to reach a sustainable and economically viable solution. Both the electrolyzer and the fuel cell create heat in the process of converting electricity to hydrogen and vice versa. It is important to capture this heat to raise the system's total efficiency. There are many applications for the heat from the system, but it is important to consider that it will be a lot of heat, often during a low period of time and it should always be captured. A district heating network is therefor a prime candidate. Such an integration is not overly complicated, and the investment for connecting the hydrogen system to a district heating network is estimated to be around 200 kSEK (R. Hagberg, Personal communication, 22 February 2023).

The price that the district network pays for the heat from the hydrogen system will follow the same pattern as the price of biomass. The underlying assumption is that the actors behind the district heat network want to pay as less as possible for the heat, and setting the same price as the biomass creates economic incentives to always choose the heat from the hydrogen system. The aim is that the heat from the hydrogen system works as a substitute for the biomass. Therefore, there is a need to estimate the future prices of biomass to calculate the future revenues for heat from the hydrogen system. The model of the future bioenergy prices, is primarily based on historical data, starting from 1993 to the end of 2021 and coming from Table 5.4. The average biofuel price is calculated for each year and presented in the rightmost column of Table 5.4. The price for biofuels has consistently increased in the years presented, with some types more than doubling their price, e.g., refined. The averages can then be used in a linear model in Excel, simulating future prices based on history.

Table 5.4: Biofuel prices (Energimyndigheten, n.d.).

Year	Refined	Wood chips	By-products	Lump of peat	Milled peat	Reclaimed wood	Average price
1993	-	119	93	113	120	-	111
1994	143	109	85	116	104	-	111
1995	146	109	91	109	113	-	114
1996	157	112	99	104	120	-	118
1997	152	113	94	108	109	-	115
1998	161	115	98	108	99	69	108
1999	164	115	96	110	111	78	112
2000	168	112	89	109	108	69	109
2001	163	109	96	110	113	66	110
2002	178	124	104	114	114	69	117
2003	196	126	109	110	116	71	121
2004	206	138	114	126	116	74	129
2005	204	137	121	118	105	80	128
2006	211	146	128	120	116	78	133
2007	244	158	134	132	126	64	143
2008	271	167	157	148	123	69	156
2009	298	181	170	148	149	78	171
2010	300	197	179	154	141	107	180
2011	300	214	184	158	146	117	187
2012	292	209	185	161	140	107	182
2013	296	199	179	166	145	102	181
2014	277	192	167	161	149	93	173
2015	286	186	159	159	155	97	174
2016	273	181	151	156	155	89	168
2017	266	180	152	152	144	80	162
2018	277	189	159	161	146	72	167
2019	294	199	168	164	143	91	177
2020	311	201	172	163	150	100	183
2021	319	195	165	171	145	100	183

5.7 The spot price

To understand and analyze the electricity spot prices, data courtesy of Nord Pool was used (Nord Pool, n.d.-b). It is “Europe’s leading power market and offers trading, clearing, settlement and associated services in both day-ahead and intraday markets across 16 European countries” (Nord Pool, n.d.-a, About us section) and the principal trading place for electricity in the Nordic countries. The data set made available by Nord Pool contained historical spot prices for all regions in their respective currencies, in the case of Sweden: SEK/MWh. Five years of daily prices were used, ranging from January 2018 through December 2022 (Nord Pool, n.d.-b). The Swedish data is divided into the four energy regions: Luleå (SE1), Sundsvall (SE2), Stockholm (SE3), and Malmö (SE4), which were used throughout the entire model to get representative results for each individual region.

5.7.1 Spot price statistics

Firstly, the daily spot price deviation for each region, which represents how the price of a given day deviates from the yearly average, was calculated using Equation 5.4. This deviation is then averaged over the five years in question through Equation 5.5, to get a representative average daily deviation for each region. Descriptive statistics are calculated based on the monthly deviations using automatic statistical functions in Excel to better understand the data. The statistics primarily used are standard deviation, variance, range, and extreme values.

$$Daily\ deviation\ per\ year_{Region} = \frac{Daily\ spot\ price_{Region}}{Yearly\ average} \tag{5.4}$$

$$Average\ daily\ deviation_{Region} = \frac{\sum Daily\ deviation\ per\ year_{Region}}{Number\ of\ years} \tag{5.5}$$

5.7.2 Estimating future spot prices

The second part of the model is to estimate the future electricity prices using data from Nasdaq (n.d.). Nasdaq Commodities is the platform on which actors can trade electricity futures up to 10 years in advance, which provides a good indication of future trends in electricity spot prices. The prices are on a system level, meaning it is traded on an aggregated Nordic level, but can be adjusted to the four Swedish regions, SE1, SE2, SE3, and SE4, through the Electricity Price Area Differential, EPAD. EPAD indicates how the price in a region differs from the system because of constraints in the transmission grid. The EPAD data, however, only run through 2027, meaning the adjustment is missing for the last 6 years. To mitigate this, the EPAD values from 2028 to 2033 were estimated as the average from 2024 through 2027 and is assumed to be decreasing by 10 % annually, see Equation 5.6. This is because the energy demands in the northern regions are expected to rise in the coming years, thus levelling out differences in the regional spot prices (SVK, 2022a).

$$Yearly\ EPAD = \frac{\sum EPAD_{Region}}{4} * 0,9^{i} \tag{5.6}$$

where: i = years after 2027

With the electricity futures adjusted for each region, they are broken down into estimations of future daily spot prices. The average daily deviation calculated in Equation 5.5 is therefore used to model the electricity futures in Equation 5.7 with the same historical price spread.

$$\begin{aligned}&Estimated\ future\ daily\ spot\ price_{Region}\\&\qquad = (Yearly\ electricity\ futures_{Region}\\&\qquad\quad + Yearly\ EPAD_{Region})\\&\qquad\qquad * Average\ daily\ deviation_{Region}\end{aligned} \tag{5.7}$$

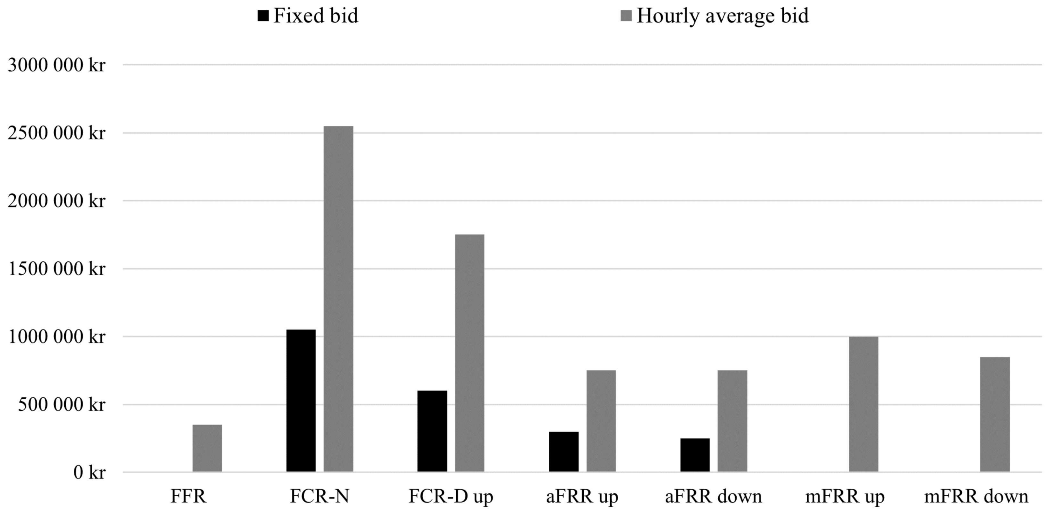
5.8 The ancillary services

A hydrogen storage system, consisting of an electrolyzer, storage, and a fuel cell can be used as an ancillary regulation system. According to a study by RISE (2022), the PEM electrolyzers have the fastest cold start and ramp-up times, exceeding the requirements for FCR and FRR services, and depending on the capacity also for FFR. There are currently few commercially available electrolyzers exceeding the capacity requirements, however, Eichman et al. (2014) argues that upscaling current systems to MW levels should not significantly change the performance. RISE (2022) calculates that electrolyzers used for producing hydrogen at a refuelling station would have their hydrogen production at a maximum decrease by 0,3 % per year if the electrolyzers are also used for ancillary services while generating substantial additional revenue. A study by Chardonnet et al. (2017) determined that revenues in the order of 1 – 2 MSEK per installed MW and year are possible. The number of operating cycles, however, is substantial, on average between 14 000 and 20 000 annually (Fingrid, 2022), independent of which ancillary service is provided. This could impact the life span and maintenance expenses of a hydrogen system. Typical fuel cells also meet the requirements for all services except FFR. If fuel cells are used for FCR-D the impact on hydrogen consumption and electricity output is assumed to be marginal, similar to RISE (2022), however, the number of operating cycles is substantially increased and could lead to the same risks as electrolyzers.

RISE (2022) investigated the potential revenue of a 1 MW system to deliver ancillary services. They conclude that the revenue, seen in Figure 5.1, is between 760 kSEK to 2,6 MSEK per year on average, depending on which type of ancillary service. The numbers are based on historical compensation between 2016-2021. The revenue is affected by the type of bidding strategy used. Offering the same bid constantly results in lower compensation. A more active bidding strategy can return a higher revenue due to the high price volatility (RISE, 2022). Most services are based on the marginal pricing model (M. Isaksson, Personal Communication, March 7, 2023). The highest bid that SVK accepts will set the price for all ancillary services in the area for the hour in question. This can result in a lesser volatile price, and the revenue will be less affected by an active bidding strategy (M. Isaksson, Personal Communication, March 7, 2023). RISE (2022) also concluded that there are opportunities to offer more than one ancillary service at the same time.

Looking at the ancillary services, based on their revenues discussed by RISE (2022) and the requirements summarised in Figure 2.2 the system fits best with FCR-D up

Figure 5.1: Average yearly revenues from ancillary services (RISE, 2022)



and down. The ramp-up speed for a fuel cell is about 50 A/s and 13 kW/s (PowerCell, 2021). This means that the system meets the requirements of the ramp-up time by assuming that the electrolyzer has the same ramp-up time. The respondent from SVK also emphasizes that hydrogen is a candidate for offering FCR-D up and down if it meets the requirement of ramp-up time (M. Isaksson, Personal Communication, March 7, 2023), which it does. In such a system, it can also have advantages against batteries regarding volume. To reach the short ramp-up time for FCR-D services, the system is needed to be on standby, meaning that the electrolyzer and fuel cell must have the right working temperature to get started quickly (J. Thorsson, Personal Communication, February 20, 2023). The water from the district heat can be used by a heat exchanger to keep the temperature of the system at the right level.

Other ancillary services like FFR and FCR-N are hard to provide with a pure hydrogen system because of, for example, ramp-up time, and oscillations. The ramp-up time for an aFFR system can be solved by using a hybrid solution including a battery that works initially. This type of hybrid system is, however, outside the scope of this report. The activation time for FFR is at most 30 seconds (SVK, 2023b), which means that the hydrogen system never starts fully and there is therefore a higher degradation on the cells. The system wants to have stable production or consumption over time (J. Thorsson, Personal Communication, February 20, 2023).

The FCR-N is activated when the frequency deviates from 50 Hz. This means that the system needs to both produce and consume to increase or lower the frequency, which is possible. However, looking at the requirements, it is more difficult to plan the system. There can also be oscillations in the system when the frequency is close to 50 Hz. It can rapidly change from production to consumption or vice versa (M. Isaksson, Personal Communication, March 7, 2023), and the problem of degradation then increases like with FFR.

The DCF model includes the revenue from FCR-D up and down. All data is from SVK (n.d.-b) and their statistical website Mimer. The forecasted compensation is based on hourly historical data between 2018 and 2022 for FCR-D up. From the historical data, a regression model is calculated for FCR-D up with the help of Excel. Then, the average price for each year can be calculated using the regression model by summarizing each compensation for each hour and dividing by the number of hours in a year. This creates a forecasted model that predicts the price for each future year. Equation 5.8 shows how the average price is calculated.

$$Price_{avg} = \frac{Hourly\ price}{8760} \tag{5.8}$$

FCR-D down, on the other hand, is relatively new, meaning that there is a lack of data. Therefore, the price for FCR-D down is set through FCR-D up. The forecasted price for FCR-D down is calculated by its relation to FCR-D up in 2022. Each year, the average price for FCR-D down is calculated by multiplying the average price for FCR-D up with this fraction. However, a limitation in the linear model is that it will rise indefinitely, which necessitates an upper limit in the price.

5.9 The grid integration

The highest installation expense is the transformer and power cables, which makes the placement of the system essential for investment. It is hard to accurately estimate the installation expenditures, due to hydrogen systems not being common in the power grid. To get a perception of the installation expenditure, it can be equated with the installation of wind turbines, which requires the same type of equipment (J. Karlsson, personal communication, March 30, 2023). Such an installation is estimated to be approximately 1 500 SEK per kW (J. Karlsson, personal communication, March 30, 2023). The estimation is likely on the higher end, since a wind turbine requires a longer distance from populated areas, meaning that it requires a lot of power cabling, groundwork and associated infrastructure (J. Karlsson, personal communication, March 30, 2023). A hydrogen system is easier to locate, meaning that the cable lengths can be reduced, and, in some cases, an existing transformer can be used (J. Karlsson, personal communication, March 30, 2023).

There are also tariffs for feeding electricity into the power grid from the fuel cell. The tariff is based on a local production system with high voltage and power greater than 1 500 kW. For such type of system, the monthly fixed fee is 900 SEK (J. Karlsson, Personal Communication, March 30, 2023). Then there is an additional yearly fixed price of 65 SEK per kW. On the other hand, there is a variable compensation for the volume of energy provided to the grid. During the season of November to March, on weekdays between 06:00 to 22:00, the electrical system is most exposed which results in a higher compensation for feeding in electricity. This compensation is set to 0,116 SEK per kWh. The compensation for the other times is 0,09 SEK per kWh. (J. Karlsson, Personal Communication, March 30, 2023). A summary is found in Table 5.5.

Table 5.5: Expenses and revenues of feeding electricity to the grid.

Fixed fee	900 SEK/month
Subscription fee	65 SEK/kW/year
Compensation (Nov. to March, 06:00 - 22:00)	0,116 SEK/kWh
Compensation (Rest of the year)	0,09 SEK/kWh

The electrolyzer needs electricity to produce hydrogen and there are tariffs for drawing electricity from the power grid besides the electricity price. There is a fixed expenditure of 24 000 SEK per year independent of the system's power and an annual subscription fee of 160 SEK per kW (J. Karlsson, Personal Communication, March 30, 2023). During the high-load months described earlier, the fee is set to 0,18 SEK per kWh. Not only that there is also a high-load fee of 180 SEK per kW based on the average peaks in each month during these times. Outside of these times, the price is 0,14 SEK per kWh (J. Karlsson, Personal Communication, March 30, 2023). A summary is found in Table 5.6.

Table 5.6: Expenses of drawing electricity from the grid.

Fixed fee	24 000 SEK/year
Subscription fee	160 SEK/kW/year
High load fee (Nov. to March, avg. peak)	180 SEK/kW
Fee (Nov. to March, 06:00 - 22:00)	0,18 SEK/kWh
Fee (Rest of the year)	0,14 SEK/kWh

5.10 The scenarios

As outlined in the problem description the report features two scenarios in which the techno-economic potential of a hydrogen energy storage system is evaluated. These are electricity spot price arbitrage and grid support through ancillary services. The following sections will outline the conditions and rationale behind both scenarios.

5.10.1 Scenario 1: Electricity arbitrage

The first scenario concerns electricity spot price arbitrage, and its parameters are summarized in Table 5.7. The basic concept is to buy energy during low electricity spot prices, which equates to a high supply, and convert the electricity through the electrolyzer to hydrogen for storage. When prices rise, the hydrogen is converted to electricity, through the fuel cell, and sold on the market. This would, at larger scales, lead to shifts in the system load, leveling out peaks in electricity demand. It is possible in theory due to fluctuations in the spot price, however, it is not known whether it would prove economically profitable in real-world applications.

The analysis is based on the electricity spot price estimations made in Section 5.7, where thresholds for buying and selling energy were set based on the 25th and 75th percentile of estimated spot prices. The system is dimensioned to have a storage capacity of approximately 2 days' worth of hydrogen to benefit from multiple consecutive days of low or high prices. While a larger storage tank could mean that there is a higher probability of the system having stored hydrogen when prices fall, or having free space when prices are low it comes at a high cost. The tank is the most expensive component, and current regulations would dictate substantially stricter demands if the storage is larger than 5 000 kg (J. Thorsson, Personal Communication, February 20, 2023).

Table 5.7: A summary of the figures assumed in Scenario 1.

Chosen technology	PEM
Electrolyzer capacity	1 MW
Electrolyzer efficiency	65 %
Fuel cell capacity	1 MW
Fuel cell efficiency	60 %
Hydrogen energy density	33,3 kW/kg H_2
Storage capacity	2 000 kg
Spot price region	Stockholm (SE3)

5.10.2 Scenario 2: Ancillary services

The second scenario of interest is the potential of implementing a hydrogen energy system for ancillary services. Its parameters are summarized in Table 5.8. A combination of Electrolyzers, hydrogen storage and fuel cells, like Scenario 1, is used for this, meaning that their input and output capacity is sold to support the grid in cases of deviating frequency. As discussed earlier, a hydrogen system is most suitable to offer the FCR-D services, both up and down. SVK (n.d.-b) publishes data on prices and volumes for the regulation services, which are used for the analysis.

There is an opportunity to both offer FCR-D up and FCR-D down at the same time (M. Isaksson, Personal Communication, March 7, 2023). This is because the power grid is hard to plan, due to consumption and production, so there is almost always demand for both up and down support. By offering the two ancillary services, it is important to have a balance in the storage, meaning that there is a need for planing. Sufficient space in the tank is needed so that either the electrolyzer or the fuel cell can run at any time. It does not need to be enormous, due to the short but frequent activation times. The system is dimensioned so, given that the storage is full, the fuel cell can run continuously for 8h. The electrolyzer can, however, run at any time even if the storage is full. The hydrogen produced can be released into the air in smaller concentrations, but this is an unnecessary waste of resources. It is important to mention that the services, FCR-D up and down, are not running at the exact same time because they counteract each other.

Because the services are selected and compensated through the marginal price model, the system is assumed to always place a price, or bid, nearly 0. This ensures that it will most likely always be procured and results in a positive contribution to the cash flow. Because the system is of the same scale as Scenario 1, meaning a 1 MW facility, it is will only contribute a small amount to the total FCR-D capacity procured. Therefore, it is likely that it will always be procured when a bid of 0 is placed, and not substantially affect the price negatively. Even though the ancillary services of FCR-D is always procured for every hour, they are not always activated, meaning that the system is often only on standby. To account for uncertainty in whether the bidding strategy always works and in estimating future FCR-D prices an additional calculation is made where all revenues are reduced by 40 % to understand how drastically lowered revenues would affect the profitability. A summary is found in Table 5.6.

Table 5.8: A summary of the figures assumed in Scenario 2.

Chosen technology	PEM
Electrolyzer capacity	1 MW
Electrolyzer efficiency	65 %
Fuel cell capacity	1 MW
Fuel cell efficiency	60 %
Hydrogen energy density	33,3 kW/kg H_2
Storage capacity	400 kg

6

Results and Analysis

The first research question is divided into two subquestions, one for each scenario. This chapter will therefore go through the results of the calculation model, and analysis the findings of both scenarios; electricity arbitrage, and ancillary services. This will be followed by a general discussion in which the second research question is answered through relevant aspects from the literature in Chapter 3.

6.1 Scenario 1: Electricity arbitrage

Scenario 1 brings together the future spot price estimations and the district heating network to create a comprehensive analysis of implementing a hydrogen system that trades in electricity. The results from the two parts are presented and analysed individually, followed by an overarching analysis of the system as a whole and whether or not it is potentially profitable.

6.1.1 Estimating future spot prices

The yearly average electricity spot price between 2018 and 2022 varied between 0,15 and 1,62 SEK/kWh. As discussed in the introduction, electricity prices are generally higher in the two southern regions of Sweden, which is evident in Table 6.1. A general increase in prices can be observed, especially in 2022.

Table 6.1: Yearly regional spot prices [SEK/kWh] (Nord Pool, n.d.-b)

Year	Luleå (SE1)	Sundsvall (SE2)	Stockholm (SE3)	Malmö (SE4)
2022	0,63	0,66	1,33	1,62
2021	0,43	0,43	0,65	0,92
2020	0,15	0,15	0,25	0,27
2019	0,40	0,40	0,39	0,42
2018	0,45	0,45	0,47	0,48

Based on the data found in Table 6.1 and daily spot prices ranging from 2018 - 2022 average daily deviations are calculated through Equations 5.4 and 5.5. This is summarized per month in Figure 6.1, which shows that the winter months have a substantially larger price spread than the rest of the year. December is on average the most expensive, with a spot price that is 1,64 times higher than the yearly average. However, this is only on average, and as seen in Figure 6.1, the spread is rather large in these months. The data also tells that while the northern regions generally have lower prices, Figure 6.2 shows that the fluctuations are higher in these regions.

Figure 6.1: Monthly deviations from yearly averages per region.

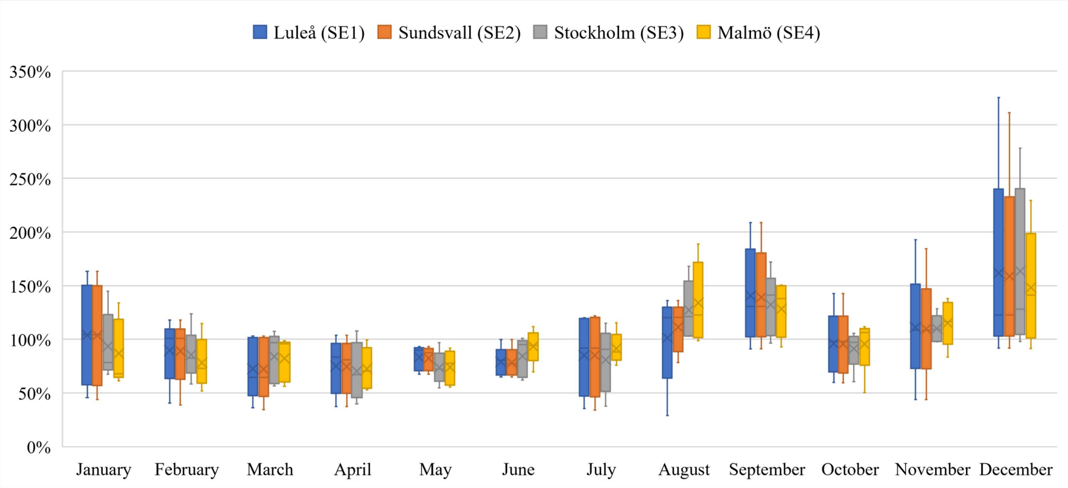
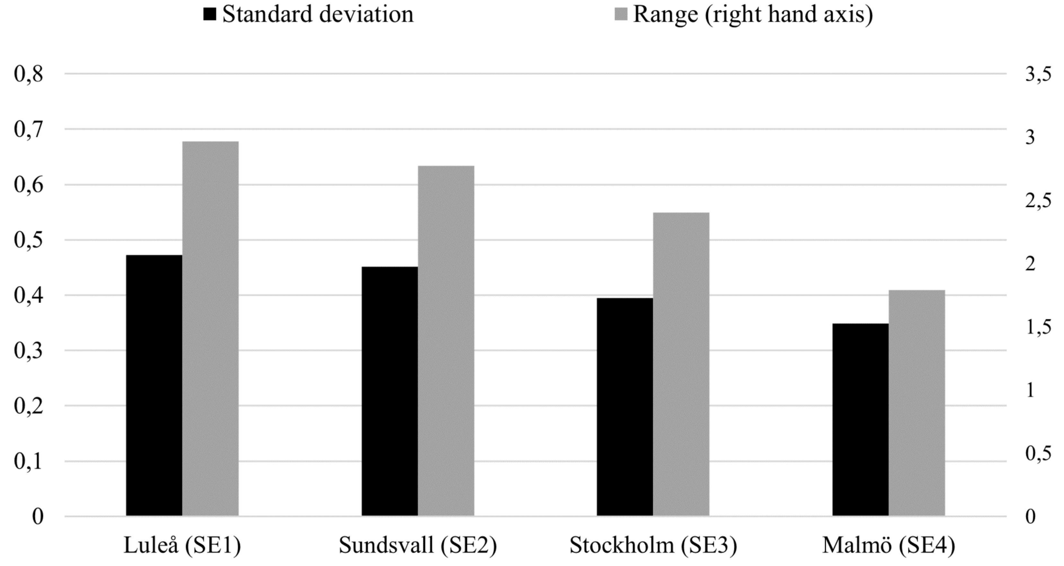


Figure 6.2: Average range and standard deviations of spot price deviations per region.

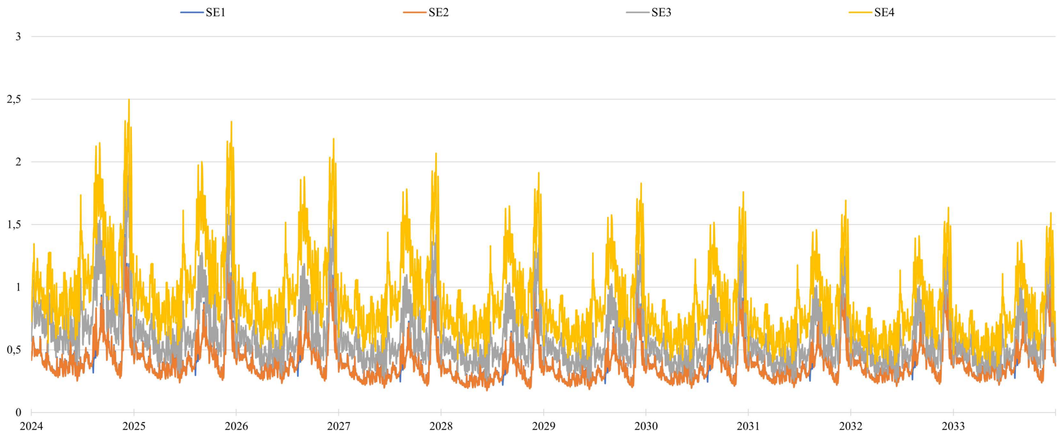


There is a trend towards lower electricity prices indicated by the futures which are represented as the system price in Table 6.2. This could have many explanations, some of which are that the supply will be higher or that energy consumers are uncertain about what their demand will be. Electricity generation is generally a long-term operation at large scales, meaning that producers plan and know well in advance their potential output and operational expenditures, given no unexpected circumstances. Because the electricity mix in Sweden is heavily leaning towards hydroelectric and nuclear power, it is generally not affected as much by fluctuations in, for example, gas or oil prices, thus being more easily predictable. While system prices from (Nasdaq, n.d.) run through 2033, the EPAD adjustments end in 2027. Therefore, the missing years in Table 6.2 are estimated (values in italics) as the average from 2024 through 2027 and adjusted with a 10 % annual decrease, due to regional differences expected to level out. After adjusting the futures with the average daily deviations an estimation of future daily spot prices is achieved, which is presented in Figure 6.3.

Table 6.2: System wide and regionally adjusted electricity futures [SEK/kWh] (Nasdaq, n.d.).

Year	System	SE1	SE2	SE3	SE4
2024	0,82	0,48	0,48	0,83	1,17
2025	0,67	0,45	0,45	0,69	1,09
2026	0,60	0,44	0,44	0,64	1,03
2027	0,56	0,37	0,37	0,60	0,97
2028	0,54	*0,33*	*0,33*	*0,56*	*0,90*
2029	0,53	*0,35*	*0,35*	*0,56*	*0,86*
2030	0,53	*0,37*	*0,37*	*0,55*	*0,83*
2031	0,53	*0,38*	*0,38*	*0,55*	*0,80*
2032	0,53	*0,40*	*0,40*	*0,55*	*0,77*
2033	0,53	*0,41*	*0,41*	*0,55*	*0,75*

Figure 6.3: Estimated future sport prices from 2024-2034 [SEK/kWh].



Validating the spot price estimations is difficult due to both the unsure nature and the long timeframe. However, SVK (2022a) simulates similar price levels which corroborates the model's results. The model also follows the same reasoning in that the price difference across the four regions will decrease, thus more closely following the system price. This is mainly due to prices in the two northern regions increasing because of increased local consumption (SVK, 2022a). Would the HYBRIT project prove successful it would further increase the energy consumption in those regions substantially and level out the prices even further (J. Thorsson, Personal Communication, 20 February, 2023). The model does differ, however, in that it estimates a relatively stable longer-term spot price, while SVK (2022a) predicts a rise in prices in the same period. The reality is difficult to pinpoint, but SVK (2022a) argues that the demand will rise faster than the supply, which would result in higher prices.

6.1.2 Estimating biofuel prices

Biofuel usage in the district heating networks has increased 11 times since 1983 and is the biggest energy source since 1997. The usage of biofuel in the systems increased until 2010 when it reached a saturation level (Naturvårdsverket, 2017). The demand for biomass, in other sectors, increased by 7 % between 2010 and 2021 and will increase by 10 % per year until 2030 (IEA, 2022a). As seen, the rising demand can be one factor in the rising prices. The assumption made is that there is a correlation between the demand for biomass and the price. Since the demand will increase in the future so will the price do in the model. Equation 6.1 shows the resulting regression visualised in Figure 6.4.

Figure 6.4: Linear regression model of biofuel prices.

$$y = 3,172x + 98,018 \tag{6.1}$$

where: R^2 = 0,8174
x = year

There are also other factors that could increase the price more than estimated. For example, the war in Ukraine affects energy prices drastically by forcing the energy systems to lower their dependence on Russian biogas (European Council, 2023). Also, other types of environmental factors will affect both the price and demand. The conclusion is that it is hard to predict the biofuel price which is used for the district heating because there are many uncertain factors. It is therefore better to not overestimate the price creating higher revenues and thus a building a higher risk. Another important simplification made, is that the model is based on the average price. Different district heating centres are using different fuel mixes, which alters their price structure and demand. It is difficult to find data on the different fuel mixes of biomass, which limits the model. However, looking at the model itself, it shows a relatively high meaning that many of the historical values can be explained by the appreciated model (Jaggia & Kelly, 2021).

6.1.3 Electricity arbitrage

Based on the spot price estimations and the biofuel prices from the previous sections, a net present value (NPV) calculation i made to evaluate the potential investment of a hydrogen storage system. In practice, the system would buy energy at low spot prices and sell the stored energy at higher prices. Based on current and near-future efficiencies of electrolyzers and fuel cells it is necessary for the spot price to vary 2,56 times for the process to break even just on the losses in efficiency. This factor increase substantially if all investment expenditures are included, reaching a price variation of 10 times. Based on this it is already clear that a purely arbitrage-based system would not prove profitable given near-future developments in efficiencies.

Given an investment in a 1 MW system, meaning an equally sized electrolyzer and fuel cell, together with a 2-ton hydrogen storage tank, the total CAPEX would amount to 67 MSEK, with a yearly maintenance expenditure of roughly 0,9 MSEK, see Table 6.3 for a detailed breakdown. Trading limits were set to the median and 75th percentile after experimentation, meaning that the electrolyzer would run if the spot price was below the median of estimated future prices and the tank was not full, and the fuel cell would run if the price surged to the top 25 % of estimated prices and there was hydrogen in the tank. This results in a negative cash flow from electricity, roughly -0,7 MSEK over the ten years, indicating that the difference in price is not large enough. The cash flow from the waste heat sold as district heating is, however, positive, amounting to 1,7 MSEK. In summary, the investment shows negative cash flows each year of roughly 1 MSEK, resulting in an NPV of -74 MSEK, as seen in Table 6.4.

The potential revenues from the scenario of a hydrogen arbitrage system does not even cover the yearly operational expenditures. This is mainly due to two factors, the losses caused by low electrical efficiencies and the high investment costs for such a system. Typical electrolyzers and fuel cells have efficiencies around 60 - 70 % and 60 % respectively, meaning that the spot price of electricity must vary at least 2,56 times, not accounting for revenue from waste heat, to reach a break-even point. While this price difference is not unreasonable given both the historical and estimated spot prices, it becomes so when the capital expenditures are included. The argument is not that a price difference of 10 times is impossible, but rather that it does not occur with such a frequency that necessary trading volumes are reached. A more advanced predictive model would be able to optimize the trading and price estimates, but since the NPV is so far below 0, the argument of not enough frequency in the price variance would still stand. The efficiencies are predicted to rise in the future (RISE, 2021b; RISE, 2021a) to around 80 % respectively which would necessitate a price variation of approximately 1,56 times, not accounting for waste heat revenue. However, this number still rises substantially when accounting for the capital expenditures, and the necessary price variation is still unreasonable in the future.

Table 6.3: Scenario 1: Expenditure breakdown.

	CAPEX [SEK]	OPEX [SEK/year]
Electrolyzer	10 286 749	360 036
Hydrogen storage	33 000 000	402 930
Fuel cell	22 000 000	120 000
Grid integration	1 700 000	249 900
Total Expenditure	66 986 749	1 132 866

Table 6.4: Scenario 1: NPV calculation [kSEK].

Year	0	1 2025	2 2026	3 2027	4 2028	5 2029	6 2030	7 2031	8 2032	9 2033	10 2034
Initial investment	-65 286,7										
Operational costs		-883,0	-883,0	-883,0	-883,0	-883,0	-883,0	-883,0	-883,0	-883,0	-883,0
Cash flow from spot price		-6,8	-50,0	-89,6	-81,2	-85,4	-85,1	-83,4	-82,9	-82,4	-82,8
Cash flow from heat		41,5	128,6	213,8	181,0	196,8	196,8	196,8	196,8	196,8	196,8
Grid integration costs	-1 700,0	-249,9	-249,9	-249,9	-249,9	-249,9	-249,9	-249,9	-249,9	-249,9	-249,9
Total cash flow	-66 986,7	-1 098,1	-1 054,3	-1 008,6	-1 033,1	-1 021,5	-1 021,2	-1 019,5	-1 019,0	-1 018,5	-1 018,9
Total discounted cash flow	-66 986,7	-1 004,7	-882,5	-772,4	-723,9	-654,8	-599,0	-547,1	-500,3	-457,5	-418,7
Accumulated discounted cash flow	-66 986,7	-67 991,4	-68 874,0	-69 646,4	-70 370,3	-71 025,1	-71 624,1	-72 171,1	-72 671,4	-73 128,9	-73 547,6
Net Present Value	-73 547,6										
Rate of Return	9,30%										

6.2 Scenario 2: Ancillary services

Scenario 2 is based on a 1 MW facility with 0.4-ton hydrogen storage for implementation as an ancillary service. The calculations for FCR-D up are based on historical data from 2018 to 2022. For FCR-D down, there is only historical data from one year since it was introduced in 2022. The average prices for each year are presented in Table 6.5.

Table 6.5: Price developments in ancillary services (SVK, n.d.-b).

Year	FCR-D up	FCR-D down
2018	0,20	-
2019	0,25	-
2020	0,18	-
2021	0,49	-
2022	0,69	0,35

Table 6.5 show that, apart from 2020, there is a pattern of rising compensation for FCR-D. The trend is a result of changing energy politics, which promotes green energy, resulting in more volatile energy production (M. Isaksson, Personal Communication, March 7, 2023). In 2022, the war between Russian and Ukraine and the supply of natural gas influenced the electricity system, resulting in a directive to make the European Union less affected by Russia (M. Isaksson, Personal Communication, March 7, 2023). Energy production and consumption are something that does not change overnight and needs a long planning period (M. Isaksson, Personal Communication, March 7, 2023). Therefore, the importance of ancillary services is essential for the future power grid. The need for these services is going to increase in the future, resulting in the market growing and the requirements for some of the services have changed to fit a broader customer base (M. Isaksson, Personal Communication, March 7, 2023). Forecasted models from SVK show that the market for ancillary services will increase in the coming years and reach a market value of 8 billion SEK (Wickström, 2023).

The price for the FCR-D up is estimated through linear regression with the help of Excel, based on the historical hourly data between 2018 and 2022 from SVK (n.d.-b). The price is assumed to continue being volatile with a similar pattern in the future as before. FCR-D down is estimated as a percentage of FCR-D up because it does not have sufficient historical data to build a significant linear regression. The ratio between them in 2022 is around 51 %, which is what is being used as the compensation for FCR-D down each consecutive year. The estimated price from the linear regression for FCR-D up and down is presented in the first two columns of Table 6.6. The two last columns in Table 6.6 refers to the yearly revenue of a 1 MW hydrogen system.

Table 6.6: Forecasted compensation for ancillary services.

Year	Average hourly price (SEK/kW)		Yearly revenue (SEK)	
	FCR-D up	FCR-D down	FCR-D up	FCR-D down
2024	0,61	0,31	5 344 478	2 716 318
2025	0,73	0,37	6 427 883	3 266 956
2026	0,86	0,44	7 509 806	3 816 841
2027	0,98	0,50	8 591 729	4 366 725
2028	1,09	0,55	9 519 250	4 838 136
2029	1,10	0,56	9 636 000	4 897 474
2030	1,10	0,56	9 636 000	4 897 474
2031	1,10	0,56	9 636 000	4 897 474
2032	1,10	0,56	9 636 000	4 897 474
2033	1,10	0,56	9 636 000	4 897 474

While the future prices of ancillary services are based on linear regression, it is only an estimate, and that comes with inherent uncertainty. While an argument can be made that the price trend will continue, i.e., prices will keep rising, it will not do so indefinitely. Market dynamics will over time push prices towards an equilibrium because of an increasing interest from actors to offer ancillary services when prices rise, and the system also becomes cheaper which in turn pushes the price back down. Therefore, a ceiling for the price of ancillary services was set in the model to 1,10 SEK/kWh for FCR-D up and 0,56 SEK/kWh for FCR-D down, i.e., 51 % of 1,10, in 2028. The celing price for FCR-D up is concluded by considering indicators such as spot price, as seen in Scenario 1 will increase, looking at how the renewable energy market will expand, and to which extent it is possible for new entrants to offer ancillary services. However, the revenue from heat can be neglected due to the low period as it is active. The system will use more heat than it emits because it needs to be on standby to keep the system preheated the whole time so it fast can be activated.

Because FCR-D is a service used only during times of disturbances in the grid, it does not always become activated even though the capacity is purchased (Fingrid, 2022). This implies that a system offering this type of service is not always active, thus only being on standby, essentially getting paid for doing nothing. This is positive in terms of wear because the actual number of cycles will be lower than the number of times it offers its services to the grid. As discussed in Section 5.8, however, is that the number of cycles is still rather high and has the risk of quickly wearing out both electrolyzers and fuel cells. This will increase the costs of the system, and potentially lead to costly stack replacements.

Statistically, the total time of the frequency between 2016 to 2021 in the grid has often become higher than 50.1 Hz instead of lower than 49.9 Hz, 2 247 127 compared to 1 946 661 (Fingrid, 2022). In other words, the electrolyzer will at least produce the same amount of hydrogen that the fuel cell consumes. Even when electricity prices started to rise in 2021, due to the lack of supply (SVT, 2021), the frequency was more often above than below 50 Hz. An overview of the average times the frequency has deviated from the normal interval, i.e., below 49,9 Hz or above 50,1 Hz is found in Table 6.7.

Table 6.7: Average frequency deviations 2016-2021 (Fingrid, 2022).

f (Hz)	0 - 1 s	1 - 5 s	5 - 10 s	10 - 20 s	20 - 40 s	40 - 60 s	1 - 3 min	>3 min	Yearly amount	Max duration [s]	Average duration [s]
>50,1	16 809,3	5 407,0	3 756,0	5 775,7	3 778,5	833,3	666,7	114,3	37 140,8	2 043,9	10,1
>50,2	56,5	26,3	28,5	25,8	10,0	2,2	1,7	0,0	151,0	155,1	7,7
>50,3	0,7	2,0	0,5	0,2	0,0	0,0	0,0	0,0	3,3	10,7	3,6
<49,9	14 857,3	5 381,7	3 453,0	5 237,8	3 417,0	698,8	534,8	89,2	33 669,7	999,3	9,6
<49,8	50,3	30,2	25,8	14,0	4,5	1,2	0,7	0,3	127,0	390,7	6,4
<49,7	0,8	1,3	2,7	1,3	0,0	0,0	0,0	0,0	6,2	17,9	6,7
<49,6	0,2	1,2	0,7	0,0	0,0	0,0	0,0	0,0	2,0	7,8	3,8
<49,5	0,0	0,2	0,0	0,0	0,0	0,0	0,0	0,0	0,2	3,5	0,0

The revenue and expenses of the power grid is depending on if the electrolyzer consumes electricity or if the fuel cell produces electricity. However, even if the variable expenses for the power grid connection, see Table 5.6, were a little bit higher compared to the revenue, see Table 5.5, the activation time for ancillary services was higher for FCR-D down compared to FCR-D up. Therefore, the assumption for the DCF model is that the revenue and costs for the system will even out each other and be set to 0 SEK. The electrolyzer will also use the electricity, while it is activated for FCR-D down, to produce the hydrogen, meaning that it is not necessary to buy electricity from the market to the system. At the same time, the fuel cell uses hydrogen when activated for FCR-D up, creating a closed system. The total investment for a 1 MW facillity is summarized in Table 6.8.

Table 6.8: Scenario 2: Expenditure breakdown.

	CAPEX [SEK]	OPEX [SEK/year]
Electrolyzer	10 286 749	360 036
Hydrogen storage	8 250 000	100 733
Fuel cell	22 000 000	120 000
Grid integration	1 700 000	249 900
Total Expenditure	40 586 749	810 522

Summarizing the cash flows results in a net present value of 32 686 761 SEK over a period of 10 years with an interest rate of 9,3 %, as calculated in Section 5.1. The net present value becomes positive during the first half of year 6, meaning that the investment will generate positive support for the cash flow. Table 6.9 gives an overview of the entire calculation.

Table 6.9: Scenario 2: NPV calculation [kSEK].

Year	0	1	2	3	4	5	6	7	8	9	10
		2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Initial investment	-38 886,7										
Operational costs		-560,6	-560,6	-560,6	-560,6	-560,6	-560,6	-560,6	-560,6	-560,6	-560,6
Cash flow from ancillary services		8 060,8	9 694,8	11 326,6	12 958,5	14 357,4	14 533,5	14 533,5	14 533,5	14 533,5	14 533,5
Grid integration costs	-1 700,0	-249,9	-249,9	-249,9	-249,9	-249,9	-249,9	-249,9	-249,9	-249,9	-249,9
Total cash flow	-40 586,8	7 250,3	8 884,3	10 516,1	12 147,9	13 546,9	13 723,0	13 723,0	13 723,0	13 723,0	13 723,0
Total discounted cash flow	-40 586,8	6 633,4	7 436,8	8 053,7	8 511,8	8 684,4	8 048,7	7 363,9	6 737,3	6 164,0	5 639,6
Accumulated discounted cash flow	-40 586,8	-33 953,4	-26 516,6	-18 462,9	-9 951,1	-1 266,8	6 782,0	14 145,9	20 883,1	27 047,2	32 686,8
Net Present Value	32 686,8										
Rate of Return	9,30%										

As a part of the risk and sensitivity analysis another NPV was calculated 40 % reduced revenues from the ancillary services. It is unsure how much the price will rise, and whether the bid would always be won. The net present value is estimated to 1 323 891 SEK, indicating that it is still a profitable investment, and that there is a substantial margin for error in the profitability analysis. This proves that the estimations need to be very wrong for the investment to not actually be profitable. The accumulated cash flow becomes positive during year 10.

The two NPV models, the original and the one with reduced revenues, show that grid ancillary services are a potentially profitable implementation of current and near-future hydrogen systems. Due to the increasing share of unplannable renewable energy in the grid, ancillary services will only become even more important in the future. This is evident in the price trends of the ancillary services in question which are both becoming more expensive, and more numerous. However, even if there will be a higher demand for ancillary services, the supply will also be greater due to the lucrative profitability. Therefore there is uncertainty about how the price will develop. Due to its natural size, this type of facility requires planning and evaluation to be connected to the power grid, meaning that in nearby, probably, the demand can be hard to meet.

One of the main advantages of offering ancillary services with a hydrogen energy storage system is that it can be combined with other purposes. For example, a bank of electrolyzers used for hydrogen production will likely have a variable production volume, meaning that it is rarely used at peak power, which would enable the system to also offer the remaining capacity for the FCR-D services. As discussed in RISE (2022), this will only affect the production of hydrogen by a relatively small amount and return a substantial additional revenue stream.

6.3 Discussion

The power grid, energy storage, and production are changing globally and a lot of innovative solutions are emerging in different places, in niches, trying to compete with established technologies such as fossil combustion. However, with the higher demand for renewable energy sources, complementary products needed to be developed in order to further switch to renewable energy sources. Otherwise, the weather-dependent energy sources are not sufficient, and we are still dependent on other sources, e.g., fossil fuels, when the weather does not allow production to meet the demand. Historically, power sources were easy to plan and could therefore easily produce electricity to meet the demand.

The new solutions, e.g. batteries, and hydrogen has created a technological discontinuity, a new regime in the energy market, which has the potential to make the power grid and the supply more stable, without the use of fossil fuels. The technologies are relatively old, but it has been a lot of innovations within these areas in recent years. The old dominant design, based on fossil fuels, has been around for many years, but with changing behavior and nudging from politics it has been dislodged.

However, by trying to connect the pattern of what is happening in the energy storage landscape to the technology life cycle, described by Anderson and Tushman (1990), the energy landscape can be categorized in the era of ferment and is described as a Mark I industry. The technologies are still in the early stages and there is much focus on development and pilot projects such as in the case with RISE (n.d.). Incumbents are needed to develop new technologies or make the current ones better to stay competitive. Otherwise, if the lock-in effects are too high, they will exit the market.

There is no established dominant design yet for storing large amounts of energy, and it is likely that multiple paths will emerge due to the rather different characteristics of e.g., batteries and hydrogen energy storage. This is also the case within the hydrogen industry, where multiple technologies are currently competing, e.g., alkaline and PEM. It is currently unsure what path the industry will take. Multiple experts are betting on the PEM technology, which today shows the best potential and are applicable in many situations as discussed in Chapter 3. As discussed by Breschi et al. (2000) there are often advantages to being an early mover when developing innovative technologies, due to the ability to experiment and accumulate valuable knowledge which can become a competitive advantage in the future. As mentioned in Chapter 1, the hydrogen market and the renewable energy sector as a whole will increase and can create opportunities for new entrants. The applications are often initially found in niches, where innovations prove competitive (Geels, 2004), and one such example is ancillary services, where a hydrogen energy system is proven to likely be profitable, both today and in the future. The niche will only become more attractive due to the changes caused by renewable energy which puts the services in higher demand. This is positive for the development of hydrogen-related technologies, which could see a boost in development through a rise in demand. Also, the incentives and nudges from governments e.g., the EU, create opportunities for niches to develop and make a transition to renewable energy.

It is also important to put hydrogen technologies in context and understand that it is heavily affected by other complementary technologies and products. For example, the power grid and its transmission capacity are essential to get the system to work. Hydrogen is currently not a widely used resource (IEA, 2023), which historically would have limited the development of electrolyzers, however as its uses increase, e.g., in steelmaking, such as the HYBRIT project, the incentives to develop electrolyzers will follow. Now, institutions such as IEA (2023) include hydrogen as a part of the transition towards renewable energy and a power grid that can handle the consequences of such a transition. This causes an increased development cycle and consequently rapidly increases performance and lower costs of the emerging technologies.

It is also relevant to look at current and future regulatory environments to understand how the industry will develop. The EU has announced substantial investments and tightening regulations to promote green energy in general, but also specifically towards hydrogen to help it develop competitively. It is clear from their efforts that many of the narratives employed are towards stretch and transform (Smith & Raven, 2012), meaning that the selection environment is forced to change to accommodate the different characteristics of green energy, particularly hydrogen.

Looking at the adopter category by Rogers (2003), a hydrogen system is not widely diffused, and projects of greater dignity are still in the early phases or even under development. It is only diffused to a small crowd of adopters that have knowledge about such a system. A hydrogen system is still capital intensive and the technology choice is very uncertain, meaning that they are more intended for early adopters, such as Innovators (Rogers, 2003). The technology is uncertain in terms of performance and if it will succeed. Today, there are other, safer, and cheaper solutions, when considering current metrics, meaning that late adopters probably will still focus on the old alternatives. However, to reach a higher diffusion it is important to reach the early adopter (Rogers, 2003). To reach this group, the uncertainty needs to be decreased, which is done by continuously developing the technology, and testing hydrogen systems in real-world applications to create awareness and attention. It is important to show the critical mass that the hydrogen system can be profitable today, e.g., ancillary services, which creates a demand for this type of system. With a growing market, there can be easier to develop the technology further, in terms of capital expenditures and performance to fit more applications. After that, the dominant design will probably emerge.

7

Conclusions

This report contributes to showing the potential of using a hydrogen system in the power grid and under which circumstances it is profitable. This can be used for finding different applications for a hydrogen system to speed up the technology development and the diffusion among customers. It aims to build an understanding of the energy grid and storage, its challenges, and what some solutions might be in the transition to renewable energy. Because of how wind and solar power change the characteristics of power generation, new solutions need to be implemented. Some problems needing solutions are large-scale energy storage and frequency balancing. The need to modulate the frequency in the grid will increase in the future, thus increasing the demand for ancillary services. However the literature on this area is scarce, and the report aims to highlight its importance and propose a hydrogen system as a potential solution. Much research focus has previously been on batteries thus creating a gap in the reach and development of hydrogen systems that can achieve similar results. Batteries and hydrogen systems are not necessarily competing, but rather complement each other. Previous literature indicate that hydrogen systems are more advantageous at larger scales relative to batteries, both in terms of energy density and expenditures, and could potentially be a relevant source of backup power as common diesel generators are phased out. This is not investigated in the report, however, it is another interesting application for further studies to explore.

The analysis concludes that the first scenario, an electricity arbitrage system is not profitable in terms of NPV. However, this is based on current selection environments, and as discussed in the socio-technical transition literature, innovations, and landscape pressures might enable a stretch and transform narrative, which alters society's selection environment and potentially makes such a hydrogen system profitable. There are however currently technical limitations with a hydrogen system due to the low electrical efficiencies, but as the development paths converge toward a dominant design performance will typically increase.

Implementing a hydrogen system as an ancillary service is proven to be a potentially profitable scenario. Forecasting the price of different ancillary services is difficult and inherently uncertain because of its dependence on how the energy grid and spot price evolve over time. To account for these risks and uncertainties the NPV is also calculated for a reduced revenue, which also indicates on such a system still being profitable.

It is important to bear in mind that the equation is likely to change in the future as selection environments transform due to climate change mitigating efforts such as taxes on fossil fuels, rare minerals, or subsidies on certain technologies. The field are rapidly evolving, and what appears to be relevant today might be obsolete in a few short years. Therefor it is relevant to continuously investigate applications for hydrogen systems, and how it can fit into society's selection environments.

While the report is limited to the Swedish power grid, the spot price and power grid are not isolated to Sweden. Therefore it is necessary to understand what is happening in Europe and what directives there are from the EU and the individual countries within the EU. Therefore one suggestion for further research is to make an international analysis of electricity price and transmission capacity. The report also concludes that there is a need for further research on hydrogen technologies to better understand its advantages compared to other solutions such as batteries, and where each technology best fits into the entire transition to renewable energy. The rate of change is increasing, and therefore there are opportunities for further investigations into not only large scale energy storage and ancillary services, but also other applications.

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A

Appendix, Interviews

Interview 1

Open interview regarding the application of hydrogen in the power grid.
Duration: 1 hour
Jan Thorsson, Sales Manager Stationary systems, Powercell Group.
20 February 2023

Vad ser du för användningsområden för vätgas?
Många gånger handlar det om att mellanlagra energi för att ta tillvara när det finns en överproduktion då det oftast är lägre priser. Vätgas kan också användas som backup i energisystemet och kan installeras för datorhallar, transformatorer och master. I vissa fall är det för att ersätta fossila lösningar. Batteri och vätgas är idag en småskalig teknik. Jag tror att vätgas kommer att användas i relativ småskalig energilagring. Batterier kommer att återfinnas i ännu mindre energilagringar.

Ser du några begräsningar med vätgas som lagringsmedium?
Elektrolysören och bränslecellen i sig finns det inga större begränsningar. Den stora begränsningen är vätgaslagringen. När kapaciteten överstiger 5 ton blir det ett annat regelverk vilket ställer andra krav på säkerhet på grund av explosionsrisken vid ett läckage. En tank på 5 ton lämpar sig bra till större fastigheter.

Hur mycket kilowattimmar (kWh) kan produceras av ett kilo vätgas?
Varje kilo vätgas (H2) ger ungefär 36 kWh.

Vilka olika användare finns det för vätgas?

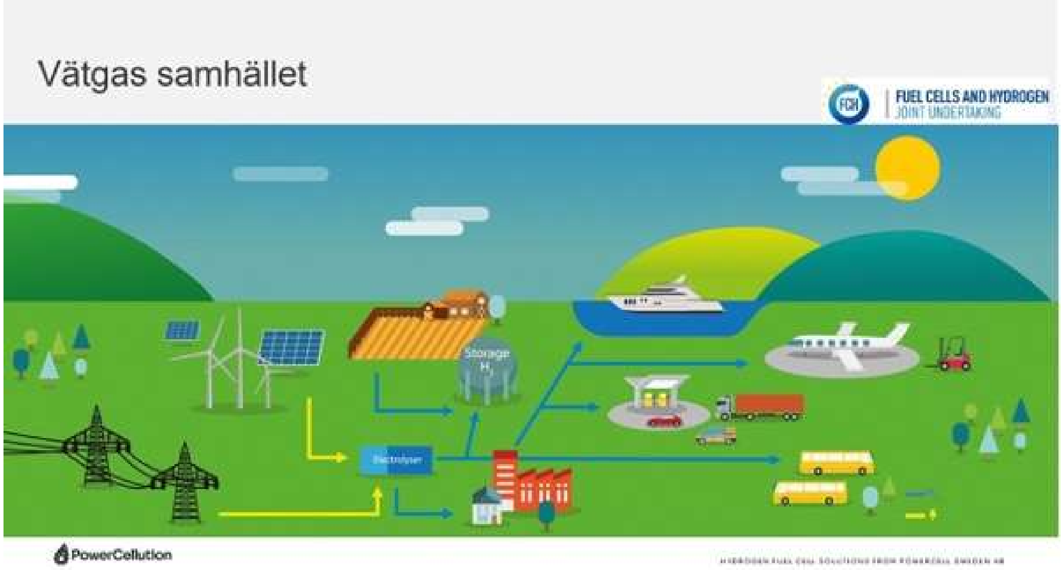
- Det kan vara lokala aktörer som vill bli självförsörjande eller minska sina inköp av el. Det kan vara strategiskt viktigt för aktören eller en ren miljöaktivitet för att undvika klimatavtrycket. Dessa aktörer efterfrågar vanligtvis en relativt småskalig lagring av energi.

- En annan typ av aktör kan vara de som efterfrågar driftsoptimering av sol och vind. Vätgaslagringen används för att effektivisera lösningen genom att lagra överproduktionen vid goda förhållanden för att sedan sälja när det är bra priser.

- En annan typ av aktör är de som fokuserar på stödtjänster. Tjänsten används för att reglera frekvensen i elnätet när efterfrågan överstiger utbud och vice versa. I elnätet är basfrekvensen 50 Hz och stödtjänster används för att sänka eller höja frekvensen. Dessa stödtjänster är inte alltid aktiva och används beroende av vilket behov som behövs. Bereoende av vilken stödtjänst som används så aktiveras inte de mest kritiska stödtjänsterna så ofta under ett år.

Vad tror du är viktigt att beakta för utvecklingen av vätgas?

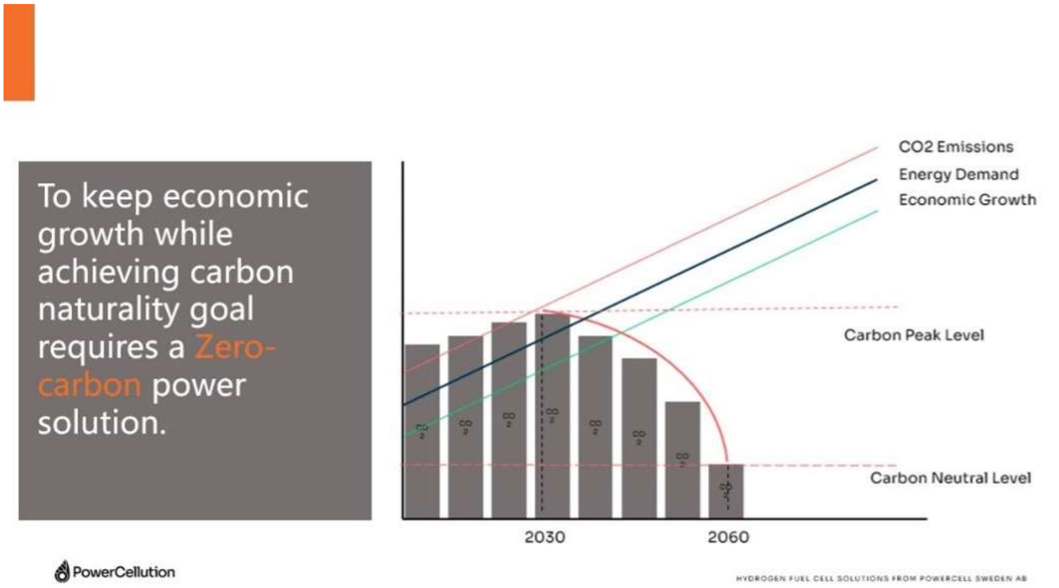
- Vi har haft en lång period med billig el, vilket många även förutsätter inför framtiden. Dock tror jag att omställningen till grön energi medför att elpriserna kommer att vara högre i framtiden.
- Jag tror det är viktigt att ha ett framåtblickande perspektiv. Detta beror på att marknaden tidigare har varit beroende av fossila bränslen, vilket framtidens elnät inte kommer vara. Därav är det viktigt att inte titta tillbaka alltför mycket utan basera olika estimeringar på vad experter inom området säger om framtiden.
- Mål från EU och från branschorganisationer är viktigt att titta på, vilket ger en fingervisning om hur branschen troligtvis kommer att utvecklas.
- Samhällstrender såsom priser, miljöfrågor, energiflöde etcetera. Bland annat pekar trenderna på att elpriset kommer att vara högre i framtiden. Ett exempel är om Hybrits lyckas och implementeras i stålindustrin vilket medför att energikonsumtionen, per år, kommer att öka med lika mycket som Danmarks årsförbrukning. Detta kommer skapa en ännu större efterfrågan på el samt kan innebära en energikris på riktigt.
- En rimlig tidsram är att ligga mellan 10–20 år framåt. Desto längre fram, ju svårare är det att göra uppskattningar och det blir mer vagare.
- Kolla inte bara inom en sektor, utan försök göra sektorkopplingar. Exempelvis kan vätgas produceras och användas i elnätet men kan även användas inom transportindustrin. Detta innebär att man inte skall se en sektor som en isolerad del i ett helt system.
- Mycket handlar om politik som aktivt kommer påverka människors vardag i deras val och riktning.



Vätgas samhället

PowerCellution

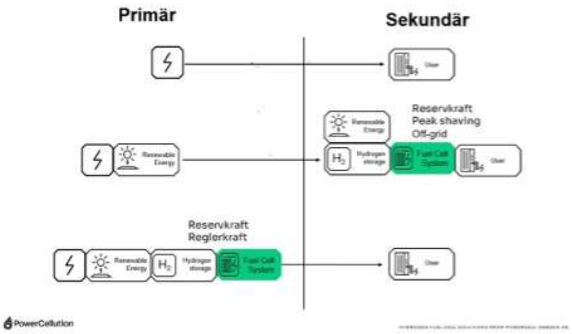
HYDROGEN FUEL CELL SOLUTIONS FROM POWERCELL SWEDEN AB



To keep economic growth while achieving carbon naturality goal requires a Zero-carbon power solution.

PowerCellution

HYDROGEN FUEL CELL SOLUTIONS FROM POWERCELL SWEDEN AB



PowerCellution

Interview 2

Open interview regarding the pricing of electricity and how the market is working.
Duration: 1 hour and 20 minutes
Jonas Karlsson, Avdelningsansvarig elhandel, Kvänum Energi.
22 February 2023

Vad ser du för trender i Sveriges elmarknad?
Vi har i dagsläget en stor andel kärn- och vattenkraft i Sverige, där större delen av produktionen sker i de norra delarna av landet. De senaste åren har vi sett en ökad skillnad mellan produktion och konsumtion. Framförallt har kärnkraften minskat i södra Sverige och ersatts med vindkraft i Norrland. Detta bidrar till en större efterfråga på överföringskapacitet till södra Sverige.
På efterfrågesidan ser vi indikationer på en markant förhöjning av konsumtionen. I Sverige pratar vi om en fördubbling, vilket delvis är på grund av elektrifiering där Hybrit är en stor faktor. Det kommer även bli ett skifte med ökad konsumtion i norra Sverige. I kontinentala Europa ser vi ett ännu större skifte, med uppemot en fyrdubbling av efterfrågan.

Hur påverkar detta elpriserna?
Sverige är uppdelat på fyra elområden, varav de två elområdena i söder, historiskt sett, haft en större volatilitet på elpriset. Detta beror på begränsningar i överföringskapaciteten mellan norr och söder, speciellt i snitt två, vilket är mellan elområde 2 och 3. Elen i Norrland kommer främst från vind- och vattenkraft och i dagsläget finns det en överproduktion, vilket genererar låga priser i norra Sverige. Detta hänger också samman med att överskott inte går att överföra till södra Sverige, vilket pressar ned priserna i norr samtidigt som det blir högre priser i söder. I elområde 3 och 4 påverkas priserna mycket av de höga kontinentala elpriserna och svängningarna.

Marginalpriset medför att det dyraste budet vinner, vilket är beroende av energislaget som används. Fossila alternativ är vanligtvis de sista alternativen som används vid produktion av el, eftersom de tenderar till att vara dyrare. De är dock vanligare i kontinentala Europa, och driver då upp priserna i södra Sverige. Det är dock viktigt att poängtera skillnaden mellan effektbrist och höga priser. De priserna vi ser idag är inte på grund av brist på effekt, utan att dyrare energislag används. Vid effektbrist finns det reserver att använda, vilket oftast är oljevärmeverk exempelvis karlshamnsverket, som kommer att pressa upp priserna ytterligare. Ett annat alternativ i detta fall är att kapa efterfråga, där aktörer får betalt för att strama åt användningen av effekt.

Vad ser du för trender i de framtida elpriserna?
Dagens priser är sannolikt för höga och en fortsättning på samma prisnivå kommer att resultera i att många hushåll och företag kommer att gå omkull, vilket skulle skapa en samhällskris. I grunden är det en utbud-efterfrågemarknad, och höga priser leder till lönsamhet i att investera i ny produktion. Således kommer priserna sannolikt att gå tillbaka på sikt, dock oklart om vi når samma låga priser som vi haft historiskt. Ett för lågt elpris medför också problem, då det slår ut de dyrare kraftslagen som ex. kärnkraft. Det skall dock tilläggas att kärnkraften inte blev lönsam både på grund av lägre priser, samt att staten beskattade kärnkraften hårt till skillnad från andra kraftslag.

Fluktuationerna i priserna kommer dock fortsatt vara höga, vilket är en konsekvens av ett högre väderberoende för förnybara energislag. Exempelvis har vi en enorm överkapacitet av vindkraft när det blåser mycket. I dagsläget har vindkraften möjlighet att generera dubbelt så mycket effekt som kärnkraften under optimala förhållanden, men mycket av överkapaciteten går inte att ta vara på. Det finns även planer på att bygga ut överföringskapaciteten i Sverige, vilket medför att priserna kommer att jämnas ut mellan norr och söder.

Hur fungerar balanskraften i Sverige?
I och med förväntningarna om en större volatilitet i elpriserna, pga. väderberoende produktion, finns det ett stort värde i olika flexibilitetslösningar både under kortare perioder för att möta svängningar under dagen och på längre sikt som flera dagar. I dagsläget hanterar vattenkraften en stor del av svängningarna mellan utbud och efterfrågan i elnätet, genom dess vattenmagasin. Vattenkraften har dock nått sin maxkapacitet och är svår att bygga ut, vilket kräver fler lösningar. Ett alternativ är batterier. Dessa klarar av snabba korta variationer, men är just nu inte rimliga för större kapaciteter under längre tidsperioder. Vätgaslagring kan vara ett alternativ för denna typ av användningsområde.

Det finns två typer av flexibilitetstjänster:

- Spotmarknaden - där lastförskjutning och kapning av abonnemang är viktiga metoder. Det handlar om att flytta toppar av efterfrågan och utbud i elnätet för att jämna ut marknaden. Elabonnemangen är en trång sektor, där det krävs utbyggnad, eftersom det inte finns plats för alla producenter. Det är alltså inte bara att koppla upp sig och erbjuda energi till nätet, utan det finns en "kölista".
- Intradagsmarknaden - Justeringar av prognosen krävs varje leveranstimme, vilket snart kommer uppgraderas till varje kvart, för att matcha utbudet och efterfrågan. Inom intradagsmarknaden finns ett antal stödtjänster där vissa automatiskt aktiveras på frekvensen, medan andra aktiveras manuellt av Svk för att återställa frekvensen till normalintervallet på 49,9–50,1Hz. Effekter om 100kW är tillräckligt för att kvalificeras sig till vissa av dessa tjänster, men de kräver en viss aktiveringshastighet. Hastighet i detta avseende innebär den tidpunkt då reserven behövs till att den är igång.

  FCR-D (Frequency Containment Reserve - Disturbance) används för att återställa frekvensen i en viss riktning, beroende på om den gått över eller under intervallet. Inom intervallet används i stället FCR-N. Det är inte vanligt att denna aktiveras, och sker endast ett fåtal gånger per år.

  FRR (Frequency Restoration Reseve) används för att snabbt återställa frekvensen och sker antingen automatiskt (aFRR) eller manuellt (mFRR), vilket har lite högre krav på volym. Tjänsten ska vara igång snabbt, men behöver oftast endast vara igång i några minuter.

  Det kommer sannolikt att bli lättare att klara kraven för stödtjänsterna i och med att leveranstimmen i stället går ner till en kvart. Samtidigt blir det allt viktigare med stödtjänsterna då elnätet får starkare kopplingar till andra länder. Effekten och frekvensen i elnätet mellan länder svänger klart snabbare på grund av den volatilitet som den enskilda aktören bidrar med.

Interview 3

Open and spontaneous phone interview regarding the district heating system.
Duration: 10 minutes
Roger Hagberg, Fjärrvärmeenheten, Skara Energi.
22 February

Hur fungerar ert fjärrvärmesystem?
Vattnet värms först upp med hjälp av en rökgaskondensering där den värms 5–10 grader till cirka 50–55 grader. Nästa steg är att värma vattnet till cirka 90–95 grader som är temperaturen ut till kund. Detta görs genom en panna där ett bränsle eldas. Vanligtvis är det flis som brukar användas i vår anläggning men det finns möjlighet att förbränna andra alternativ. Systemet är en sluten process där returledningen från hushållen har en temperatur som är omkring 40–45 grader.

Är det teknisk möjligt att implementera vätgas som stödkälla i uppvärmningsprocessen?
Ja, det är teknisk möjligt och inte speciellt svårt att implementera ett vätgassystem i vårt befintliga fjärrvärmesystem. Spillvattnet som är cirka 80 grader från både elektrolysören och bränslecellen skulle kunna fungera som ett mellansteg mellan rökgaskondenseringen och flispannan. Det innebär att det inte behövs lika mycket energi från flispannan, eftersom vattnet som kommer in i flispannan är högre.

Vad uppskattar du kostnaden till för att implementera ett system som kan ta vara på spillvärmen från elektrolysören och bränsleceller i en vätgasanläggning?
Jag uppskattar kostnaden till ett par hundra tusen kronor. Det kommer fungera som ett bypass system, och därav krävs det värmeväxlare, rördragning och ventiler fur att installeras. Tekniskt bör det inte alls vara svårt att implementera i befintligt system.

Vad finns det för hinder för att implementera denna typ av stödkälla i ert fjärrvärmesystem?
Ett hinder som jag ser är att värmen i form av vatten från vätgasproduktionen och konsumtionen inte kommer upp i lämplig drifttemperatur för att kunna agera som stöd i våra processer. Det skall dock inte vara några problem om drifttemperaturen är 80 grader.

Interview 4

Open interview regarding the regulation power services.
Duration: 30 minutes
Maja Isaksson, Analyst balance market, Svenska kraftnät (SVK).
7 March 2023

Hur fungerar stödtjänster i elnätet?
För att elnätet ska fungera behöver frekvensen hållas omkring 50 Hz. Produktionen av el för att möta den förväntade efterfrågan upphandlas ett dygn i förväg, vilket innebär att det finns risker att matchningen inte är perfekt. Till exempel kan en produktionskälla missa den planerade effekten, eller helt och hållet faller bort på grund av ett oväntat problem. Händer detta drar de olika stödtjänsterna igång för att kompensera, eftersom det kommer att ske en avvikelse från frekvensen.

Vilka typer av stödtjänster finns det?
FFR (Fast Frequency Response) är den snabbaste typen, och består idag vanligtvis av batterier, eller att flexibel förbrukning minskar eller ökar. Dessa är däremot inte speciellt uthålliga, utan är ämnade för att möta snabba förändringar tills de andra tjänsterna hunnit starta. aFRR och mFRR (Frequency Restoration Reserve) tar över efter hand, och dessa tjänster aktiveras linjärt mot frekvensen för att återställa den till 50 Hz. FCR-D (Frequency Containment Reserve Disturbance) syftar till att jämna ut svängningarna i frekvensen när det sker större störningar dvs utanför intervallet 49,9–50,1. Det varierar hur ofta dessa tjänster används. FCR-D aktiveras ungefär 1 % av tiden, vilket är relativt sällan.

Hur bestäms priserna på tjänsterna?
Kapacitet upphandlas 24h i förväg. Aktörer får ersättning oavsett om tjänsten används eller ej. Undantaget är mFRR som idag upphandlas likt elmarknaden, men kommer att bli en kapacitetsmarknad. För FCR-N och aFRR ges även ersättning för aktiverad tid enligt energiaktiveringsmarknaden. Från och med 2024 kommer alla tjänster att upphandlas med en marginalprissättning, vilket redan sker idag på alla utom FCR. I dagsläget förhandlas FCR genom en traditionell budning.

Hur tror du marknaden och prisbilden kommer att förändras i framtiden?
Både aFRR och mFRR kommer att bli viktigare på grund av en allt större intermittent elproduktion, ex. ökning av andel vind. FCR-D beror mer på oförutsedda störningar, vilket sannolikt inte kommer att öka såvida inte det kommer att tillkomma nya energikällor i liknande storleksordning som Oskarshamns OK3.

Ser du möjligheter för vätgas att fungera som en balanseringstjänst? Hybrit kommer att kunna vara en stor aktör i balanseringen om de tekniskt sett kan vara flexibla med sin vätgasproduktion. Beroende på hastigheten i teknikerna kan vätgasen vara aktuell i majoriteten av tjänsterna. Troligtvis inte FFR då den kräver en mycket snabb reaktionstid.

Vilka aktörer erbjuder stödtjänster?
Oftast är det elbolagen i olika storlekar som erbjuder stödtjänster. Balansansvarig på företagen arbetar mot Svenska kraftnät och ansvarar för att producenterna är i balans.

Denna roll kommer att delas upp i två, där BRP (Balance Responsible Person) ansvarar för att utbud och efterfråga möts, samtidigt som BSP (Balance Service Provider) arbetar med att möta stödtjänsterna. Detta innebär att det kommer att bli lättare för nya och mindre aktörer att erbjuda stödtjänster då de inte behöver ta hänsyn till BRP-rollen.

Interview 5

Open interview regarding installation cost
Duration: 40 minutes
Jonas Karlsson, Avdelningsansvarig elhandel, Kvänum Energi
30 Mars 2023

Vad är viktigt att beakta vid en anslutning av en stor produktions eller konsumtionsanläggning?
Det finns några viktiga saker att beakta så som vem som skall bära kostnaderna, äga produkterna samt placering av utrustningen. Det har kommit nya direktiv från EU angående kostnader för anslutning till elnätet. I de nya direktiven skall den som ansluter sig till elnätet bära sin egen kostnad.

Det finns olika kostnadsalternativ till att ansluta till nätet. Bland annat kan aktören helt och hållet ansluta själv genom att kunden står för alla kostnader, vilket resulterar i att kunden äger dessa produkter. De största kostnaderna är transformator, markanläggning och kabel. Ett annat alternativ är att markägaren för elnätet installerar nödvändig utrustning, men då äger elnätsbolaget utrustningen. Vid en sådan typ av anslutning brukar den som vill ansluta få stå för cirka 70 % av kostnaderna.

Vid anslutning av denna typ av produktion och konsumtionsanläggning är det även viktigt att tänka på placering. Ju bättre placering, exempelvis nära transformator eller ett kort avstånd för att minska kabellängd, desto mindre investering för anslutning. Det kommer även att behövas en transformator för att konvertera 400V till 10kV så att elen kan transporteras ut i elnätet.

En annan viktig sak att tänka på är att överliggande nät ska klara av att ta emot överföringen från det underliggande nätet på lokal nivå. Därav kommer Svenska Kraftnät att göra en utredning av vilka effekter en anslutning av produktions- eller konsumtionsanläggning får på det överliggande stamnätet.

Vad kostar det att ansluta en produktion- eller konsumtionsanläggning till elnätet? Prisbilden kommer att förändras framöver för större anläggningar, vilket gör det svårt att uttala om prisbilden. Nya tariffer kommer att introduceras på kraftverk över 1500 kW. De stora kraftverken som ansluts till elnätet idag är mestadels vindkraftverk och är även det enda som har anslutits i närhet i vårt nät. Vi brukar använda oss av ett riktpris på cirka 1500 kr per kilowatt, men det kan variera kraftigt beroende av geografi och hur överföringskapaciteten ser ut för den aktuella platsen.

Vad är de variabla kostnaderna för en produktionsanläggning?
Den fasta kostnaden är 900 kr per månad för inkoppling till nätet. Sedan tillkommer en årlig avgift om 65 kr per kW för anläggningen. Det finns en rörlig kostnad för överföringsavgift som varierar med volymen. Denna är beroende av tiden. Det är höglast i elnätet november till mars, mellan klockan 06–22 på vardagar och då är kostnaden 11,6 öre per kW. Den resterande tiden är överföringskostnaderna 9 öre per kW.

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