Increasing utilization of solar PV in Sweden through large-scale seasonal energy storage

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Abstract: This report examines the feasibility of integrating large-scale seasonal hydrogen storage with solar photovoltaics (PV) to facilitate the diffusion of solar PV in Sweden by allowing electricity that cannot be used directly to be utilized at a later date. Sweden's geographical position makes it an interesting point of study because of the significant fluctuations in solar energy availability and energy demand across different seasons. Methodologically, the report is a combination of a literature search, qualitative calculations, and interviews. The results include an analysis of current technologies for converting electricity to hydrogen, hydrogen storage methods and converting hydrogen back to electricity. This is followed by a calculation that models a potential scenario of a hydrogen storage-backed solar PV system in Sweden. Lastly, a holistic review of this kind of energy system is done with societal, economic, and environmental aspects considered. The main findings of the report show that using hydrogen as an energy carrier for storing electricity might not be feasible for large-scale applications due to problems justifying it economically, which is a result of the large capital costs needed for the infrastructure to accommodate the storage demand. An alternative approach where hydrogen is utilized directly in industry instead of converting it back to electricity was found to be a more feasible solution. This could still facilitate the diffusion of solar PVs in Sweden, as the need to replace hydrogen that is sourced from fossil fuels will support this development.

Contents

1 Introduction

The threats of climate change are increasing the necessity for countries to transition their current energy systems by expanding the use of low-carbon energy technologies such as wind, solar, hydropower, and some forms of bioenergy [1]. Since 2017, Sweden has committed to a reduction in greenhouse gas (GHG) emissions by 85% by 2045 compared to 1990 levels [2]. As of 2020, roughly three-quarters of Sweden's GHG emissions (measured in CO_2-equivalents) originated from electricity, heating, cooling, and transportation [3, 4]. While improvements in energy efficiency are likely to reduce these emissions to some extent, societal and economic trends make decreasing the overall energy demand a difficult task [5]. Consequently, decarbonizing the energy supply might be the only way to achieve the emission goals.

Solar energy has immense potential for electricity production, particularly with solar photovoltaics (PV). Sandén et al. (2019) identified that 700 million TWh/yr is the theoretical potential that can be utilized for power globally. When taking technological, economic, environmental, and social concerns into account, a more feasible potential was found to be 1 million TWh/yr [6], which is still many times more than the current global energy demand of 116 000 TWh/yr (2019) [7]. Despite this potential, solar PV's contribution to Sweden's 508 TWh/yr energy supply is today minimal, accounting for only 0.2 % (1 TWh/yr) of the total energy supply [8]. For Sweden to further tap into this vast supply of energy, some challenges are apparent. The most obvious is the large fluctuations of solar irradiation between summer and winter due to the country's high latitude position. This seasonal fluctuation is also coupled with higher energy demand during the winter months due to increased heating demand [9]. This can create the need for seasonal storage technologies to mitigate the intermittency of solar PVs in Sweden.

If enabled by energy storage technologies, solar PV may become a helpful component for Sweden to achieve its climate goals. The mention of Sweden however is not because of its climate policy but rather for its geographical and environmental context making it an interesting topic for study when it comes to solar energy. As a Finnish study by Haukkala et al. 2017 pointed out about their very similar neighboring country, "This extreme situation could then serve as a model for other countries at high latitudes, both north and south, of how solar PV can play a role in a highly developed and industrious society. If it can work in Finland, perhaps it can work almost anywhere." [10], for which the same could be said for Sweden.

1.1 Aim and scope

This report aims to explore how large-scale seasonal energy storage solutions could facilitate the diffusion of PVs in Sweden. The term "large-scale seasonal energy storage" in this context refers to systems that are of a similar order of magnitude as Sweden's national energy usage (TWh) and capable of storing energy over the span of one year. The primary storage in focus is hydrogen, but other emerging technologies will be covered briefly. While providing a technical background, the report mainly attempts to assess the scalability of hydrogen storage coupled with solar PVs to derive further insight into its feasibility.

The scope of the report is limited to the production and storage of electrical power but with the ongoing electrification of industrial processes and automotive powertrains traditionally reliant on the combustion of chemical energy in fuels [11], this scope remains highly relevant in the context of the total energy demand.

1.2 Research questions

Some questions that this report will attempt to answer are:

- Does seasonal storage enable a larger dispersion of solar PVs in Sweden?

- Is hydrogen storage a good candidate for large-scale energy storage?
- What is the current status of hydrogen storage technology?
- What are the barriers and facilitators for implementation of this technology?

2 Methodololgy

Initially, a literature search was conducted with the purpose of creating a better understanding of the Swedish electricity grid and determining which functionalities are relevant for hydrogen storage to be viable on a national scale. Some examples of these functionalities are storage efficiency, storage capacity, life cycle length, and cost. The technological background and various configurations of the storage technologies were looked at and evaluated based on these functions, with an emphasis on technologies that have seen examples of implementation under similar conditions to those in Sweden. Following this was a quantitative analysis of upscaling the hydrogen storage type that was found to be most feasible along with the required power capacity of solar PV installation, taking into account the functions identified in the earlier parts. This analysis employed so-called *back-of-the-envolope* (BOTE) calculations [12] in order to approximate results within an order of magnitude. More precise calculations were deemed outside of the scope of this report as more extensive data is required. The concluding part of the report included identifying barriers and facilitating factors to the diffusion of solar PV in co-occurrence with energy storage. This part was compiled from a more recent literature search that considered technical, economic, societal, and environmental aspects.

2.1 Göteborg Energi

An interview was conducted with Eric Zinn who has the role of sustainability manager at Göteborg Energi [13], to get expert insight on the outlook of solar power and hydrogen storage in Sweden. The interview also sought general insights into Sweden's energy system as a whole and Eric's predictions on how the energy landscape will change in the future. Göteborg Energi is an energy company owned by the city of Gothenburg that supplies heating, cooling, electricity, network, and gas services for large parts of Gothenburg and is largely invested in renewable energies. While the discussion occasionally extended beyond the focus of solar and hydrogen storage, it was still of great help for the authors to give a clearer direction for the project as well as facilitate the literature search used in the report.

2.2 Nilsson Energy

Another Gothenburg based company called Nilsson Energy was also consulted. Nilsson Energy, established in 2017, the company specializes in system integration of renewable energy systems using hydrogen as an energy carrier. The company representative, Abdallah Abou-Taouk, Senior Technical Sales [14], provided a walkthrough of the company's portfolio while giving a brief technical description of how the systems they help integrate are constructed. A large part of the conversation was centered about their largest completed project - a preschool in Mariestad, Sweden with off grid capabilities [15]. Despite the smaller scale of this project compared to the scope of this report valuable information was gained, particularly surrounding the process of dimensioning hydrogen storage for year round self-sufficiency. A similar approach was used in the calculations made in this report, although in a simplified manner, since Nilsson Energy utilizes a lot more specific data for their projects compared to what is generally available in literature.

2.3 PVGIS simulation

To estimate the potential electricity production of solar PV in Sweden, the Photovoltaic Geographical Information System (PVGIS) from the European Comission was utilized [16]. A location in Västra

Götaland, Sweden (coordinates 58.166, 12.505) was used for as basis for the simulation. For complete list of input parameters used see table 1.

Table 1: Input parameters for PVGIS simulation.

Variable	Input
Solar radiation database	PVGIS-SARAH2
PV technology	Crystaline silicon
Installed peak power	1 kWp
System loss	14 %
Mounting position	Free-standing
Slope	45 °
Azimuth	0 ° (south facing)

It is important to note that the simulation accounts for location-specific losses such as angle-of-incidence (3 %) and temperature losses (5.08 %). The simulation also takes into account the effects of clouds and spectral effects. The nominal peak power P_{pk} (kWp) is defined as the power output of the modules measured at standard conditions (STC) (1000 Wm^{-2}, 25 °C, solar spectrum with an air mass coefficient of 1.5) [17]. The area of solar panels required per installed kWp was calculated considering the efficiency of the solar panel η_{PV} as well as PV-to-ground-area ratio F_{pvtg}.

$$A = \frac{P_{pk}}{\eta_{PV} F_{pvtg}} \tag{1}$$

where A is the required land area (m^2). For the calculations $\eta_{PV} = 0.20$ and $F_{pvtg} = 0.5$ was assumed.

3 Technical analysis of hydrogen storage

3.1 Why seasonal storage?

Seasonal energy storage can be used to address the decrease in electricity production from solar PVs during the Swedish winter, which could eventually enable increased utilization of solar PVs in the Swedish energy mix. However, this would be at a future point where saturation of solar PVs and battery energy storage solutions (BESS) has been reached, and further implementation of solar PVs would entail technical challenges that require seasonal storage. The unusable electricity overproduced from solar PVs in the summer can be stored to avoid unnecessary curtailment [18]. That electricity would later be used in the winter to meet demand instead of, e.g., peaking power plants that usually have higher operating costs and use fossil fuels such as gas turbines [19]. Implementing seasonal storage technologies on the scale necessary to accommodate a large share of variable renewable energy (VRE) in an energy system demands investments in infrastructure and technological advancement. The development of economical and effective seasonal storage technologies, the augmentation of transmission and distribution networks, and the seamless integration of storage devices into power system operations and markets are needed and are far in the future [18]. Hydrogen can offer the possibility of storing energy on a larger scale, which is needed to support supply and demand in systems with high integration of VREs [19].

3.2 What about batteries?

The electric grid goes through daily fluctuations that can lead to imbalances. Hydropower has historically been the backbone of the Swedish national grid, providing its balancing needs and acting as natural energy storage [20]. With the increase in VRE sources, such as solar PVs, in the country's energy mix, these fluctuations are expected to increase. To enable large-scale integration of VREs in the electric system, they can be combined with BESS, which stores and releases energy as needed. This offers flexibility for the grid. The majority of BESS technologies being implemented today are short-duration, with a discharge duration of up to 10 hours before being depleted. These are effective in addressing daily fluctuations. The market for ancillary services is expanding, with larger BESS installations in countries that are integrating VREs. However, there is still debate regarding whether short-term storage such as BESS will enable an energy transition to VREs without the risk of insufficient base load. The arguments against point out the long-term variability of renewable sources as a risk [21]. In Sweden for example, the notion is that the winters are long and dark, which makes solar PVs ineffective in producing electricity to meet demands during the season. There is also the issue of scarce material use. Additionally, the scarcity of materials used in BESS could be a future barrier at some point.

3.3 From solar to hydrogen

3.3.1 Water electrolysis

Currently, hydrogen can be produced on a large scale via several processes, including methanol-reforming, ammonia decomposition, gasification, and water electrolysis. Among these methods, water electrolysis is considered the most promising pathway for green electricity production, as it splits water into hydrogen and oxygen using electricity generated from renewable sources such as solar and wind [22]. This process results in negligible emissions, with the only by-products being water and alkaline electrolyte residues, depending on the type of electrolyser. There are two main types of water electrolysis technologies that are used commercially as of writing this report: alkaline water electrolysis, a mature technology suitable for large-scale applications due to its relative cost-effectiveness and stability; and polymer electrolyte membrane (PEM) electrolysis, which, despite the higher cost, offers higher purity of hydrogen and more compact design compared to alkaline electrolysers [23].

Table 2: Summary of characteristics for Alkaline and PEM electrolysers. [23]

	Alkaline	PEM
Anode reaction	$2\,OH^- \rightarrow H_2O + \frac{1}{2}\,O_2 + 2\,e^-$	$H_2O \rightarrow 2\,H^+ + \frac{1}{2}\,O_2 + 2\,e^-$
Cathode reaction	$2\,H_2O + 2\,e^- \rightarrow H_2 + 2\,OH^-$	$2\,H^+ + 2\,e^- + \rightarrow H_2$
Overall cell	$H_2O \rightarrow H_2 + \frac{1}{2}\,O_2$	$2\,H_2O \rightarrow H_2 + \frac{1}{2}\,O_2$
H2 purity	99.5-99.9998 %	99.9-99.9999 %
Typical efficiency	0.50-0.78	0.50-0.83
Operating temperature	70-90 °C	50-80 °C
Lifetime (stack)	60 000 h	50 000-80 000 h
Capital costs (10 MW stack)	\$500-\$1000/kW	\$700-\$1400/kW

Efficiency refers to the quote of output energy and input energy. The input energy is in the form of electricity, while the output is in chemical form. The energy content of a chemical is measured in its heating value, which for hydrogen is 33.33 kWh/kg (lower heating value) [24]. So an electrolyser with an efficiency of 0.65 would require roughly 50 kWh to produce 1 kg of hydrogen. By coupling an electrolyser with solar PV, excess electricity produced can be used to produce hydrogen as an energy carrier for backup power generation [25]. The losses from the process are mainly in the form of heat so to fully utilize the electricity produced by PV it is beneficial to couple the electrolysis with another process that can use the heat such as a cogeneration plant for example.

3.3.2 Direct Water Splitting

Direct water splitting is the process of converting water molecules into hydrogen and oxygen using only sunlight or heat. This process is considered a promising alternative hydrogen production method. At present, there are two emerging solar-to-hydrogen pathways including photoelectrochemical (PEC) and solar thermochemical (STCH) water splitting.

PEC water splitting utilizes semiconductors to absorb the photons from sunlight and directly split water into hydrogen and oxygen at the semiconductor-water-based electrolyte interface. The excited electrons from the semiconductor are transported to the cathode, where they combine with protons from the electrolyte to form hydrogen gas. Simultaneously, oxygen is released at the anode. The advantages of this process include efficient conversion with low operating temperatures and cost-effective materials. PEC efficiency ranges from 4% to 16%. The current highest efficiency of the PEM system is 16.2%, achieved by researchers at the National Renewable Energy Laboratory (NREL) in the United States in 2016 [26].

STCH water splitting STCH employs a series of chemical reactions to split water into hydrogen and oxygen using high temperatures up to 2000 °C from concentrated solar power. This process is a closed-loop system in which chemicals used can be recycled and only water is consumed. In general, STCH can be divided into two cycles: direct cycles, which use only thermal energy from concentrated solar, and hybrid cycles, which include electrolysers driven by electricity from solar as part of the process [26]. The current highest efficiency of STCH is 20%, achieved by researchers at Australian National University (ANU) in 2021 using perovskite solar cells and silicon photoelectrodes [27].

Although PEC and STCH are still in their early stages of development, they offer long-term sustainable hydrogen production on a large scale that is not reliant on the grid. Additionally, it reduces the total energy loss of the process, as the electrolyser has a system efficiency of around 70%, and 10% of the energy is lost during production. In addition, while converting AC power to DC power, there are also significant power losses [26]. The lecture from Maria Abrahamsson also mentioned the direct hydrogen production via molecular approach by mimicking photosynthesis of the plant although further research and development of stability, mechanisms, and choices of element use still required [28].

3.4 Hydrogen storage

The storage of hydrogen can be achieved with a multitude of different technologies. When keeping hydrogen in its pure, molecular form, it can be stored in both the gas and liquid phases by controlling temperature and pressure. It is also possible to chemically bind the hydrogen to other compounds that might be easier to store, and then run the reaction in reverse to access the hydrogen when needed. In this chapter a brief walkthrough of the technical aspects behind some different storage types is given, starting with compressed gas and liquid hydrogen which technologies are most mature as of today [29].

3.4.1 Compressed gas (pure hydrogen)

With a boiling point of -259.16 °C at atmospheric pressure, hydrogen naturally occurs as a gas. At 0 °C and atmospheric pressure its density is 0.0899 $\mathrm{kg\,m^{-3}}$ [30] which is problematic when looking at storage solutions as volumetric energy density is an essential factor. By increasing the pressure the density of hydrogen is increased, allowing for more compact storage. Typically compressed hydrogen is stored at pressures between 100 and 200 bar depending on the material properties of the storage container and whether or not the storage is above or below ground [29]. At 100 bar and 20 °C hydrogen has a density of 7.8 $\mathrm{kg\,m^{-3}}$. Vessels that can withstand pressure of up to 700 bar are commercially available however very expensive due to material and operating costs [29]. Investment costs for above-ground storage are much higher compared to its underground counterparts and are therefore not preferred for large-scale solutions.

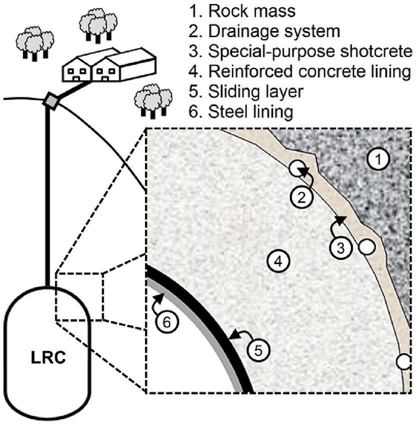

Figure 1: A schematic sketch of the lined rock cavern (LRC) storage plant Skallen in Halland, Sweden [31]

Underground storage can utilize geological formations such as salt caverns and man-made rock caverns to lower construction costs. The surrounding rock can withstand the high pressure exerted by the gas and in the salt cavern case, minerals with low permeability provide a natural seal for preventing diffusion of hydrogen. In rock caverns a metal lining around the cavern as well as a layer of concrete is commonly employed to reduce leakage (see figure 1). An example of this can be seen at ”Skallen”, located in the southwest of Sweden, which is a lined rock cavern made for high-pressure storage of natural gas. The excavated cavern capacity of 40 000 $\mathrm{m^3}$ and can withstand a pressure of up to 200 bar [32], giving it a theoretical storage capacity of approximately 700 t if used for hydrogen. Both of these of course region-specific as not all regions have these geological conditions. An alternative solution that is not region-specific and shows good promise is underground pipe storage which has been used to store natural gas for the past 40 years [33]. The setup is rather simple, a series of individual steel pipes are welded together and laid, usually on a bed of sand or ballast, a couple of meters into the ground to form pipelines of several hundred meters which then can be staggered next to each other.

Figure 2: A photography of the 6112 m^3 natural gas pipe storage in Urdorf, Switzerland under construction [34].

In Switzerland in 2012, a pipe storage solution was built in 8 months with a geometrical volume of 6112 m^3 to store natural gas reserves for roughly €17 million (see figure 2). This kind of storage could also be used for storing hydrogen. The working pressure range of these pipelines can reach 100 bar and would enable a capacity of 45 t of hydrogen to be stored [33]. However, 45 t is not a large capacity compared to geological gas storage such as the mentioned lined rock caverns and salt caverns for which the latter has examples of implemented hydrogen storage capacities of 3720 t in Moss Bluff, USA [33]. However, the advantage of pipe storage comes with its universal applicability and ease of scalability. It is also a mature technology because it has been widely used since the 1980s to store natural gas. Although no large-scale pipe storage specifically for hydrogen has been employed yet, the technology is feasible since the construction would not differ largely from natural gas pipe storage. However comparing the volumetric energy density of hydrogen and for example methane, which are approximately 2.997 kWh/m^3 and 9,9524 kWh/m^3 (0 °C, 1 bar) respectively [35]. It can be seen that, for the same volume and pressure configuration, it is possible to store more than 3.3 times more energy if storing methane instead of hydrogen.

3.4.2 Liquid state (pure hydrogen)

Another way of increasing the density of hydrogen and therefore increasing the energy density is to manipulate the temperature to induce a phase transition from gas to liquid state. At 1 bar pressure, saturated hydrogen liquid has a density of roughly 70.9 $\mathrm{kg\,m^{-3}}$ allowing for much more volume efficient storage [36]. However, the process of reaching this state is very energy intensive as, at 1 bar pressure, temperatures of sub -253 °C need to be achieved and maintained to retain it in its liquid state. After liquefaction, the hydrogen must be stored so that evaporation is minimized. Evaporation not only reduces the efficiency of the energy used for liquefaction but can also lead to the need to vent excess hydrogen gas back into the atmosphere to avoid pressure buildup. Because of the energy-demanding process and problematic storage, cryogenic liquefaction of hydrogen is mainly fit for transportation of hydrogen to remote areas and for niche applications such as heavy machinery [22] or rocket engines [37]. Therefore it is not considered a viable candidate for a large-scale storage system.

3.4.3 Solid state

Storage of hydrogen in a solid state can typically be achieved in two ways, adsorption in porous storage materials, and bonding to metal hydrides. Adsorption is achieved with materials such as carbon-based materials, polymeric materials, and metal-organic frameworks to name a few [29]. This type of storage utilizes van der Waals bonding between the hydrogen molecules and storage materials. Due to the weak bonding force of van der Waals bonding, cryogenic temperatures of around -200 °C and low pressures have to be employed to stabilize the bonds [38]. This means that the same problems that apply to cryogenic liquid storage also apply to adsorption.

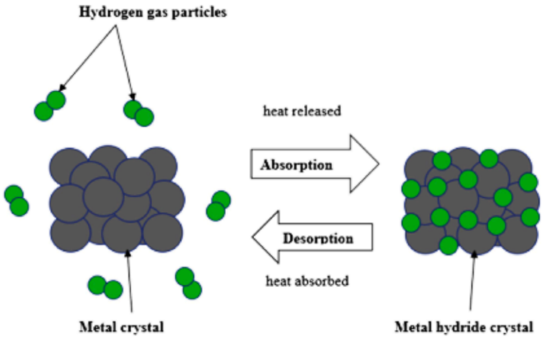

Figure 3: A metal hydride storage model [25]

Storage in metal hydrides involves chemically bonding the hydrogen in metal hydrides with hydrogen bonds [22]. Since hydrogen bonds are much stronger than the previously mentioned van der Waals bonding this storage method allows for very stable storage with high volumetric density even around standard conditions [39]. However, another result of these strong bonds is that it requires a lot more energy to convert hydrogen back to its gaseous form which is mainly done through heating or hydrolysis. Nevertheless, the low maintenance required for this storage type along with the high volumetric storage capacity make it feasible for long-term storage. One of the most promising hydrides for large-scale hydrogen storage is magnesium hydride (MgH_2). Magnesium, which is the eighth most abundant element in the earth's crust and is quite cheap, can in its hydride form have a volumetric hydrogen storage density of $86\ \mathrm{kg\,m^3}$ [40]. Magnesium hydride does unfortunately have a downside due to its quite slow kinetics both for hydrogenation and dehydrogenation. Additionally, the dehydrogenation step is an endothermic reaction that requires a temperature of over 300 °C for practical use [41]. There are some examples of solutions to this heating and kinetics issue, for example by integration of phase change materials (PCM), but no implementations further than proof of concept experiments were found in the literature [42, 29].

3.4.4 Chemical Hydrides

Storage of chemical hydrides offers the advantages of low-cost hydrogen storage with a lower pressure requirement, being capable of large capacity and long-distance transportation, and high safety regarding hydrogen handling in a wide temperature range. Typical chemical hydrides for hydrogen storage mediums include methanol, ammonia, and formic acid. For methanol, the operating pressure for the hydrogenation process ranges from 10 bar to 80 bar, with an operating pressure between 220 and 280 °C. For ammonia, it is possible to store high-capacity hydrogen with 17.6 wt% at 10 bar. However, the main shortcoming of both chemicals is the high-temperature requirement for the dehydrogenation process, which removes hydrogen from the chemical for further use. On the contrary, formic acid can solve the temperature requirement issue but has a lower storage capacity of 4 wt% [22].

Liquid organic hydrogen carriers (LOHC) like toluene and methylcyclohexane are promising technologies for long-range transportation. Basically, hydrogenation and dehydrogenation result from a catalytic process with an operating pressure and temperature around 10 bar and 200 °C. Typical storage densities of LOHCs are approximately 5–6 wt%. Even though it is lower than ammonia, LOHCs are still considered to be promising for their longer duration, scalability, and ability to be integrated with existing infrastructure in the industry for dehydrogenation. In addition, a recent experiment by Jorschick et al. showed that it is possible to use the same catalyst and reactor for both the hydrogenation and dehydrogenation processes by varying the process conditions. After that, LOHC can be re-hydrogenated in cycle, which reduces investment cost and operating cost [43]. At present, these technologies have already been employed on a large scale, coupled with solar PV plants. Framatome Company in Germany produces 10-15 Nm^3 of hydrogen/hr using a 75 kW electrolyser with H0-dibenzyltoulene and H-18 dibenzyltoulene as LOHC, which can store 2 kWh of energy per liter and generate 5 kWh of electricity after dehydrogenation using fuel cells as shown in the figure below. Therefore, LOHC is also suitable for large storage systems [22].

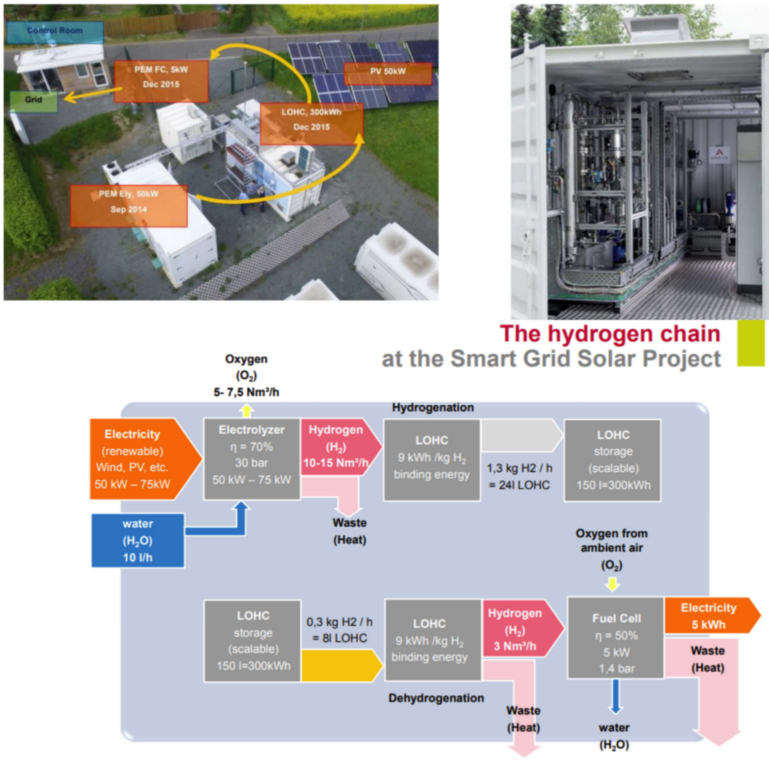

Figure 4: Framatome Smart Grid Solar Project [22]

3.5 From hydrogen to electricity

To convert the chemical energy of hydrogen back into electricity a fuel cell is used. A fuel cell in principle performs the reverse operation of the electrolyser discussed in section 3.3.1. Hydrogen and oxygen are recombined to produce water and energy in the form of electricity E_{el} and heat E_{heat} [44]:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + E_{el} + E_{heat}. \tag{2}$$

The chemical energy stored in hydrogen is then directly converted into DC as electrons travel, supplying electric power to an external circuit [25]. See figure 5 for a simplified schematic visualization of a fuel cell generator.

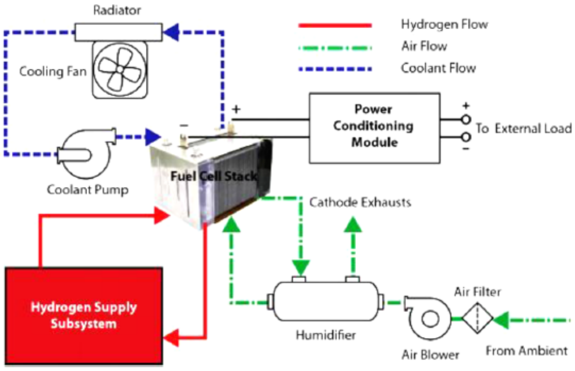

Figure 5: Fuel cell generator [25]

There are five main types of large stationary fuel cells with a rated power of over 200 kW used commercially. Out of these five types, there are currently three dominating technologies for large-scale stationary applications. Molten Carbonate Fuel Cells (MCFC), Solid Oxide Fuel Cells (SOFC), and Phosphoric Acid Fuel Cells (PAFC) [45]. See table 3 for a short summary of the characteristics of these fuel cell technologies.

Table 3: Characteristics of the three dominating fuel cell technologies.

Fuel cell type	Operating temperature	Typical electrical efficiency	Typical power range (kW)
Phosphoric Acid (PAFC)	150-200 °C	0.40	5-400
Molten Carbonate (MCFC)	600-700 °C	0.50	300-3000
Solid Oxide (SOFC)	500-1000 °C	0.60	1-2000

As seen in table 3 MCFC and SOFC achieve the highest electrical efficiency but are requiring very high operating temperatures. This makes it very beneficial to couple these fuel cells with other processes that can utilize the heat from the operation of the fuel cells.

3.6 Others storage technologies

According to the U.S. Department of Energy, the technologies for energy storage for grid applications include flywheels, compressed air energy storage, hydrogen, pumped hydroelectric storage, thermo-electric storage, and batteries, as summarized in Table 4. Which are still undergoing rapid research and development to maximize storage capacity via materials and system components [46]. However, it will not be covered in this report.

Table 4: Summary of Storage Categories and Technology Advancement[46]

Storage category	Associated technologies	Market readiness	Duration potential
Mechanical	Pumped hydro	commercial	0-15 h
Mechanical	Compressed air energy storage	commercial	6-24 h
Mechanical	Gravity based	pilot	0-15 h
Mechanical	Liquefied air	pilot	10-25 h
Mechanical	Liquid CO_2	pilot	4-24 h
Chemical	Hydrogen	pilot	500-1000 h
Chemical	Synthetic gas	pilot	500-1000 h
Thermal	Sensible heat (molten salts, rock)	R&D,pilot	200 h
Thermal	Latent heat (aluminum alloy)	commercial	25-100 h
Thermochemical	Thermochemical heat (zeolites,silica gel)	R&D	unknown
Electrochemical	Lead-acid batteries	commercial	< 8 h
Electrochemical	Lithium-ion batteries	commercial	< 8 h
Electrochemical	Zinc-alkaline batteries	commercial	< 8 h
Electrochemical	Flow batteries	commercial	< 8 h

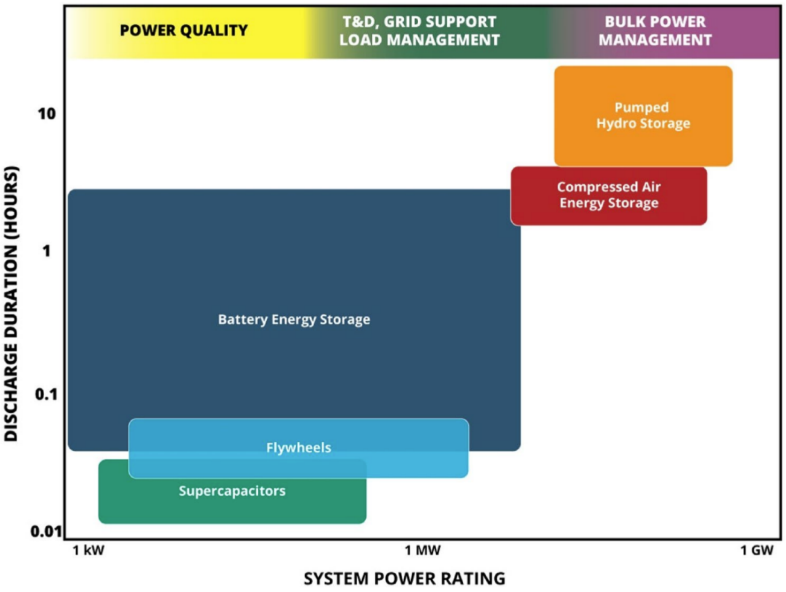

Figure 6: Comparison of existing energy storage for grid applications [46]

4 Qualitative estimation of scalability

In the year 2021, Sweden had a total electricity usage of 143 TWh [47]. As an example of the potential scalability of solar PV electricity generation coupled with hydrogen storage, we consider a scenario where 10 % of Sweden's yearly electricity usage is supplied by a self-sufficient, hydrogen-backed solar PV system. By "self-sufficient" it means that the system should be able to store the surplus electricity generated in the summer for utilization during the winter months. Daily and weekly fluctuations are assumed to be managed effectively (through stationary batteries or vehicle-to-grid storage for example) with little to no losses, thereby enabling efficient short-term utilization of PV-generated electricity. For these calculations assume an Alkaline electrolyser (see section 3.5) was used to produce hydrogen and the hydrogen stored as compressed gas (see section 3.4.1). To convert the hydrogen back to electricity Solid Oxide Fuel Cell stacks were assumed to be used due to their high efficiency.

Looking at the monthly fluctuations of electricity usage over the year (see figure 7) we see larger demand during the winter months (October-March) compared to lower in the summer (April-September).

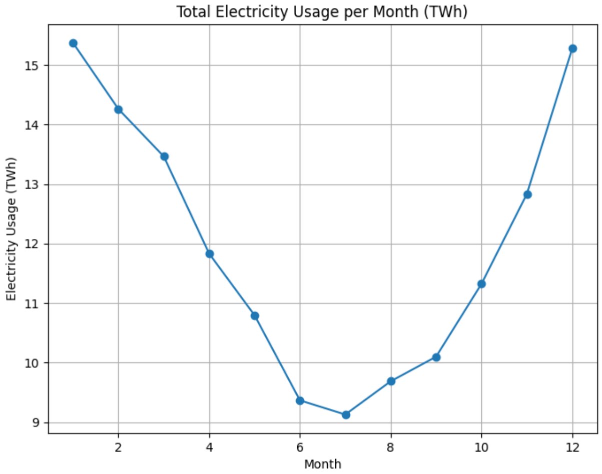

Figure 7: Total electricity usage in Sweden during 2021 [47].

From the PVGIS tool discussed in section 2.3, an approximation of the amount of electricity that could be generated in Västra Götaland, Sweden over the course of one year per installed kWp solar PV was derived (see figure 8).

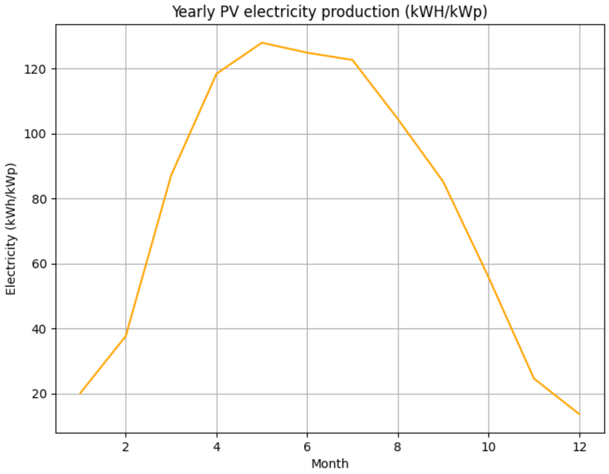

Figure 8: Results from PVGIS simulation of yearly PV electricity production in Västra Götaland per kWp installed capacity [16].

By comparing figures 7 and 8 the unfortunate pattern as mentioned in section 1 can be seen. The highest electricity production capacity occurs simultaneously as when the usage is lowest.

To estimate the required installed PV capacity and the corresponding hydrogen storage capacity required for the proposed scenario, these two variables were optimized to ensure that the sum of stored energy (in terms of output electricity) and the monthly production would cover the usage for each month. The results are presented below in figure 9. For the electrolyser an electrical efficiency $\eta_{H_2,e}$ of

0.6 was assumed including additional losses from compression of the gas. Fuel cell electrical efficiency η_{e,H_2} was also assumed to be 0.6 meaning the round trip efficiency (from electricity to hydrogen and back to electricity) η_r was equal to 0.3. These efficiencies are based on characteristic values from tables 2 and 3.

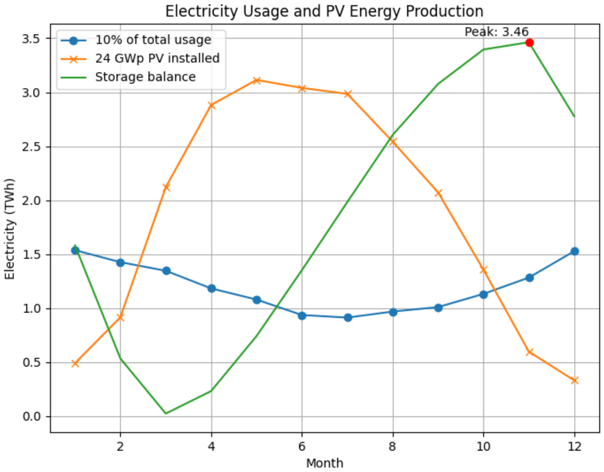

Figure 9: Estimation of installed peak power PV and storage capacity to enable 10 % of yearly electricity usage in Sweden to be covered.

It can be seen from the results that 24 GWp peak power PV is needed as well as 3.46 TWh of electricity storage capacity. For context, 40 GWp was installed in the European Union during 2022 reaching a cumulative capacity of over 211 GWp [48]. The 24 GWp installed capacity of PV is roughly equivalent to 240 km^2 needed ground area, which is about 0.05 % of the total land area of Sweden or approximately the size of the urban area of Gothenburg (230 km^2). This is based upon equation (1) which gave that for 1 kWp installed capacity, 10 m^2 of land area is needed. For more specifications regarding parameters see section 2.3. The 3.46 TWh of electricity storage is with round trip efficiency included. Since the fuel cell efficiency was assumed to be 0.6, the storage capacity in terms of chemical energy in stored in the hydrogen equates to 5.77 TWh. Using the lower heating value of hydrogen (33.33 kWh/kg) [35] this means the storage capacity in terms of tonne hydrogen is 173 000 t. This implies that around 3844 storage sites each of the size as Urdorf's natural gas pipe storage discussed in section 3.4.1 (45 t) would be needed to facilitate this. Alternatively, 47 sites of the same size as today's largest hydrogen storage facility in the world (3720 t) would be required.

5 Holistic review of hydrogen storage

5.1 Techno-economic aspects

In the future, energy storage systems with longer discharge times, reaching up to one week or more, can become cost-competitive. This is in combination with the increased implementation of VREs. Monetizing grid requirements such as reliability and resilience will further increase the cost-competitiveness of seasonal storage such as hydrogen [18]. During the interview with Nilsson Energy, they mentioned that further hydrogen price reductions will likely not be attributed to the technical side of hydrogen production, such as the electrolyser becoming cheaper. The price of hydrogen is predicted to decrease, but it is mainly linked to its scale of use and the electricity price [14]. Electricity prices in themselves are predicted as the cost of VREs is declining. Nilsson Energy's point is underlined in the literature that investigates hydrogen as part of the energy future in the Nordics. One such paper interviews stakeholders in Norway to assess hydrogen's role in the country's energy transition. They note that large multinationals such as Equinox and Statkraft see hydrogen as a promising business area while already investing heavily in VREs. The stakeholders see decreasing VRE costs as the main driver for hydrogen [49].

Hydrogen storage may offer a more cost-effective solution compared to pumped hydro storage (PHS) in scenarios demanding discharge durations of 16.9 days or longer in the 2025–2045 time frame and 3.1 days in the 2050–2070 time frame. This is mainly caused by the fact that the capital cost associated with the energy capacity of hydrogen storage is lower than that of PHS. To elaborate, for a discharge duration of 2 days, the proportion of the total capital cost attributable to the energy capacity of hydrogen storage is merely 5.5%, compared to PHS, where it exceeds 70%. Hydrogen is already more cost-efficient in terms of energy capacity. In 2050, it is projected to become almost as cost-competitive as PHS in terms of power capacity. The looked-at study suggests a cost of 650 USD per kW for hydrogen, which is a decrease from a predicted 1507 USD per kW in 2025. As for PHS, the predicted cost of power capacity is not predicted to change, meaning it will stay at 573 USD per kW in 2050. This study investigated the Western Interconnection power system and considered the deployment of wind and solar power from 24% in 2024 to 61% in 2050 [18].

5.2 Environmental aspects

While energy storage is generally associated with renewable energy sources, which are to the benefit of the environment, the different technologies have different impacts in and of themselves. These impacts are to be investigated on their own and in a systemic context. This way, a comprehensive assessment of sustainability can be conducted.

Hydrogen production heavily relies on electricity, so the environmental impact is usually related to the resources used in electricity production. If electricity is produced with renewable resources like wind and solar, it can be considered green hydrogen [22]. The electrolysis process only uses water as a resource, and the environmental impact depends on the type of electrolyser. For alkaline electrolysers, alkaline electrolyte residues can be found, but PEM only has water as a by-product, so the impacts are minimal. In addition, electricity production from hydrogen is considered green since fuel cells operate with oxygen from the air, and the byproducts are water and waste heat [23]. In the interview with Nilsson Energy, they mention, that if large-scale production is employed, waste heat could and should be utilized for heating to increase the total energy efficiency [14].

The International Panel on Climate Change (IPCC) has emphasized the critical importance of transitioning to low-carbon energy sources to limit global warming to 1.5°C above pre-industrial levels [1]. As Sweden has committed to reducing GHG emissions by 85% by 2045 compared to 1990 levels, the widespread deployment of solar PV can, according to the IPCC, play an important role in achieving this ambitious target [2]. If seasonal storage can enable a larger dispersion of solar PVs in Sweden, the environmental benefits of it will also indirectly be those of solar PVs. In the case that it is, the benefits provided by hydrogen for this purpose may prove to be positive looking over the whole system. Unfortunately, there is a lack of studies investigating this. Instead, hydrogen is looked at in different contexts, such as transportation, industry, off-grid systems, etc. Studies that specifically investigate the production of green hydrogen for any use can be reviewed to at least understand the impact of producing it on a large scale. One such study using life cycle analysis finds that, unsurprisingly, green hydrogen from wind or solar energy reduces greenhouse gas emissions compared to hydrogen from fossil fuels. However, their projections of future hydrogen production indicated that it would still transgress planetary boundaries allocated for climate change. The root of the negative impacts would be primarily attributed to the extraction and processing of metals for VRE infrastructure. This is called burden shifting. In this case, an example of one such shift is that more green hydrogen indirectly causes increased emissions of nitrates into water due to wastewater from solar PV production [50]. This study highlights the importance of assessing the sustainability of seasonal storage from a systems perspective.

Another environmental impact of large-scale green hydrogen production discussed is the land area required if it is powered by solar PVs. The calculations in this report indicate that this will not be an issue. As illustrated in section 4, to cover 10 % of the Swedish electricity usage (14.3 TWh) with solar PVs and hydrogen storage, a land area of 0.05 % is needed for the solar PVs which can be considered reasonable. This is contrasted by the large volume of hydrogen that is required for such a scenario. The indication is that if there are potential land use issues, they are related to the storage of the hydrogen.

5.3 Socio-technical aspects

Solar PV is a technology that is rapidly increasing. It is and will be evermore essential to initiating energy transitions to energy production from low-carbon emission sources. Energy transitions occur in complex contexts where the social, economic, and technological aspects are interlocked, meaning an energy transition is not as simple as exchanging technologies, such as a coal plant with a solar farm, equal in nameplate capacity. The way energy is converted, distributed, consumed, etc., in society can and will change not only with deliberate energy transitions but naturally over time. If the diffusion of solar PV is taken as a certainty, there are still different pathways to this low-emission energy future. This section will dive into the social implications of an increased share of solar PVs in parallel with large-scale seasonal energy storage development.

Hydrogen has uses beyond seasonal storage, and these can potentially enable reductions in emissions, looking at the larger system of energy. Considering other uses of hydrogen, such as in industry and transportation, there may be a new demand to produce hydrogen, which requires electricity. Production of green hydrogen would then be optimal in periods with high availability of wind and solar resources, which would encourage the further integration of VREs. Investing in hydrogen electrolysis capacity and hydrogen storage would still be a variation management strategy (VSM) by regulating the production of hydrogen to be reduced when the price of electricity is high. This increases the value of VREs and their competitiveness relative to base load generation. Using hydrogen for VSM can replace other methods to meet peak-load demand, such as generation from gas turbines. This scenario still includes hydrogen storage, which is needed for industrial operations to be maintained during periods when hydrogen is not being produced. This VSM also decreases curtailment through the flexibility it provides [19].

As aforementioned, the decreased cost of VREs is integral to the economic feasibility of green hydrogen production, and in return, increased production of green hydrogen might increase the need for VREs. This is a positive feedback loop. VREs are increasing at a rapid pace. Wind farms have been built in Sweden on a utility-scale for a while now, and solar PV is growing more than ever. However, there are still uncertainties about future trends in energy development. As their numbers are increasing, Swedish wind farms are seeing resistance at the local and municipal levels [51]. The resistors are not questioning wind power's efficiency in meeting energy demand, mitigating climate change, or its economic benefits. They acknowledge the technology and its positive sides but are against its localization in their communities. The arguments against them are of sentimental origin rather than logical ones. As solar PVs increase in Sweden, there might be a similar increase in resistance to them. This uncertainty is worrisome because of earlier explanations given regarding what is needed for green hydrogen to become more economically feasible and how it could affect the diffusion of solar PVs [19, 49].

The ongoing electrification and transition to renewable electricity generation has so far been battery-focused. Solar PVs, BESS, and electric vehicles (EVs) are almost packaged together and presented in visions of carbon-neutral futures. Before this, fossil fuels had dominance, leading to a fossil-fuel-based regime. In this regime, the infrastructure accommodates, for example, internal combustion engine cars. By combining solar PVs, BESS, and EVs, their synergy made it easier to disrupt the old, established regime. However, now they are running the risk of creating new lock-ins that are not beneficial from an energy sustainability point of view. This draws funding from other technologies that could be part of the future energy transition, such as hydrogen [49]. Such a trajectory is worrisome, as relying on a few technologies can lead to less flexibility and resilience. A future energy system that is heavily reliant on batteries could be the cause of material shortages that are troublesome as reliance on that technology and the materials needed for it increases.

The need for seasonal storage has been questioned, at least as a requirement to start an energy transition and electrification. A study made to explore the need for seasonal storage found that an oversizing of about 20% with 3h BESS can be enough to supply 85% of the whole electrifiable load. Their definition of an electrifiable load included domestic heating and transportation, indicating the load size is significant. The analysis does not consider wind power and its seasonal compensating factor, i.e., that wind and solar complement each other in generating electricity. Also, hydropower for electricity production and storage purposes is not considered, making the results possibly less applicable to Sweden. They conclude that what they call long-term storage is synonymous with seasonal storage in this report and will have the main role of eliminating the need for full-scale fossil backup systems [52]. As aforementioned, similar conclusions have been drawn by other studies that analyze the future role of hydrogen production in the energy system [19].

Sweden has hydropower, which can act as seasonal storage and a barrier, reducing the urgency to develop hydrogen for the same purpose. It is also used to meet peak load demand here in Sweden. During Lisa Göransson's guest lecture, she presented future scenarios where the Swedish energy mix was made up of large shares of wind, solar, and hydropower. Hydropower would also act as seasonal storage, which it has done before in Sweden [53]. Still, the unpredictability of our future energy needs does beg the question: is hydropower enough for seasonal storage? During the interview with Nilsson Energy, they explained that right now their services are not employed purely for economic reasons; instead, their customers see value in addition to the robustness and resilience of their systems [14]. There is value in diversifying the energy system and adding to its flexibility. Despite heavy investments in dedicated BESS and its profitability, there are actors such as Nilsson Energy exploring the role of hydrogen in the energy system. An endeavor that is, as mentioned, reliant on the promises of increased robustness and resilience. Actors such as Nilsson Energy play an integral role if hydrogen as seasonal storage is to break into the socio-technical regime. It is important to remember that green hydrogen production can have more uses than seasonal storage, such as in industry, increasing its chances of becoming commercial. If one of the niche uses of green hydrogen builds enough momentum to break into the socio-technical regime, the other uses might follow and become feasible.

5.4 Hydrogen strategy/Road map

The Hydrogen Roadmap is a strategic plan for the development and deployment of hydrogen technologies in Europe. The roadmap outlines a vision for how hydrogen can play a key role in decarbonizing the European economy, to achieve a 24% share of hydrogen in total energy consumption or 2250 TWh by 2050. The roadmap identifies five different areas where hydrogen can contribute to decarbonization including power generation, transportation, heating and power for buildings, industry energy, and new industry feedstock.

For power generation, even though the percentage is small compared to the other areas the need for significant advances in hydrogen storage technologies is also highlighted in the planning scenario to enable the large-scale deployment of hydrogen in the energy system. Promising storage options include compressed gas, liquid hydrogen, and high-pressure solid-state storage mentioned in the previous sections of this report. Hydrogen will play a systemic role in the energy transition by increasing balancing across the year and using seasonal energy storage by combining with existing gas grids, salt caverns, and depleted gas fields to store energy at a low cost.

To summarize, The Hydrogen Roadmap is an ambitious and comprehensive plan that has the potential to significantly reduce greenhouse gas emissions and transform the European energy system. However, it will require significant investment and collaboration between governments, industry, and research institutions to make it a reality [54].

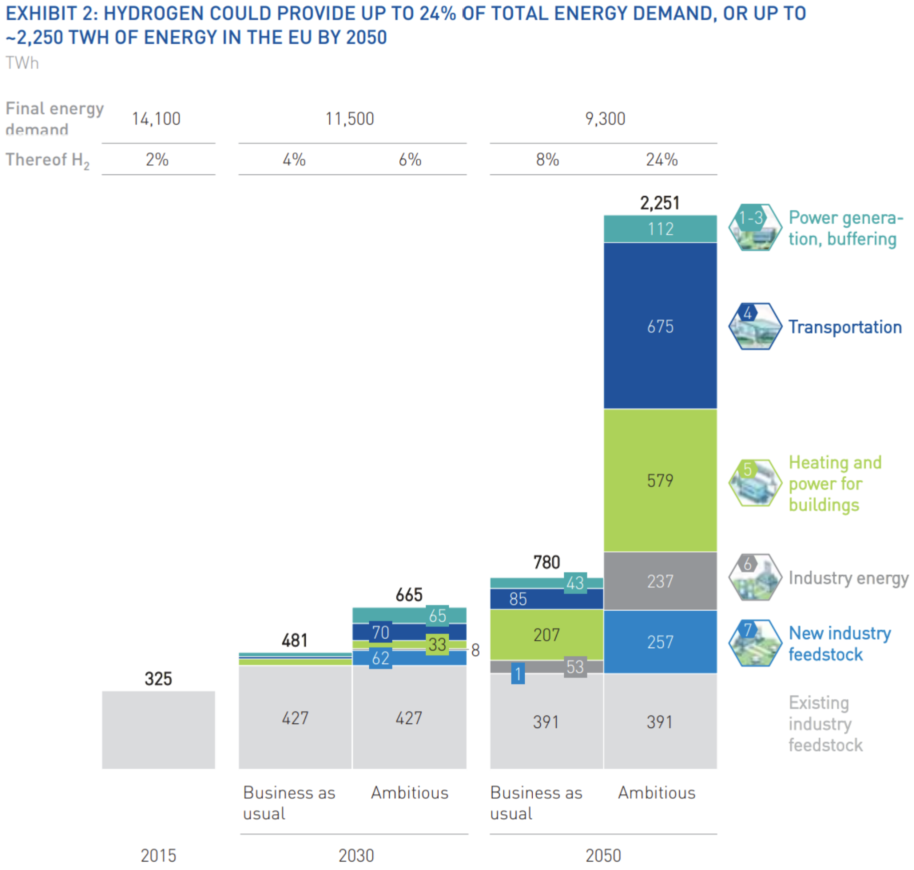

Figure 10: EU Hydrogen road map [54]

6 Discussion and conclusion

The analysis in section 3.4 reveals that, while technically possible, no current hydrogen storage method is ideally suited for large-scale applications. The main problem seems to be balancing storage density with capital costs. Compressed gas storage most merit today with the potential of expanding using infrastructure that previously has been used to store natural gas. Due to the low volumetric density of this storage method, however, space is the main challenge. Because of the much lower energy content of hydrogen compared to other fuels like methane, much more volume is needed to achieve high storage capacity. Metal hydrides such as MgH_2 can achieve the highest volumetric storage density but it has yet not seen any large commercial applications. Chemical hydrides also see much higher volumetric density however suffer a lot of efficiency losses in the dehydrogenation process. A natural way to circumvent this problem is to simply use the chemicals directly in industry applications as a way to reduce fossil fuel use in the production of bulk chemicals such as methanol and ammonia. While these mentioned storage methods are all technically feasible, even if some are still in developing stages, the main problem with them seems to be the economical feasibility. In all storage methods resources in the form of materials, mechanical energy, or heat are required. Again, because of the low energy density of hydrogen, the energy storage capacity is quite low for the price you pay.

One of the goals of this report was to determine whether or not hydrogen is a good candidate for large-scale energy storage. In section 4 we saw that the required hydrogen mass storage capacity coupled with solar PV to be able to handle the seasonal fluctuations of 10 % of Sweden's electricity use was astronomically large when compared to any current example of hydrogen storage. Even if these calculations are very rough and are therefore not to be considered a precise estimation, the order of magnitude still makes for an unfeasible case. With that said the idea of using surplus electricity from PVs to produce and store hydrogen should not be dismissed. When expanding the scope to energy usage as a whole, there is likely large potential in these kinds of systems. By utilizing hydrogen directly, or in the form of other chemicals such as methanol or ammonia, as a commodity in the industry, there is a large potential to reduce GHG emissions by replacing fossil fuel-based production of these commodities. The problem of meeting electricity volume demands during the winter months in Sweden does, however, remain.

Section 5.1 suggests that hydrogen storage could become more cost-competitive in the long term, especially as the costs of renewable energy sources decrease. The cost of other energy sources is, of course, also going to have an effect. As the cost of fossil fuels most likely will continue to increase in the future, this might facilitate a shift toward more hydrogen storage for electricity. It is important to note that the way forward in the transition to renewable energy systems is largely dependent on market dynamics, as companies that are looking to be a part of it want to generate a profit. This means that the lowest-cost option will most likely be the dominant one. Policy interventions from governments that incentivize the investment of such technologies could likely be deciding which technological paths we will see implemented, especially if these coincide with decreased subsidies for fossil fuels.

The environmental impact of hydrogen storage and solar PV systems is critical to consider. While the production of green hydrogen and the deployment of solar PVs offer clear benefits in terms of reduced GHG emissions, the environmental impact of the manufacturing and maintenance of these systems should be continuously evaluated. This includes the sourcing of materials for solar panels and storage systems and the potential impacts of land use on ecosystems.

The socio-technical implications analyzed in section 5.3 highlight the fact that the expansion of solar PV capacity in Sweden or elsewhere is not merely an economic and technical challenge but also requires consideration of social resistance at the municipal level as well as pushback from the well-established fossil-fuel-based regime. There is also the case of guaranteeing energy robustness and resilience in the future. Transformative events such as natural disasters, nuclear accidents, wars, or economic crises are not unlikely to affect the choices made for the energy landscape going forward.

In conclusion, the idea of seasonal hydrogen storage for electricity might not be the ultimate path to increasing solar PV diffusion in Sweden. However, the storage of energy in the more general sense in the form of hydrogen might very well be a driver that can facilitate an increase in solar PV capacity in Sweden. To achieve the climate goals to minimize GHG emissions, industrial production of green hydrogen from electricity generated from solar PV will increase along with low-carbon sources such as steam methane reforming coupled with carbon capture and storage instead of traditional fossil-based methods. Still, the transition will also depend on the price of electricity in the future. There is also a case to be made for industrial hydrogen production to be used for variation management applications to meet peak electricity demands, again replacing fossil-based fuels. This is enabled by the synergy that a large capacity of electrolysis can have in an energy system with a high number of VREs integrated into it. Larger capacities of electrolysis will be reached in the future as green hydrogen production increases with demand from the industry. Green hydrogen and VREs are looking to be dependent on each other's developments. However, their relationship is not necessarily going to be through the use of hydrogen as large-scale seasonal storage, which this report initially sought to investigate. Hydrogen use could emerge in other sectors and, through that, become the key driver for broader adoption of solar PV systems, surpassing the role of hydrogen storage.

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A Appendix

In the following appendix, the main questions asked in the interviews with Göteborg Energi and Nilsson Energy are presented to indicate what was discussed. These were not the only questions asked, as the interviews had a discussion-like structure with follow-up questions. Göteborg Energi was more so than Nilsson Energy, which started the meeting with a presentation of their work, and the rest of the interview followed more of a question-and-answer structure.

A.1 Göteborg Energi

How do you evaluate the potential of hydrogen as a large-scale seasonal energy storage solution for balancing the intermittency of solar PV?

Do you envision green hydrogen complementing or enhancing the integration of solar PVs in Sweden's energy landscape?

What are the technical challenges of green hydrogen from your point of view?

Can you see it becoming economically feasible?

Are there any other barriers or obstacles to the widespread adoption of green hydrogen as seasonal storage in Sweden?

How are regulatory and policy frameworks shaping your decision regarding seasonal storage, specifically hydrogen?

Will villkorade avtal play a role in a transition to large-scale hydrogen?

How does Göteborg Energi assess public perception and acceptance of green hydrogen as a seasonal storage solution?

A.2 Nilsson Energy

How is the hydrogen stored? And is this storage method viable for larger-scale applications?

How large is the storage capacity compared to the demand during the winter? Or the yearly demand? (%)

Could the energy system be completely independent? What is the main reason for it still being grid-connected?

Can you describe the process of dimensioning the hydrogen storage capacity for your preschool project?

You mention on your website that the project resulted in pushing for new permitting procedures and legislation. Could you give any examples of what these were?

From an infrastructural point of view, do you think it is more likely that hydrogen storage expands independently or is scattered, e.g., one system per building, or do you see the possibility of large plants that cover the demands of larger areas or even cities becoming a reality in the future?

Do you believe we still require technological advancements to facilitate the scale-up of these kinds of systems?

Are you looking at alternative ways of storing hydrogen, such as metal hydrides or chemical hydrides?

What economic challenges do you consider associated with hydrogen energy storage systems?

Are there any government incentives for hydrogen-based energy systems today?

Does Nilsson Energy have any goals in the context of increasing the scale of its projects in the future?