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Roadmap towards utilization of hydrogen technologies in the energy network

Bachelor thesis

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Abstract

The study focuses on elucidating hydrogen production pathways and associated technologies as pivotal elements in the overarching transition toward a sustainable energy landscape. Diverse methods of hydrogen production, notably steam methane reforming and electrolysis, are comprehensively presented. Despite the zero-carbon-emission nature of hydrogen at the end-use phase, its environmental impact is contingent upon the cleanliness of the production pathway and the energy inputs involved. Consequently, ensuring the traceability and cleanliness of the hydrogen's origin is imperative for its recognition as a genuinely clean energy source.

Furthermore, the paper scrutinizes innovative hydrogen storage solutions, providing a comparative analysis of the merits and limitations of compressed hydrogen gas and liquefaction methods. The integration of hydrogen production and storage within the broader context of renewable energy systems is thoroughly discussed, emphasizing the versatile role of hydrogen as an energy carrier. The manuscript also addresses the challenges and opportunities inherent in large-scale hydrogen production and storage, particularly in response to the escalating demands across various sectors such as transportation, industry, and power generation.

In conclusion, this paper synthesizes the current state of hydrogen production and storage technologies, accentuating noteworthy trends, technological breakthroughs, and identifying avenues for future research. The insights presented aim to contribute substantively to the ongoing academic discourse on advancing sustainable energy solutions through hydrogen technologies.

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1 Introduction

1.1 Motivation

Contemporary energy dynamics are defined by a confluence of factors, including escalating global population, resource scarcity, the specter of climate change, and the perilous predicament of hazardous waste disposal. Consequently, discourse on the climate crisis and the imperative quest for viable solutions has become inescapable, assuming a heightened sense of urgency. Within this discourse, hydrogen emerges as a pivotal element, poised to play a substantive role in shaping the future of energy. This assertion is underscored by the substantial investments and rigorous research currently directed toward harnessing the potential of hydrogen.

The impetus for my deepened engagement with this topic can be traced back to a seminal event – the explosion of a hydrogen filling station in the town of Sandvika in 2019, situated in close proximity to my hometown of Oslo. This incident not only served as a catalyst for my interest but also encapsulated the dualistic perspectives surrounding hydrogen. Throughout my academic pursuit, notably within the confines of my bachelor's program, various modules have explored facets of hydrogen technologies, thereby further nurturing my intrigue.

Hydrogen, as a prospective solution to our contemporary energy challenges, elicits divergent sentiments. Proponents are enthused by the promise of an energy source that yields only water as a byproduct, while skeptics harbor trepidation concerning the inherent instability and potential for catastrophic explosions, exemplified by the Sandvika incident. This schism in perspectives underscores the nuanced nature of the discourse surrounding hydrogen's viability as an energy solution.

In light of the aforementioned considerations, this discourse traverses beyond mere conceptualization, evolving into a critical examination of the dichotomous viewpoints that permeate discussions on hydrogen. As we navigate through this landscape, it becomes imperative to scrutinize not only the scientific and technological dimensions but also the sociopolitical and ethical dimensions that accompany the integration of hydrogen into our energy paradigm.

1.2 Aims of thesis

This research paper seeks to develop a roadmap or guidelines for the effective utilization of hydrogen technology in the energy network, with a particular focus on enhancing safety measures and thermal management. The project, undertaken during the period spanning from August 20th, 2023 to January 15th, 2024, represents a pursuit of solutions to address the pressing global concerns of clean energy and sustainability.

1.2.1 Research questions and goals

Research questions

1. What precautions need to be taken to implement hydrogen into our energy network?
2. What is the current state of hydrogen technologies in the energy sector?
3. How to have hydrogen storage as a part of everyday life with minimum safety risks?
4. How does the future of hydrogen utilization in our energy network look like?

Project goals

- Increase consciousness of hydrogen's possibility to contribute to solutions for clean energy in the future
- Contribute to research on how to make hydrogen a more safe energy source
- Write a comprehensive and cohesive plan for utilizing hydrogen in the energy network

1.3 Methodology

This literary review aims to assess the existing body of literature on the utilization of hydrogen in the energy network and its different stages. The goal is to synthesize current knowledge, identify gaps, and understand the methodologies employed in studies examining the different aspects of hydrogen as an energy source.

Criteria:

- Studies published in reputable peer-reviewed journals.
- Incorporation of research utilizing diverse methodologies, including field studies, modeling, and experimental approaches.
- Reports published by reputable energy associations and organisations, both in Europe and the US
- Books published on this topic by reputable scientists

- Relevance to the utilization of hydrogen.

A systematic literature search was conducted using scientific databases such as Google Scholar, ScienceDirect, and NTNU's Oria. Some of the keywords included were ”hydrogen,” ”energy storage,” ”hydrogen production,” and ”hydrogen technologies.” The search favored articles published in the last four years to ensure a comprehensive overview of recent research.

2 Theory

The theoretical underpinnings of the project are established in this section, providing a framework for the derivation of knowledge and insights. This theoretical foundation facilitates the execution of the project and the comprehension of its outcomes. The section comprehensively presents all technologies, concepts, and information essential for the completion of the thesis.

2.1 Renewable energy production

Energy resources are categorized into two primary groups: renewable and non-renewable. Renewable energy sources are characterized by their ability to replenish themselves naturally, ensuring a sustainable supply for future generations. Some of these sources include the sun's radiant energy, the wind's kinetic energy, and the gravitational potential energy of tides. In contrast, non-renewable energy sources, such as fossil fuels like coal and oil, are finite resources formed over millions of years through geological processes. Their extraction and utilization are unsustainable, as their reserves are depleted with their consumption.

The burgeoning field of renewable energy has witnessed significant advancements driven by dedicated research, technological innovations, and substantial investments. This transformative landscape has not only led to a reduction in the overall cost of renewable energy (figure 2.1) but has also resulted in a substantial increase in the efficiency of various technologies. Consequently, renewable energy sources are progressively emerging as pivotal contributors to the global energy mix [1].

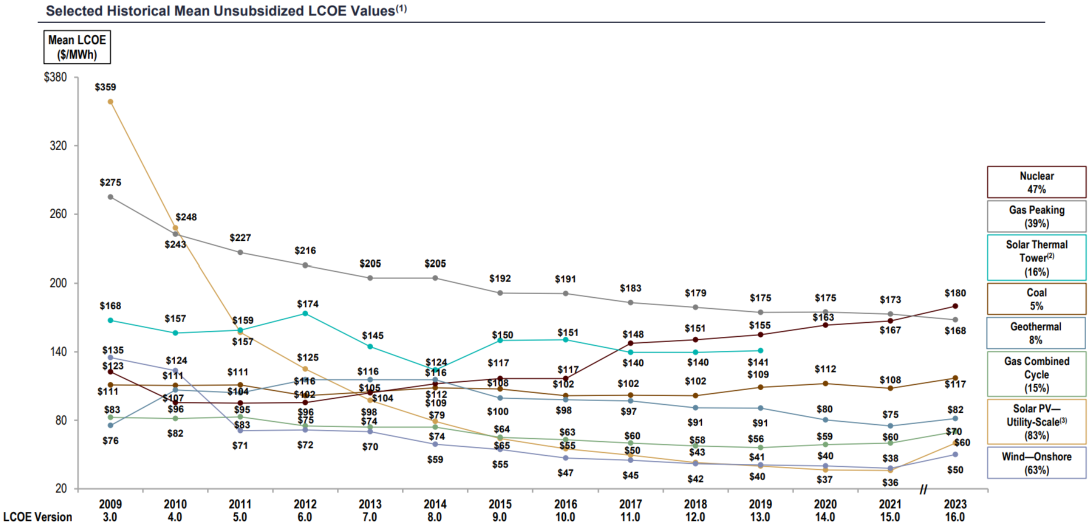

Figure 2.1: Lazard's levelized cost of energy comparison [2]

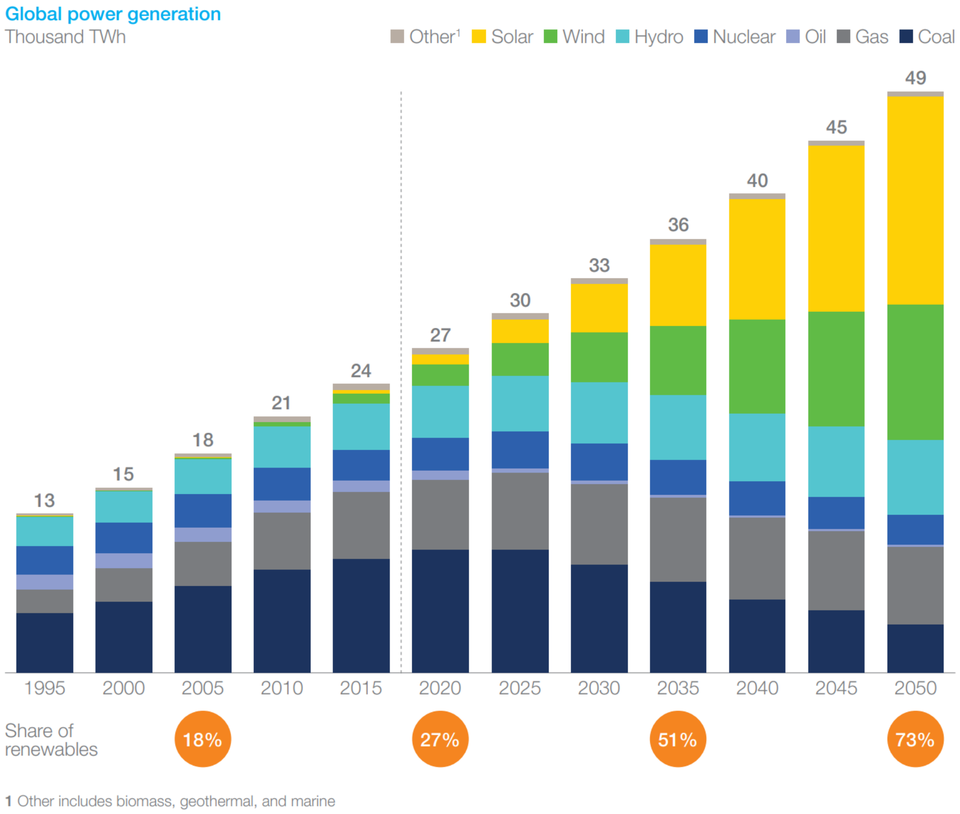

Figure 2.2: Share of renewables in the global power generation [3]

One notable trend in this paradigm shift is the substantial scaling up of renewable energy projects. Large-scale endeavors, exemplified by expansive offshore wind farms and solar facilities, underscore the growing significance of renewables on the macroeconomic level. These ambitious projects, often spanning vast expanses of land or water, demonstrate the capacity of renewable technologies to generate substantial power outputs, contributing significantly to the diversification of energy sources. Examples of this are Dogger Bank offshore wind farm in the North sea with the capacity of 4800 MW [4] and the Noor solar complex in Marocco with a capacity of 580 MW [5] seen in figure 2.3.

(a) Dogger Bank wind farm in the North sea [4]

(b) The Noor solar complex in Marocco [5]

Figure 2.3: Renewable energy production on a larger scale

Concurrently, the decentralized nature of renewable energy has given rise to smaller-scale applications, emphasizing local and individual contributions to sustainable energy production. Residential setups, characterized by home wind turbines and solar panels affixed to houses or boats, exemplify the democratization of renewable energy as seen in figure 2.8. This decentralization not only empowers individuals to actively participate in the generation of clean energy but also enhances energy security and resilience at the community level [1].


(a) Solar panels on a private boat [6] *(b) Solar panels on a house [7]* *(c) Private wind turbine on a house [8]*

Figure 2.4: Examples of a smaller scale renewable energy production

The ascendancy of renewable energy is resulting in a displacement of conventional fossil fuels in the power sector. This transition affords the advantageous consequence of diminished emissions, particularly of carbon and assorted pollutants. However, it is essential to acknowledge that not all energy sources labeled as ”renewable” uniformly contribute to environmental well-being. Biomass and large hydroelectric dams pose intricate trade-offs, necessitating a comprehensive evaluation of their impact on wildlife, climate change, and related concerns [1].

2.1.1 Advantages and challenges of renewable energy

Renewable energy, derived from naturally replenishing sources, has emerged as a promising alternative to conventional fossil fuels, offering a plethora of advantages while presenting certain challenges.

Advantages:

1. **Sustainable Supply:** Unlike finite fossil fuels, renewable energy sources like solar, wind, hydropower, and geothermal are virtually inexhaustible, ensuring a long-term energy supply.
2. **Environmental Protection:** Renewable energy production processes emit lower levels of greenhouse gases compared to fossil fuels, mitigating climate change and air pollution. It is estimated that renewable energy sources typically emit about 50 g or less of CO_2

emissions per kWh over their lifetime, compared to about 1000 g CO_2/kWh for coal and 475 g CO_2/kWh for natural gas [9].

3. **Reduced Reliance on Imports:** Shifting to renewables can minimize dependence on foreign energy sources, fostering energy security and economic independence. [10]
4. **Job Creation:** The renewable energy sector offers employment opportunities in various fields, including manufacturing, installation, maintenance, and research and development. [11]
5. **Health Benefits:** Renewable energy sources contribute to cleaner air and water, leading to improved public health and reducing the prevalence of respiratory and cardiovascular diseases [12].

Challenges

1. **Intermittency:** Renewable energy sources like solar and wind are intermittent, meaning their energy generation fluctuates depending on weather conditions. This variability poses challenges for grid stability and energy storage.
2. **Limited Storage Capabilities:** Storing renewable energy for periods when production is low, such as during nighttime or periods of calm winds, is still a technological challenge. Energy storage is not keeping pace with the energy-generating technologies [13].
3. **Geographic Limitations:** Renewable energy sources are not evenly distributed across the globe, making it challenging to meet the energy demands of certain regions.
4. **High Upfront Costs:** The initial investment in renewable energy technologies, such as solar panels or wind turbines, can be significantly higher than conventional fossil fuel-based systems [14].
5. **Visual Impacts:** Large-scale renewable energy installations, such as solar farms and wind farms, can have a noticeable visual impact on the landscape, raising concerns about aesthetics and biodiversity [15].

2.1.2 Intermittent energy production

The intermittent nature of energy production inherent in renewable sources stems from their reliance on natural resources, whose presence and consistency are inherently unpredictable.

Primarily, renewable energy sources are contingent upon naturally occurring phenomena such as sunlight, wind, and water, which exhibit substantial variability in intensity and availability. This dependence introduces fluctuations in energy output, posing challenges to achieving a continuous and stable power supply.

For instance, the efficacy of hydropower generation is contingent upon the sufficient availability of water in the reservoir. Similarly, solar energy extraction is confined to daylight hours and is subject to fluctuations induced by cloud cover. Likewise, wind energy production is contingent upon the speed of the wind, a factor characterized by unpredictability and temporal variability. Moreover, the geographical disposition of renewable energy resources further compounds the intermittency challenge. Regions with heightened sun exposure are more conducive to solar energy harnessing, while areas characterized by consistent wind patterns exhibit greater potential for wind energy generation. Consequently, the interplay of geographical factors introduces spatial disparities in the availability and efficiency of renewable energy resources. The storage of energy derived from renewable sources constitutes a formidable and economically demanding undertaking at present. The inherent variability in both electricity production and demand, fluctuating over diurnal and seasonal cycles, exacerbates the intricate integration of intermittent renewable sources into the existing energy landscape. The necessity to harmonize energy production with distinctive demand patterns is imperative for sustaining grid stability. Additionally, the provision of storage solutions possessing adequate capacity to effectively bridge periods of low or negligible energy production is paramount. The extant challenges in mitigating the intermittency inherent in renewable energy systems are underscored by the present limitations of energy storage technologies. Although advancements are perceptible, particularly in the realm of battery technologies, constraints about their storage capacity and cost persist as pivotal impediments in efficaciously addressing the intermittent nature of renewable energy production. The requisite alignment of energy supply with demand dynamics, coupled with the need for storage systems characterized by heightened capacity and cost-effectiveness, underscores the multifaceted nature of the contemporary challenges confronting the seamless integration of intermittent renewable energy into existing grids. Moreover, integrating large amounts of intermittent renewable energy sources into the power grid poses technical challenges. The grid needs to be able to manage fluctuations in supply and demand, which requires sophisticated forecasting and balancing mechanisms. [16]

In 2013, the California Independent System Operator introduced the 'duck curve' (figure 2.5), a widely cited graph illustrating the disparity between electricity demand and solar photovoltaic (PV) power availability over a 24-hour period. The curve, resembling a duck, depicts a surplus of solar energy during daylight hours, followed by a decline when electricity demand peaks in the evening. This phenomenon is most pronounced in spring when sunny conditions prevail, but lower temperatures mitigate the need for extensive air conditioning or heating, resulting in reduced overall electricity demand. The duck curve underscores the challenge of aligning renewable energy generation, specifically solar, with fluctuating energy consumption patterns. [16]

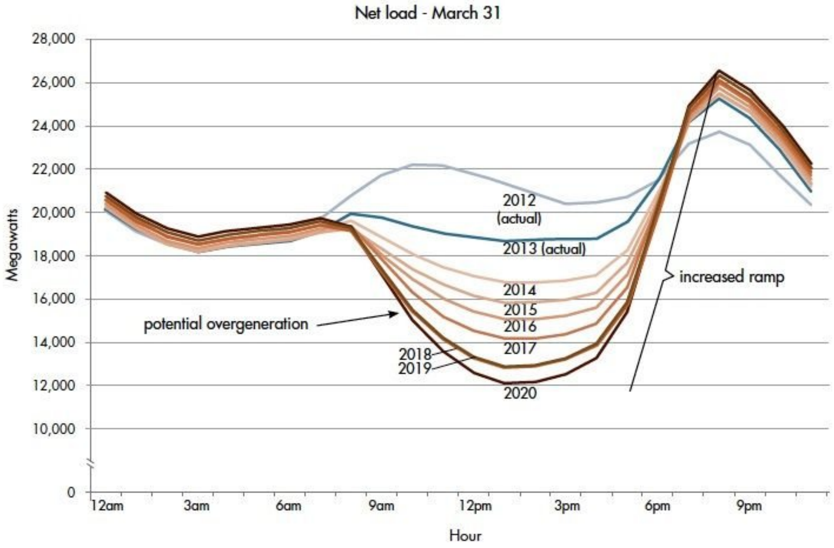

Figure 2.5: The duck curve [16]

The widespread adoption of solar energy poses challenges for grid management as utilities must adeptly balance supply and demand due to the rapid decrease in solar production after sunset. The increased reliance on solar photovoltaic (PV) power also introduces the risk of over-generation, where PV systems produce more energy than the grid can effectively utilize. System operators may resort to curtailing PV generation, limiting its economic and environmental advantages. While occasional curtailment has a modest impact, its potential escalation with higher PV penetration levels could significantly affect the overall benefits of solar adoption. [16]

Despite these challenges, intermittent energy production from renewables is becoming increasingly manageable as technologies advance and grid management strategies evolve. With continued innovation and investment in renewable energy infrastructure, intermittent energy production can be effectively addressed, paving the way for a more sustainable and clean energy future.

One of the strategies for battling the peaks of energy demand causing high costs and overstraining of the power grid is called peak shaving, also known as load shedding. It is aimed at mitigating peak demand charges on the electrical grid. This involves rapidly reducing power consumption during periods of high demand, achieved through equipment shutdown or the use of on-site battery storage systems (figure 2.6). The primary goal is to eliminate short-term spikes in demand, thereby lowering overall electricity costs. Peak demand significantly influences electricity prices, with utility bills typically comprising consumption charges (measured in kilowatt-hours) and demand charges (measured in kilowatts). While demand charges traditionally apply to commercial and industrial customers with higher peak loads, the rising prevalence of electric vehicles and residential fast-charging infrastructures may extend the impact of demand charges to residential utility bills. Understanding and implementing peak shaving strategies is crucial for managing costs in the evolving landscape of electricity consumption. [17]

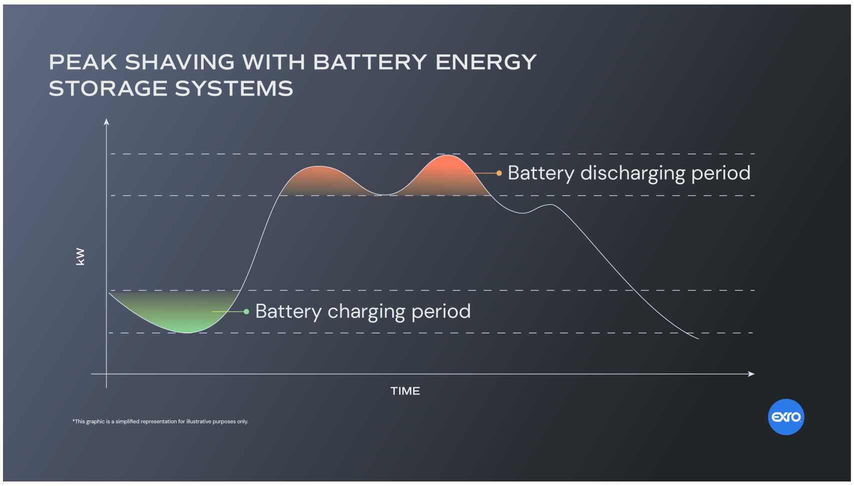

Figure 2.6: Peak shaving - Optimising power consumption with battery as an energy storage system [17]

2.1.3 Wind energy

Wind energy is a form of renewable energy that uses the power of wind to generate electricity. Wind turbines are used to harness the kinetic energy of the wind and convert it into electricity. It is also a very efficient source of energy, with modern wind turbines being able to convert up to 80% of the kinetic energy in the wind into electricity. The wind blows across the blades of the turbine, creating lift. This lift forces the blades to turn. The turning blades are connected to a shaft, which turns a generator. The generator converts the mechanical energy of the turning shaft into electrical energy. The electrical energy is then sent to a transformer, which increases the voltage so that it can be transmitted to the power grid. The electricity from the wind turbine can then be used to power homes and businesses. Horizontal axis wind turbines are the most commonly used turbines due to their strength and efficiency. The base of the towers have to be extremely strong, allowing the rotor shaft to be installed at the top of the tower which allows the turbine to be exposed to stronger winds. With the blades of the turbine being perpendicular to the wind, the rotation of the blades can generate more power compared to the vertical axis wind turbine. However, the construction of this type of turbine requires a heavy support for the tower to support the weight of the blades, gearbox and generator as well as utilizing a sizable crane to lift the components to the top of the tower. In a situation where the wind is blowing downwards, the turbine structure may suffer from metal fatigue which could lead to a structural failure. This is resolved by designing the turbines with an upwind design. Additional yaw control is needed for the horizontal axis wind turbines in order to track the direction of the wind, to prevent damaging the turbine. [18]

Vertical axis wind turbines are less affected by frequent wind direction changes as compared to the horizontal axis wind turbines due to the blades being rotated on the rotor shaft perpendicular to the ground. With the blades and shaft installed in this way, the turbine does not need to rotate to track wind direction. The shaft is mounted near ground level due to the difficulties of mounting the shaft and its components on the tower. An advantage of being mounted at ground level is that maintenance of the turbine is easier and can be installed at locations such as rooftops. Disadvantages to this turbine installation is that the efficiency is lower due to air drag and the lower wind speeds compared to the higher wind speeds encountered at higher elevations. [18]

Wind power is a valuable renewable energy source, but its intermittency poses challenges to power system stability and reliability. While some argue that wind power is unreliable due to intermittency and its large-scale utilization should be reconsidered, numerous studies have demonstrated that intermittency can be mitigated through technological solutions and should not preclude the adoption of wind power. Effective mitigation of wind power intermittency requires accurate measurement of intermittency levels. Existing metrics, however, lack a strict definition of intermittency and do not fully capture its characteristics. A new definition of intermittency based on the physical nature of wind is proposed, along with specific metrics that

(a) Horisontal axis wind turbine [19]

(b) Vertical axis wind turbine [20]

Figure 2.7: Different types of wind turbines

better represent the characteristics of wind power intermittency. Further research is needed to refine intermittency definitions, metrics, characteristics, and forecasting methods. As wind power penetration levels increase, additional solutions are needed to mitigate intermittency and maintain power integrity. These solutions include wind farm optimization, generation-side measures, demand-side management, and energy storage. While all of these methods can be effective, the optimal approach for a given case depends on factors such as technology availability, management considerations, cost, and topographic conditions. With the development of technological and managerial approaches, the integration of intermittent wind power into power systems is expected to increase in the future [21].

2.1.4 Solar energy

Solar energy constitutes the radiant amalgamation of light and thermal radiation emanating from the sun, proficiently exploited through a range of technologies for the purpose of electricity generation, luminosity provision, and thermal applications such as water heating. Three fundamental classifications within solar energy technologies are photovoltaics (PV), concentrated photovoltaics (CPV) and concentrating solar power (CSP). Photovoltaic cells, composed of semiconductor materials, particularly silicon, exhibit the capacity to directly transmute solar irradiance into electrical energy through the absorption of photons, inducing the liberation of electrons and the concomitant initiation of an electric current. It is noteworthy that PV efficacy depends on the amount of sunlight, but not the heat. The efficiency of electricity production from PV is among other things dependent on cell temperature and decreases with the increase in temperature. In parallel, Concentrated Photovoltaic (CPV) technology employs lenses or curved mirrors to focus sunlight onto diminutive yet highly efficient solar cells. These systems, augmented by solar trackers and occasionally cooling mechanisms, aim to optimize efficiency while necessitating a reduced physical footprint and a diminished quantity of solar panels. However, the deployment of costly lenses remains a notable constraint. [22]

Conversely, Concentrating Solar Power (CSP) systems harness mirrors or lenses to concentrate solar irradiance onto a delimited area, instigating the transformation of sunlight into thermal energy. This thermal energy is subsequently harnessed for diverse applications, encompassing electricity generation, water heating, and desalination processes. It is imperative to underscore that CSP, due to its spatial demands and the incorporation of solar trackers for optimal sun exposure, is unsuitable for residential applications. The requisite expansive land area further underscores its inapplicability to smaller-scale deployments. Types of CSP can be: parabolic troughs, linear mirrors, solar tower and parabolic dish. [22]

(a) Solar tower [23] *(b) Parabolic troughs [24]* *(c) Parabolic dish [25]*

Figure 2.8: Examples of different CSP plants

2.1.5 Other renewable energy sources

Hydropower constitutes a versatile and stable energy source. Water can be stored in reservoirs during periods of surplus energy for subsequent use during periods of low natural power generation and high demand, thereby providing electricity as needed. Hydroelectric plants exhibit the capability to initiate and cease production promptly. Well-regulated reservoirs afford significant flexibility, enabling power generation to be tailored to demand, whether on an hourly basis or within a more protracted temporal framework spanning days, weeks, and seasons. This renders hydropower particularly well-suited as an energy source in future power systems that integrate flexible hydroelectricity with variable power production from wind and solar sources. Norway's hydropower infrastructure functions as Europe's preeminent renewable energy reservoir. Approximately 50 percent of Europe's reservoir capacity is situated in Norway. [26]

Biomass, comprising renewable organic material derived from plants and animals, encapsulates stored chemical energy from solar radiation, synthesized by plants during photosynthesis. This energy reservoir can be harnessed to generate electricity or heat. Biomass may be employed in its raw form, burned directly for heat, or subjected to diverse processes resulting in the production of liquid and gaseous fuels. Although biomass energy is inherently renewable, its environmental cleanliness is not universally guaranteed. Various conversion methods exist, such as direct combustion for heat generation, thermochemical conversion leading to the creation of solid, gaseous, and liquid fuels, chemical conversion yielding liquid fuels, and biological conversion resulting in both liquid and gaseous fuels. Prevalently, direct combustion represents the primary approach for transforming biomass into usable energy, applicable across diverse sectors, including heating, industrial process heat, and electricity generation through steam turbines. [27]

Geothermal energy is a renewable energy source that harnesses the heat from the Earth's interior. This heat is generated by the decay of radioactive elements and the friction of tectonic plates. There are three main types of geothermal energy: dry steam, flash steam, and binary-cycle. Dry steam plants use natural underground steam from hot rocks, being the most efficient but rare. Flash steam plants pump hot water, converting it to steam for electricity, more common but less efficient. Binary-cycle plants utilize lower-temperature geothermal fluids, transferring heat to a secondary fluid for electricity generation without direct contact with reservoir fluids. [28]

Tidal energy is another renewable energy source that harnesses the power of the tides. The tides are caused by the gravitational pull of the moon and the sun on the Earth. There are two main types of tidal energy: tidal barrage and tidal stream. Tidal barrages are dams that are built across estuaries or bays to trap the water as the tide comes in. The trapped water is then released through turbines to generate electricity. Tidal stream turbines are placed in the ocean and generate electricity from the movement of the tides. These turbines are more efficient than tidal barrages, but they are also more expensive. [29]

2.2 Overproduction of energy from the network

Overproduction or oversupply of energy refers to the situation where more energy is generated than is currently needed or can be immediately consumed by the existing demand. This phenomenon can occur in various energy systems, including electricity generation, renewable energy sources, and industrial processes. Managing and storing excess energy is crucial to ensure a reliable and stable energy supply, especially as the energy demand fluctuates throughout the day and across seasons.

One significant challenge in the context of overproduction is the intermittent nature of some renewable energy sources, such as solar and wind power. These sources may generate surplus energy during periods of high availability, such as sunny or windy days, but less during times of low or no availability. Efficient storage solutions play a crucial role in addressing this intermittency and ensuring a continuous and reliable energy supply. [30]

2.2.1 Requirement for energy storage

Energy storage plays a pivotal role in the integration of renewable energy sources due to several imperative reasons. One primary challenge associated with variable renewable energy, such as solar and wind power, lies in their intermittent nature, leading to non-constant electricity generation. To mitigate this intermittency, energy storage serves as a crucial mechanism by capturing surplus energy during periods of high generation and subsequently discharging it during periods of heightened demand. [31] This ensures a consistent and reliable electricity supply even when environmental conditions do not favor continuous energy production. Furthermore, energy storage facilitates peak shaving, a strategic approach aimed at reducing peak demand – the zenith of electricity consumption within a given day. By deploying energy storage systems to offset peak demand, there is a consequential reduction in the necessity for costly investments in new power plants and transmission infrastructure. This not only optimizes the existing grid but also minimizes the economic burden associated with expanding power generation and distribution capacities.

In the realm of grid stability, maintaining a narrow frequency range is imperative to ensure the safe and efficient delivery of power to end-users. Energy storage systems play a crucial role in frequency regulation by absorbing or releasing energy as dictated by the grid's frequency requirements. This dynamic regulation helps in upholding the stability and reliability of the electrical grid. [32] Moreover, energy storage serves as a linchpin in providing backup power during grid outages, offering a lifeline to critical infrastructure such as hospitals, data centers, and communication towers. The reliability of such backup systems is instrumental in ensuring continuous operations and averting potential disruptions in essential services. [33]

In the context of demand response initiatives, energy storage emerges as an enabler for participation in programs designed to incentives consumers to reduce their electricity consumption during peak demand periods. By actively engaging in demand response, energy storage aids in alleviating stress on the grid, thereby mitigating the risk of blackouts and contributing to overall grid resilience. All in all, the multifaceted role of energy storage in addressing the challenges posed by variable renewable energy sources underscores its indispensability in fostering a sustainable and resilient energy landscape. [34]

2.2.2 Types of energy storage

Supercapacitors store energy through segregated charges creating an electric field, allowing for enduring charge and discharge cycles without efficiency degradation. However, they face a limitation in energy density, storing less energy per unit weight compared to conventional batteries. While they boast an extended operational lifespan, the financial constraints associated with supercapacitors hinder widespread adoption. Their specialty lies in meeting transient, high-rate charge and discharge requirements. [35]

Lead-acid batteries remain prominent for autonomous and self-sustainable renewable energy systems due to their favorable energy storage-to-cost ratio. While lithium-ion batteries are becoming more cost-effective, the market is approaching a point of cost parity. Battery energy storage systems, commonly used in homes and small industries, store excess renewable energy for independent off-grid operation. However, challenges such as energy dissipation over time and the impractical size and weight of large batteries limit their use in diverse large-scale applications. Industry efforts are focused on developing extensive battery arrays to address these limitations. [35]

Power-to-Gas (P2G) is an energy storage approach converting excess renewable energy into hydrogen through quick electrolysis, then injecting it into existing gas networks. P2G integrates technologies, leveraging current infrastructure and potentially replacing conventional fuels. Storing the energy carrier in a gaseous state is crucial. While hydrogen and methane can be produced, the additional step of methanation impacts efficiency and costs. Future progress requires enhancing efficiency and reducing costs, particularly in methanation processes, to establish P2G as a practical and scalable solution for large-scale energy storage. [35]

Pumped Hydro Storage constitutes a methodical approach to energy storage whereby surplus energy is employed to elevate water to a reservoir at an elevated position during periods of energy surplus. Subsequently, during elevated energy demand intervals, the stored water is released, facilitating its passage through turbines to generate electricity. In the realm of energy storage, Flywheel Energy Storage emerges as a sophisticated system wherein excess energy is harnessed to accelerate a rotor, colloquially known as a flywheel, to an exceedingly high rotational velocity. Upon demand, the stored energy is methodically reclaimed through the deceleration of the flywheel, effectuating the reconversion of kinetic energy into electricity. [36]

Compressed Air Energy Storage (CAES) represents an innovative technological paradigm encompassing the compression of air and its storage within subterranean caverns or designated containers. During periods of heightened electricity demand, the pressurized air is judiciously released, propelling turbines that engender the generation of electricity.In the context of energy storage solutions, Thermal Energy Storage manifests as a methodological approach wherein surplus energy is transformed into thermal energy for subsequent storage. This process often entails the heating of substances such as molten salt, which, when requisite, can be employed to produce steam, consequently driving turbines for the generation of electricity. [36]

Efficient energy storage assumes paramount importance not merely in harmonizing the equilibrium between energy supply and demand but also in optimizing the assimilation of renewable energy sources into the extant energy grid. As technological advancements persist, the imperative development of economically viable and scalable energy storage solutions is poised to assume a pivotal role in the establishment of a more sustainable and resilient energy infrastructure. [36]

2.3 Hydrogen

Hydrogen, the most prevalent element in the universe, serves as the source of energy dissipation in stars through nuclear fusion, transforming into helium. On Earth's surface, hydrogen is also the most abundant element on a molar basis. However, molecular hydrogen (H_2) is infrequently found here due to the prevalence of electronegative elements, such as oxygen (O_2). Hydrogen tends to donate electrons to these elements, forming hetero-atomic hydrogen-containing molecules, with water being the most abundant among them. While water is crucial for all life, extracting energy directly from it to sustain biological processes is not a straightforward endeavor. [37] Additionally, hydrogen boasts a specific energy value of 119.93 MJ/kg, surpassing that of other common fuels like natural gas (43.45 MJ/kg) or gasoline (47.14 MJ/kg). Moreover, hydrogen is non-toxic and non-corrosive, posing no harm to humans or the environment. [38]

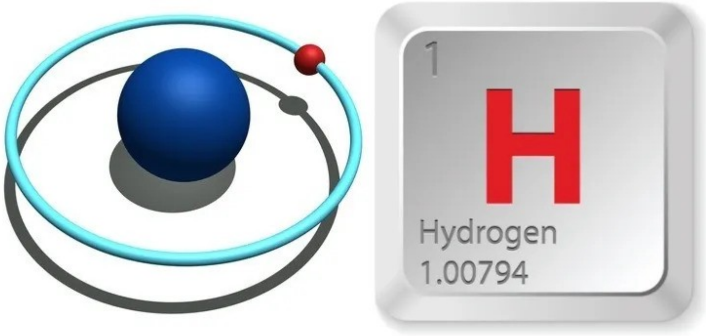

Figure 2.9: Hydrogen symbol and it's atomic diagram [39]

2.3.1 H_2 production

Numerous methodologies exist for the production of hydrogen. Conventionally, hydrogen synthesis encompasses electrochemical, biochemical, and thermochemical routes, as delineated in table 2.1. [37] With its high energy density and zero carbon emissions at the point of use, hydrogen offers a promising solution for decarbonizing hard-to-abate sectors such as heavy industry, long-distance transport, and energy storage. [40]

Table 2.1: Overview of ways to produce hydrogen [37]

Electrochemical	**Biochemical**	**Thermochemical**
Proton exchange membrane electrolysis	Microorganisms	Reforming
Alkaline elktrolysis (AWE)	Fermentative	Pyrolysis
Solid oxide electrolysis (SOEC)	The wood-ljungdahl	Biomass steam gasification
		Supercritical water gasification

Hydrogen production presently relies predominantly on fossil fuels, with approximately 95% of the global output derived from natural gas through the steam methane reforming (SMR) process. However, this method results in substantial carbon dioxide emissions. To mitigate this environmental impact, there is a discernible shift toward low-carbon and renewable hydrogen production approaches. Low-carbon hydrogen entails the capture and sequestration of carbon emissions from SMR, while renewable hydrogen is generated through electrolysis utilizing electricity sourced from renewable outlets such as solar and wind power. Despite a growing interest in these environmentally friendly methods, the global capacity for such clean hydrogen production remains constrained. As of 2023, the collective supply of clean hydrogen is estimated at approximately 0.8 million tonnes per annum (Mtpa), with low-carbon hydrogen constituting approximately 740 ktpa and renewable hydrogen around 60 ktpa.[41]

Hydrogen is commonly categorized by various colour codes, with prominent distinctions such as green, turquoise, blue, and grey being the most famous and their production ways will be presented here. However, there are also brown/black, yellow, red, white, purple, and pink hydrogen. These designations serve as colloquial monikers within the energy sector, aiming to differentiate hydrogen types based on distinct production methods. Notably, hydrogen is inherently an invisible gas; hence, despite their colourful descriptions, there is no visible difference between the different types of hydrogen. [42]

(i) Grey - hydrogen obtained by steam methane reforming

Steam reforming (SMR) stands as the predominant method employed for contemporary hydrogen production. Notably, the existing paradigm of steam reforming relies upon fossil resources, thereby engendering noteworthy process-associated carbon dioxide (CO_2) emissions. Given the extant annual emission rate of approximately 530 million metric tons per annum, this methodology significantly exacerbates the phenomenon of climate change. [43] Consequently, hydrogen derived from steam reforming is commonly denoted as conventional or grey hydrogen.

(ii) Blue - hydrogen obtained by SMR with carbon capture and storage

Carbon capture and storage (CCS) technologies represent auspicious methodologies for mitigating process-related CO_2 emissions and facilitating the generation of low-CO_2 hydrogen. The SMR-CCS approach is grounded in the identical production process and fossil resources as grey hydrogen derived from steam methane reforming (SMR). However, in contrast to the conventional release of CO_2 into the atmosphere, a predominant fraction of the resultant CO_2 is systematically sequestered and securely stored in geologic repositories. By virtue of averting the majority of direct CO_2 emissions, hydrogen produced through the SMR-CCS paradigm is commonly denoted as low-CO_2 or blue hydrogen, contingent upon the condition that the captured CO_2 is durably sequestered. [44]

(iii) Turquise - hydrogen obtained by methane pyrolysis

In the process of methane pyrolysis (MP), colloquially termed methane ”decomposition” or methane cracking, the molecular dissociation of CH_4 results in the production of gaseous H_2

and elemental carbon (C).

$$CH_4 \rightleftarrows 2H_2 + C \quad \Delta H_R^0 = +74.9\ kJ/mol \tag{2.1}$$

Analogous to steam methane reforming (SMR), substantial quantities of CH_4, primarily sourced from natural gas and thus constituting a fossil hydrocarbon reservoir, are employed in MP. Notably, MP necessitates even greater quantities of CH4 for hydrogen generation, given that the molar ratio of H_2 to CH_4 is 2:1, in contrast to the 4:1 ratio characteristic of SMR. Despite this heightened demand for CH_4, MP does not engender direct CO_2 emissions. Consequently, hydrogen derived from MP is frequently denoted as CO_2-free or ”turquoise” H_2. MP is recognized as a prospective transitional technology for environmentally sustainable hydrogen production in the context of climate mitigation efforts. [44]

(iv) Green - hydrogen obtained by polymer electrolyte membrane water electrolysis

Water electrolysis refers to the electrochemical dissociation of water (H_2O) into hydrogen (H_2) and oxygen (O_2).

$$H_2O \rightleftarrows \frac{1}{2}O_2 + H_2 \quad \Delta H_R^0 = +285.9\ kJ/mol \tag{2.2}$$

Unlike alternative technologies, water electrolysis does not depend on fossil resources and does not generate process-related greenhouse gas (GHG) emissions. Notably, no carbon feedstock is directly consumed during the water electrolysis process. As a result, hydrogen produced through water electrolysis is frequently denoted as carbon-free or ”green” hydrogen. Nevertheless, it is imperative to recognize that the climate change impact associated with water electrolysis extends beyond the operational phase. Substantial environmental implications arise from the manufacturing of electrolysis plants, the development of infrastructure, and the intricate supply chains governing water and electricity provision. Addressing and mitigating these factors is crucial for a comprehensive understanding of the overall environmental footprint of water electrolysis technology. [44]

Acknowledging the significant role hydrogen holds in attaining climate objectives, nations globally are substantially allocating resources to hydrogen-focused research, development, and demonstration initiatives. Governmental policies, inclusive of financial subsidies and tax incentives, emerge as pivotal drivers in incentivizing private sector contributions and expediting the commercialization of hydrogen technologies. In the year 2020, global investments in hydrogen reached an approximate value of \$1.4 billion, with the United States, China, and the European Union assuming leadership positions. Projections indicate a sustained upward trajectory in these investments in the imminent years, propelled by ambitious national hydrogen strategies and the escalating demand for environmentally sustainable hydrogen solutions. [45]

Despite considerable advancements in recent years, the hydrogen sector continues to confront various challenges. The production cost of low-carbon and renewable hydrogen persists at levels surpassing that of conventional fossil fuel-derived hydrogen. Furthermore, the establishment of a resilient hydrogen infrastructure, encompassing transportation and storage facilities, is imperative to underpin the extensive adoption of hydrogen. Notwithstanding these challenges, the prospects for hydrogen are expansive. Through sustained technological progress, cost diminutions, and the implementation of supportive policy frameworks, hydrogen is positioned to exert a transformative influence in the global energy transition, thereby fostering a more sustainable future. [46]

2.3.2 Hydrogen storage

Hydrogen (H_2) emerges as a promising candidate for mitigating environmental pollution and potentially supplanting fossil fuels. Its combustion, when governed by controlled flame temperatures or facilitated by a catalyst burner operating at an appropriate H_2/O_2 ratio, ostensibly yields only water and heat. Additionally, hydrogen boasts a superior specific energy value compared to prevailing commercial fuels, lacks toxicity, corrosiveness, and poses no harm to human health. Despite these considerable advantages, the perception of hydrogen as a hazardous fuel persists primarily due to its characteristic flammability range and remarkably low ignition energy (0.017 mJ in air). The colorless and odorless nature of hydrogen further exacerbates concerns, rendering it challenging to detect potential leakages. This dichotomy underscores the imperative of comprehensive safety measures and innovative detection technologies to fully harness the potential of hydrogen as a clean and sustainable energy source. The challenges associated with hydrogen (H_2) extend to its containment, given its status as the smallest and lightest naturally occurring element. This intrinsic property engenders a proclivity for H_2 leakage in certain instances. Notably, hydrogen exhibits a low density under standard temperature and pressure conditions ($0.0838\ \mathrm{kg/m^3}$ at 293 K, 101.3 kPa), juxtaposed with other conventional fuels. This characteristic renders hydrogen buoyant in air, facilitating its facile dispersion into the atmosphere in the event of leakage within an unconfined environment. Conversely, in a confined setting, the manifestation of an explosive atmosphere becomes imminent, accentuating the nuanced challenges inherent in handling and containing hydrogen. [37]

In comparison to alternative fuel sources, hydrogen (H_2) necessitates a more substantial storage volume under atmospheric conditions. The criticality of storage volume represents a prominent concern across various applications. Consequently, extensive research efforts have been dedicated to exploring diverse H_2 storage methodologies over the past decades. These approaches encompass the compression or liquefaction of H_2 to augment its volumetric efficiency. Additionally, alternative strategies involve the incorporation of H_2 into porous materials, exemplified by metal-organic frameworks (MOFs) or zeolites, utilizing physical adsorption and desorption mechanisms. Furthermore, H_2 storage can be achieved through chemical bonding, specifically adsorption within metal hydrides (MH) or liquid organic hydrogen carriers (LOHC). [37]

Compressed gaseous hydrogen (CGH_2) storage stands out as the prevailing and practical technique. Through compression, H_2 density can reach 39.2 kg/m^3 at 700 bar and room temperature. However, elevating H_2 pressure results in an increased energy demand for compression. Theoretical calculations indicate a requirement of 1.05 kWh/kg H_2 for isothermal compression from 20 to 350 bar and 1.36 kWh/kgH_2 for compression up to 700 bar. Notably, the energy needed for compression exhibits non-linearity. In practice, compressors absorb 1.7–6.4 kWh/kg H_2. Additionally, the initial costs of equipment (e.g., compressors, tanks, pipes, and valves) escalate with higher pressures. Presently, there are four types of H_2 tanks (Type I, II, III, and IV), constructed from diverse materials such as metal, composite (carbon fibers and resin), and plastic. These tanks exhibit varying pressure resistance capabilities. Accurate material selection is crucial to optimize costs and adhere to safety criteria when utilizing H_2. [37]

Liquid hydrogen (LH_2) emerges as a viable solution for storing substantial quantities of hydrogen. LH_2 possesses a density of 70.9 kg/m^3 at 20.4 K under atmospheric pressure conditions. Owing to its markedly low boiling temperature (-253°C), hydrogen exhibits rapid evaporation tendencies. Consequently, LH_2 storage tanks employ a design comprising two metallic enclosures separated by a vacuum jacket filled with insulating material. Despite meticulous insulation, the interaction with the ambient atmosphere leads to noteworthy heat losses, resulting in the evaporation of LH_2. The formation of boil-off gas (BOG) represents a prominent drawback associated with the LH_2storage methodology. [37]

2.4 Hydrogen uses

Hydrogen is currently employed in diverse sectors, including industrial processes, rocket propulsion, and as a power source for vehicles and electricity generation through fuel cells. Notably, operators of several natural gas-fired power plants are actively exploring the integration of hydrogen into their systems, considering its potential to supplement or replace natural gas. Beyond its applications, hydrogen emerges as a promising solution for energy storage in electric power generation. This multifaceted role positions hydrogen as a versatile and valuable resource across various domains. [47]

2.4.1 Electricity

The potential applications of pure hydrogen or hydrogen-rich blends, such as in electric power generation and space heating, present opportunities. Nevertheless, the utilization of hydrogen and its blends with natural gas in existing infrastructure and combustion equipment raises several challenges, primarily concerning materials compatibility and combustion characteristics. While advancements have been made in adapting commercially available combustion turbines to accommodate high-hydrogen blends, including up to 100% hydrogen, ongoing research, development, and demonstration (RD&D) efforts are essential for hydrogen to become a viable option for utility-scale power generation. Furthermore, RD&D is crucial to evaluate the compatibility of hydrogen and hydrogen-natural gas blends in heating appliances. [47]

2.4.2 Transport

Accounting for 28% of greenhouse gas emissions, the transportation sector has prompted a surge in the adoption of electric vehicles (EVs), given their emission-free operation, cost-effective refueling, and low maintenance expenses. Despite these advantages, EVs come with drawbacks such as extended battery charging times, limited driving ranges, and high upfront costs. On the other hand, hydrogen-based fuel cells showcase their capacity to store and convert chemical energy directly into electricity, accompanied by various benefits. The integration of hydrogen and fuel cell technologies has become a focal point on the agenda of major global car manufacturers. [48]

The widespread adoption of hydrogen-fueled vehicles is hindered by the expensive nature of fuel cells and the scarcity of hydrogen refueling infrastructure. The production of such vehicles remains constrained as potential buyers are reluctant to invest without convenient access to refueling stations. Simultaneously, the reluctance of companies to build refueling stations stems from the lack of a substantial customer base owning hydrogen-fueled vehicles. [47]

2.4.3 Chemicals

Hydrogen is emerging as a valuable feedstock for diverse chemical production applications, owing to its distinctive properties such as high reactivity and energy density. This transition from traditional fossil fuels to hydrogen in chemical processes is underpinned by its potential contributions to cleaner and more sustainable practices. A notable example is the synthesis of ammonia (NH_3), a pivotal component in fertilizers, plastics, and pharmaceuticals. Traditionally, ammonia has been synthesized through the Haber-Bosch process, involving the combination of atmospheric nitrogen and hydrogen under elevated pressure and temperature. In addition to ammonia, hydrogen is integral to the synthesis of methanol (CH_3OH), a versatile alcohol utilized as a fuel, solvent, and chemical precursor. The methanol synthesis process involves the interaction of hydrogen with carbon monoxide (CO) using a catalyst under high-pressure and high-temperature conditions. Beyond these primary applications, hydrogen finds application in upgrading hydrocarbons from crude oil, resulting in cleaner and more valuable fuels and chemicals. Moreover, it plays a crucial role in the production of key industrial acids such as sulfuric acid, nitric acid, and hydrochloric acid. Hydrogen is also involved in the production of polymers like polyethylene and polypropylene, essential materials for plastics and various products. The adoption of hydrogen in chemical production offers several advantages over conventional fossil fuel-based processes. Hydrogen production through renewable sources, such as electrolysis using solar or wind power, holds the potential to significantly reduce greenhouse gas emissions compared to fossil fuel-based methods. Furthermore, hydrogen-based chemical processes exhibit a propensity for generating fewer pollutants and hazardous byproducts, while the high reactivity and energy density of hydrogen contribute to enhanced efficiency and improved yields. However, the widespread integration of hydrogen in chemical production faces several challenges that necessitate attention. The economic viability of hydrogen production, particularly from renewable sources, demands cost reduction. Establishing a comprehensive hydrogen infrastructure encompassing pipelines, storage facilities, and distribution networks is imperative to support widespread adoption. Addressing public concerns regarding the safety aspects associated with hydrogen production, storage, and transportation is pivotal for fostering widespread acceptance. As ongoing research and development endeavors continue, hydrogen is poised to assume an increasingly significant role in the chemical industry, offering a promising trajectory toward a cleaner, more sustainable future. [49]

3 The roadmap

This chapter will compare different technologies for production and energy storage as well as present some safety measures and concerns.

3.1 Production

In pursuit of future clean energy objectives, this chapter undertakes a comparative analysis of the electrochemical methodologies employed in hydrogen production, discerning the electrochemical route as the most environmentally sustainable. Various electrochemical water electrolyzers are available for hydrogen generation, with the tho predominant modalities being alkaline electrolysis and proton exchange membrane electrolysis

Alkaline electrolysis cells (AECs) play a crucial role in electrochemical water-splitting, particularly in military applications involving H_2 isotopes. Originating in the 20th century, the development of AECs gained momentum with the construction of the first heavy water electrolysis plants in Norway, focusing on deuterium production, like the one in Rjukan in Telemark. Today, companies like NEL Hydrogen in Norway, are global leaders in manufacturing AECs. Their electrolyzers can produce high-grade H_2 at rates ranging from 50 to 485 Nm^3 per hour, maintaining a purity of 99.9%. Notably, AECs find applications in diverse industries, addressing the increasing global demand for H_2. Key sectors utilizing industrial H_2 include electrical power generator cooling, semiconductor manufacturing, flat screen production, heat-treatment plants, and scientific laboratories. The energy consumption for AECs typically ranges from 4.1 to 4.3 kWh per $Nm^3 2$ H_2, with current densities reaching up to 0.3 A/cm^2. Hydrogen (H_2) has diverse industrial applications, including food processing, glass manufacturing, welding, heat-treating, and meteorology. In recent decades, H_2's role as an energy carrier has expanded, opening avenues for smart grid management, renewable energy storage, and transportation. Alkaline electrolysis cells (AECs) are established technologies, with several megawatt-scale industrial units in operation, capable of producing approximately 60 kg H_2 per hour. Despite their maturity, AECs face limitations in operating at very low current densities, impacting flexibility when integrated with renewable energy sources such as wind and solar. Nevertheless, existing AECs exhibit satisfactory lifetimes of several tens of thousands of operational hours, supporting continuous and profitable use in various industries. [37]

Extensive research and development efforts have been dedicated to proton exchange membrane electrolyzer cells (PEMECs) worldwide, positioning them as a promising choice for future electrolysis applications powered by renewable energy. In recent decades, significant advancements in PEMEC technology have been achieved, exemplified by programs like Japan's WE-NET, where an impressive energy conversion efficiency of 95.1% was attained. This success is attributed to the close proximity of the electrolysis cell voltage to the thermoneutral cell voltage, approximately 1.48 V. Furthermore, successful developments in PEMECs operating at elevated pressures, reaching up to 5.0 MPa, further highlight their potential for widespread use. [50]

The potential market for Proton Exchange Membrane Electrolyzers (PEMECs) closely aligns with Alkaline Electrolyzers (AECs); however, presently available PEMECs exhibit lower production capacities in comparison to their AEC counterparts. AECs possess a well-established status with decades of accrued technical expertise, boasting a commendable track record. Furthermore, AECs incur lower capital expenses and operate at reduced current densities, thereby diminishing operational costs. Despite these advantages, PEMECs demonstrate significant potential for advancement, with considerable scope for improvement in the future. Their adaptability to operate efficiently with low electrical input makes them particularly conducive for integration into renewable energy networks. Anticipations suggest that in the forthcoming years, PEMECs will achieve industrial competitiveness with AECs, especially as large-scale hydrogen production becomes prevalent. [37] Protonic Membrane Fuel Cell (PMCFC) technology is particularly poised for applications in long-haul trucks, as well as personal vehicles and buses. Various major cities globally, such as Beijing, Chicago, and London, have either experimented or are currently experimenting with hydrogen fuel cell-powered buses. [51] The process of filling hydrogen into vehicles can be accomplished either as compressed gas or as chilled liquid. In fuel cells, the reaction of H_2 with air yields electrical energy, surplus heat, and water. Conceptually, a hydrogen-powered train parallels a battery-electric train equipped with a hydrogen-driven battery charger. [52]

3.2 Energy storage

Hydrogen (H_2) compression has emerged as a widely adopted solution for H_2 storage, owing to its cost-effectiveness in comparison to alternative methods and its superior energy efficiency at equivalent energy densities. Conversely, liquefaction stands out as a storage approach

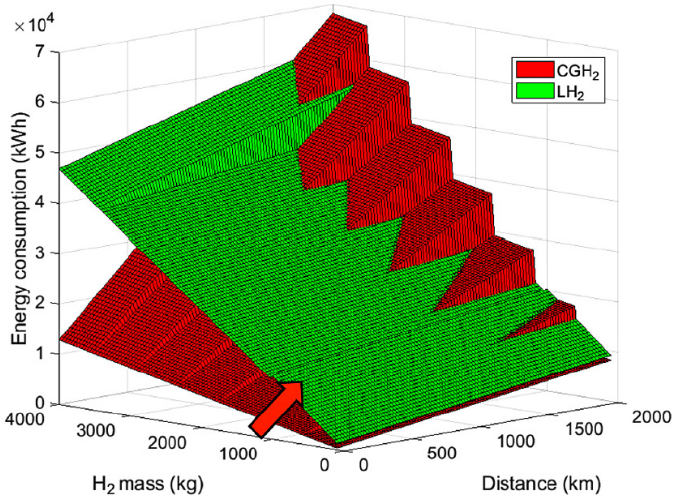

Figure 3.1: Energy consumption of the overall processes studied by J.J. Lamb and B.G. Pollet

characterized by heightened technical demands. Noteworthy among its merits is the capacity to achieve a notable H_2 density of 70.9 kg/m^3 [53]. Only cryo-compressed H_2 storage surpasses this density, reaching levels of up to 80 kg/m^3. Liquefied hydrogen (LH_2) storage becomes imperative in specific applications, exemplified by aerospace rocket propulsion systems, where substantial quantities of H_2 are employed. [37]

The energy expenditure associated with liquefaction consistently exceeds that of compression. Conversely, the energy demand for road transportation exhibits considerable variability contingent upon driving range and the quantity of trucks employed. In specific case studies conducted by Lamb and Pollet as documented in "Hydrogen, Biomass, and Bioenergy: Integration Pathways for Renewable Energy Applications," this energy requirement can peak at 55,372 kWh. This scenario arises when seven trucks are utilized for transporting 4000 kg of compressed gaseous hydrogen (CGH_2) over a distance of 2000 km. Figure 3.1 illustrates a three-dimensional chart depicting the aggregate energy demands of the CGH_2 and liquid hydrogen (LH_2) solutions, accounting for variations in hydrogen mass and delivery range. The CGH_2 solution is represented by the red surface, while the LH_2 storage solution is depicted in green. These surfaces exhibit a non-smooth profile, characterized by discrete steps that correspond to the number of trucks required for each hydrogen mass value. [37]

The findings suggest that LH_2 becomes economically advantageous when transporting substantial hydrogen quantities ($> 1{,}200$ kg), particularly when the driving range exceeds 1260 km. In instances where the demand surpasses 500 kg/day at mid-range distances, LH_2 is deemed more cost-effective than CGH_2. [37]

3.3 Safety

Hydrogen is susceptible to material degradation, posing a risk of leakage. High-pressure hydrogen leaks, given its combustion characteristics, are highly prone to spontaneous combustion, potentially culminating in jet fires or explosive incidents. Such occurrences have the potential to inflict severe casualties and substantial property damage. [54]

In the context of compressed hydrogen storage and its safety, the selection of an appropriate pressure tank is contingent upon factors such as volume and pressure, leading to the delineation of four distinct types. Type I tanks, typically constructed from steel or aluminum, exhibit a capacity to endure maximum pressures ranging from 175 bar (aluminum) to 200 bar (steel). While cost-effective, the considerable weight of Type I tanks, owing to their exclusive metallic composition, renders them suitable for the storage of hydrogen in both liquid and gaseous states. Type II tanks, fabricated from aluminum, incorporate filament windings around the metal cylinder, utilizing materials such as glass fiber/aramid or carbon fiber. The resultant structural configuration imparts enhanced strength, enabling these vessels to withstand pressures of up to 299 bars. Despite their reduced weight and increased strength, Type II vessels incur higher production costs. Type III tanks adopt a composite composition with a metal liner, affording them the capacity to withstand elevated pressures. Variants such as aluminum/aramid and aluminum/carbon composites exhibit pressure tolerances of up to 438 bar and 700 bar, respectively, contributing to their heightened cost. Type IV tanks, devoid of metallic components, are entirely composed of carbon fiber with a polymer liner. Despite their reduced weight and the ability to withstand pressures of up to 700 bars, the extensive use of carbon fiber renders them comparatively more expensive than their counterparts in other categories. [55]

Hydrogen exhibits deleterious effects on the mechanical characteristics of various materials, inducing a proclivity toward embrittlement. This phenomenon manifests in diminished tensile strength, ductility, fracture toughness, and an accelerated progression of fatigue crack growth in metals. The extent of such deterioration is contingent upon factors such as material composition, hydrogen pressure, temperature, and mechanical loading conditions, thus necessitating a discerning selection of materials for applications involving hydrogen exposure. Consequently, meticulous material testing under anticipated operational conditions is imperative to ascertain the adequacy of performance. In cases where direct testing is unfeasible, certain materials have been commonly employed. Noteworthy examples include austenitic stainless steel, aluminum alloys, low-alloy ferritic steels, C-Mn ferritic steels, and copper alloys. Conversely, materials exhibiting high strength ferritic and martensitic steels, gray, malleable, and ductile cast irons, as well as nickel and titanium alloys, are advised against due to their susceptibility to adverse hydrogen-induced effects. [55]

In the realm of hydrogen plant safety, the selection of an appropriate storage vessel is accompanied by the critical consideration of the optimal installation location. While the indoor storage of small hydrogen cylinders is feasible, it is not advisable for larger volumes. Outdoor storage emerges as a preferable and, in certain cases, mandatory choice for substantial hydrogen quantities. This outdoor arrangement enhances safety by facilitating the efficient dissipation of the gas in the event of accidental hydrogen leaks. [55]

The occurrence of leaks poses a significant challenge for hydrogen operations, given the inherently small nature of the element, contributing substantially to operational incidents. An effective strategy to preclude such occurrences involves the installation of leak detectors, necessitating periodic maintenance and testing. Routine leak assessments, inclusive of operational checks for valves, constitute an essential practice. Two prevalent methods for conducting leak tests involve the application of a soap bubble solution or the utilization of a handheld hydrogen detector. In addition to scheduled tests, vigilant checks for leaks should coincide with the reassembly of joints. Moreover, thorough inspections of the system's connections are imperative, encompassing assessments for indicators of corrosion, erosion, cracking, bulging, blistering, or any form of deterioration. [55]

An imperative safety measure involves the incorporation of sensors for the detection of leakages, mandated for hydrogen facilities, equipment, and refueling stations. The heightened significance of these sensors arises from the inherent characteristics of hydrogen, which is both colorless and odorless, rendering it imperceptible to human senses. Present-day technological capabilities facilitate remote hydrogen sensing to ensure a resilient capacity for the detection of any potential hydrogen leaks. Furthermore, stringent testing standards, encompassing exposure to extreme temperatures and pressures, are imposed upon hydrogen storage tanks utilized in fuel cell vehicles prior to their deployment. These instances underscore a subset of the established standards and codes aimed at fortifying the safety parameters associated with hydrogen applications. [56]

In the Norwegian context, Det Norske Veritas (DNV) undertakes safety analyses of hydrogen applications, conducts experimental investigations to garner insights into the repercussions of full-scale incidents, and provides technical recommendations to ascertain solutions that are both temporally and economically optimal. The organization establishes and verifies criteria for the secure and dependable design, construction, and utilization of hydrogen, delivers comprehensive risk assessments, and engages in the formulation and endorsement of regulatory documentation. [57]

4 Conclusion

Hydrogen is a promising energy carrier with the potential to play a significant role in the future of energy. It is a clean fuel that produces only water when burned, and it can be used to generate electricity, power vehicles, and heat homes and businesses. However, there are currently a number of challenges that need to be addressed before hydrogen can become a mainstream energy source. One of the biggest challenges is the cost of producing hydrogen. Currently, 95% of hydrogen is produced from fossil fuels [41], which is a relatively expensive process and not renewable and therefore not sustainable. For hydrogen to be competitive with other energy sources, it needs to be produced using cleaner and more efficient methods, such as electrolysis.

Another challenge is the lack of infrastructure for hydrogen production, storage, and distribution. Currently, there are very few hydrogen fueling stations in operation, and the technology for storing and transporting hydrogen safely and efficiently is still under development. As these challenges are addressed, the cost of hydrogen is expected to come down, and the infrastructure will be developed to support a wider-scale deployment of hydrogen technologies. Regarding green hydrogen production, AEC technology is stronger in bigger industries where it has already developed, while PEMFC is promising a strong future for clean transport. When it comes to LH_2 and CH_2 hydrogen storage technologies, studies have shown that LH_2 becomes more economical for larger hydrogen quantities.

Despite the challenges, there is growing interest in hydrogen as a clean and renewable energy source. The International Energy Agency (IEA) has identified hydrogen as one of the key technologies that will be needed to achieve a low-carbon energy future. The IEA predicts that the demand for hydrogen will increase by 10-20 times by 2050. [41]

5 Future posibilities

The envisaged paper may undergo future revisions to accommodate an expanded scope of technologies, production methods, storage mechanisms, and a heightened focus on utilization. Moreover, the examination of additional factors associated with these evolving technologies could yield novel insights and necessitate revised conclusions.

Anticipation surrounds the trajectory of technological advancements and the advent of new discoveries, promising a dynamic landscape for research and development. Notably, in the year 2023, Sweden has allocated a substantial investment of 200 million euros into hydrogen technologies within the Nordics, as reported by finansavisen.no. This financial commitment is poised to galvanize empirical investigations into the practical applications of hydrogen, transcending theoretical frameworks.

The infusion of resources into hydrogen-related initiatives will likely instigate a multifaceted exploration of its integration into everyday life. This exploration extends beyond theoretical discourse, encompassing practical considerations spanning transportation, storage, and utilization methodologies. The resultant confluence of advancements is anticipated to furnish a rich substrate for scholarly inquiry and empirical scrutiny.

Furthermore, the forthcoming surge in research activities and the concomitant proliferation of scholarly articles will afford a unique opportunity for comparative analyses. This surge promises to facilitate a comprehensive understanding of the evolving landscape by juxtaposing diverse research outcomes, thereby augmenting the discourse surrounding hydrogen technologies. As such, the envisaged paper stands to benefit from this unfolding milieu, providing an enriched foundation for the exploration of hydrogen-centric developments.

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A Appendix: Pre-project content list

Contents

Figure A.1: Screenshot of the content list from the forprosjekt (pre-project)