FEASIBILITY STUDY OF INDUSTRIAL SCALE GREEN HYDROGEN PRODUCTION IN FINLAND

Lappeenranta-Lahti University of Technology LUT

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ABSTRACT

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This master's thesis conducts a feasibility study on industrial-scale green hydrogen production in Finland, exploring both technical and economic dimensions. Green hydrogen emerges as a critical driver for transitioning to a zero-emission future. The investigation emphasizes the dominance of alkaline water electrolyzer in large-scale applications due to its cost-effectiveness, despite the appeal of proton exchange membrane water electrolyzer for direct coupling with volatile renewable energies. Business cases reveal the role of renewable energy source quality, with Finnish wind energy presenting a promising avenue. The estimated levelized cost of hydrogen in Finland anticipates a significant reduction by 2030, rendering green hydrogen economically viable. Analysis of cost structures highlights the importance of capital expenditures (CAPEX) elements and identifies key strategies for cost reduction. As the urgency to transition from fossil fuels intensifies, electrolyzer technologies are poised for large-scale development, with alkaline electrolyzers emerging as a mature and cost-effective choice. Looking forward, the thesis expresses confidence in the essential role of hydrogen applications. Future research recommendations include optimizing entire plant performance, exploring diverse energy resources, advancing material science for cost-effective alternatives, addressing barriers to scale-up, and fostering interdisciplinary collaboration for a holistic understanding of green hydrogen production's potential.

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Lappeenranta, June 4, 2024

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SYMBOLS AND ABBREVIATIONS

Symbols

A	Area [m^2]
E_{HE}	Heat exchanger energy input [J]
E_{K}	Kinetic energy [J]
E_{red}	Redundant energy required [J]
F	Faraday's constant [C/mole]
$F_{\mathrm{H_2}}$	Hydrogen gas out flow rate [Kg/hr]
M	Mass flow rate [kg/h]
m	Mass of air stream [kg]
P	Power of wind [W]
P_{E}	Electrical power supply [kW]
T	Operating temperature [K]
U	Wind velocity [m/s^2]
U_{act}	Activation overvoltages [V]
U_{cell}	Actual cell voltage [V]
U_{con}	Concentration overvoltage [V]
U_{ohm}	Ohmic overvoltage [V]
U_{rev}	Reversible cell voltage [V]
U_{th}	Thermoneutral voltage [V]
Z	Number of exchanged electrons
ΔG	Change in Gibbs free energy of reaction [J/mol]
ΔH	Enthalpy change of reaction [J/mol]
ΔS	Entropy change of reaction [J/mol K]
η	Efficiency [%]
ρ	[Kg/m^3]

Abbreviations

AC	Alternating Current
AEMWE	Anion Exchange Membrane Water Electrolyzer
ATR	Autothermal Reforming
AWE	Alkaline Water Electrolyzer
BESS	Battery Energy Storage Systems
BoP	Balance of Plant
CAPEX	Capital Expenditures
CCM	Catalyst Coated Membrane
CCP	Central Collection Point

CCS	Carbon Capture and Storage
CG	Coal Gasification
DC	Direct Current
DEA	Diaphragm Electrode Assembly
EU	European Union
FLH	Full Load Hours
GHG	Greenhouse Gas
GHPS	Green Hydrogen Production System
HER	Hydrogen Evolution Reaction
HAWT	Horizontal Axis Wind Turbine
HHV	Higher Heating Value
KOH	Potassium Hydroxide
LCOH	Levelized Cost Of Hydrogen
LHV	Lower Heating Value
MEA	Membrane Electrode Assembly
MMO	Mixed Metal Oxide
MPPT	Maximum Power Point Tracking
NaOH	Sodium Hydroxide
NaCl	Sodium Chloride
OER	Oxygen Evolution Reaction
OPEX	Operating Expenses
PEMWE	Proton Exchange Membrane Water Electrolyzer
PFSA	Perfluorinated Sulfonic Acid
POM	Partial Oxidation of Methane
POX	Partial Oxidation of Oil Products
PPS	Polyphenylene Sulfide
PTL	Porous Transport Layers
PV	Photovoltaic
RES	Renewable Energy Sources
SCWG	Super Critical Water Gasification
SMR	Steam Methane Reforming
SOWE	Solid Oxide Water Electrolyzer
SWOT	Strengths, Weaknesses, Opportunities, Threats
VAWT	Vertical Axis Wind Turbine
WACC	Weighted Average Cost of Capital
WT	Wind Turbine

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1 INTRODUCTION

The Paris agreement, a legally binding commitment to limit global average temperature rise to well below 2°C above pre-industrial levels and aim for 1.5°C, has set a critical benchmark for countries to align their renewable energy efforts with climate action. Participants, such as the European Union (EU), have further increased their ambitions, with the EU updating its emissions target to achieve at least a 55% reduction by 2030 below 1990 levels, a significant increase from its previous 40% goal [1, 2].

The urgent need to combat climate change and embrace sustainable energy solutions has thrust green hydrogen into the forefront as a versatile and carbon-free alternative to conventional fossil fuels. Green hydrogen, produced through water electrolysis using renewable energy sources, holds immense promise, with solar energy emerging as a key player due to its abundance and potential to support clean hydrogen production. This aligns with the global interest in harnessing renewable resources to meet the rising demand for clean and versatile energy carriers, while addressing the pressing concerns about climate change and the importance of transition towards renewable energy sources.

Historically, hydrogen has witnessed periodic increases in attention driven by factors such as oil price fluctuations, apprehensions about peaking oil demand, environmental pollution concerns, and explorations into alternative fuel sources. Hydrogen plays an important role in enhancing energy security by introducing an additional energy carrier characterized by distinct supply chains, producers, and markets. This diversification contributes to a more resilient energy system. The latest increase of interest revolves around the search for low-carbon solutions and exclusive advantages uniquely offered by green hydrogen. Fig. 1 illustrates the primary drivers behind the uptake of green hydrogen [3].

Various obstacles are relevant to all types of hydrogen, encompassing the absence of specialized infrastructure (such as transport and storage facilities). Specific challenges are predominantly associated with the production phase of electrolysis for green hydrogen, including issues like energy losses, insufficient recognition of its value, sustainability concerns, and elevated production costs. Fig. 2 outlines the primary obstacles in this regard [3].

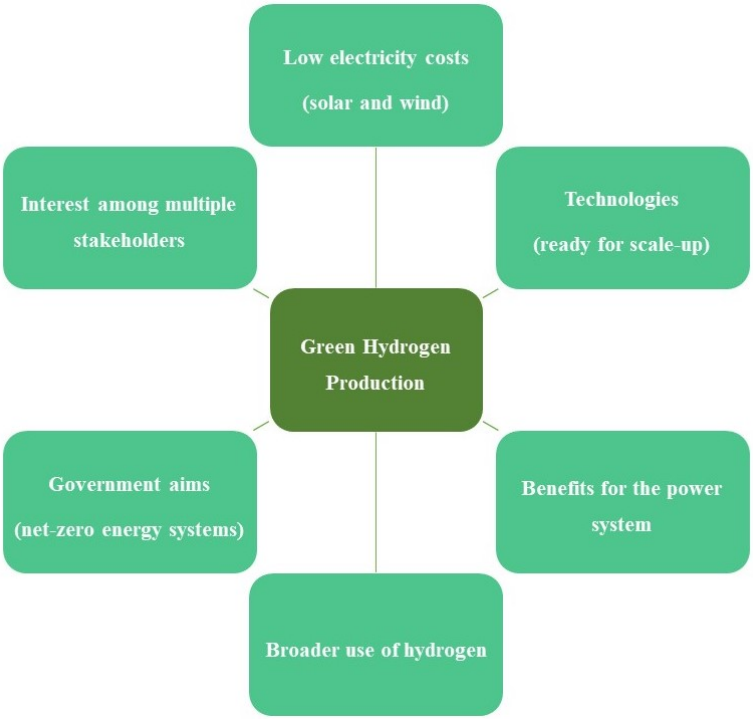

Figure 1. New drivers for green hydrogen.

1.1 Background and motivation

In 2021, global hydrogen demand rebounded to 94 million tonnes, surpassing pre-pandemic levels and accounting for approximately 2.5% of global final energy consumption. The increase in demand was primarily driven by traditional uses in refining and industry, while new applications showed promising growth. These developments highlight the growing interest and adoption of hydrogen as a clean and versatile energy carrier across diverse sectors [4].

In 2022, hydrogen constituted less than 2% of Europe's total energy consumption and was predominantly utilized for manufacturing chemical products. A striking 96% of this hydrogen was derived from natural gas, leading to substantial CO_2 emissions. In response, the european commission has put forth an ambitious plan to produce and import renewable hydrogen by the year 2030 [5].

Many studies have explored different aspects of producing green hydrogen. Some of these studies focused on explaining how to make hydrogen, looking at various methods and comparing them [6–8]. At the same time, another set of research has compared different types of electrolyzers, discussing their strengths and weaknesses [9–11]. In addition, researchers have spent a lot of time using math to create models of alkaline water

Figure 2. Barriers to green hydrogen uptake.

electrolysis processes, which can be find in many research articles [12–14]. Notably, a significant portion of the research in this field has centred on techno-economic analysis, particularly investigating the cost and benefits of making green hydrogen using renewable resources like solar or wind power [15–17].

In addition to the research conducted on a small and laboratory scale, good studies have also been conducted on the industrial scale of hydrogen production. Kumar and Lim [18] conducted an extensive documentary review on large-scale green hydrogen production, offering an in-depth analysis of water electrolysis-based systems. Their assessment covered various aspects, including the cost of hydrogen production, progress in materials, and challenges. Hoisang and Sakaushi [19] addressed electrode material-related challenges, highlighting the need for scientific development for net-zero society goals. Kojima et al. [20] reviewed fluctuating energy features and challenges in water electrolysis, suggesting transformative changes for a self-sustaining hydrogen-based society.

Several studies explored green hydrogen applications. Kakavand et al. [21] assessed green hydrogen's role in urea synthesis, emphasizing its economic and environmental viability. Sollai et al. [22] investigated low-temperature water electrolysis, showcasing its potential to reduce energy consumption and costs. Demirdelen [23] studied a hybrid solar-wind

system for green hydrogen production, demonstrating its reliability. Terlouw et al. [24] conducted a technoeconomic assessment, revealing reduced costs and carbon emissions with renewable energy.

The studies by Juarez-Casildo et al. [25], Norouzi [26], and Kannah et al. [27] explored cost scenarios, sustainability, and economic analyses. Messaoudi et al. [28] identified optimal locations for solar hydrogen production. Cany et al. [29] explored ideal sites for solar hydrogen production. Hassan et al. [30] developed an improved solar-hydrogen system for residential use.

Kakoulaki et al. [31] evaluated renewable energy resources' capacity for hydrogen production. D'Amore Domenech et al. [32] favored proton exchange membrane electrolysis. Brandle et al. [33] proposed low-carbon hydrogen production methods in various countries. Pfennig et al. [34] assessed production costs using geographic information.

However, the literature on solar and wind-based green hydrogen production systems (GHPSs) reveals several gaps warranting further investigation. These gaps encompass: the absence of data-driven models from empirical studies; a lack of detailed transient models for GHPSs without battery storage and grid interaction; insufficient coverage of battery safety and degradation in GHPS studies; and a general oversight of electrolyzer degradation. Furthermore, in line with the EU's proposed strategies, there is a pressing demand for extensive large-scale research in the industrial sector, with a clear focus on bolstering investments in this domain.

1.2 Research objectives

The primary focus of this research is to conduct a comprehensive assessment of the feasibility of industrial-scale green hydrogen production in the context of Finland. To achieve this main aim, the study is guided by several specific research objectives. Firstly, it seeks to examine into the technical aspects of industrial-scale green hydrogen production, encompassing critical areas such as electrolyzer technology, power sources, battery storage, efficiency, and the complex challenges that arise in the transition to large-scale production. Secondly, the research aims to closely examine the economic dimensions of this endeavour, including a detailed cost structure analysis, an exploration of demand and supply dynamics, and the determination of the final hydrogen price. Furthermore, the study aims to evaluate the renewable energy resources available in Finland, and it investigates analysing the current and projected scenarios of hydrogen demand and supply

in the country. Lastly, the research briefly discusses investment opportunities in green hydrogen production in Finland, outlining strategic avenues for future development and highlighting key implications for the sector's growth.

1.3 Scope and limitations

The scope of the study primarily encompasses an investigation into the feasibility of industrial-scale green hydrogen production in Finland. This involves a comprehensive examination of technical and economic aspects and the assessment of renewable energy resources in the country. The temporal scope extends to some projections. While the research aims to provide valuable insights, it might not cover every possible angle of the complicated field of green hydrogen production.

Limitations include the availability and accuracy of data, which may be subject to constraints beyond the researcher's control. Moreover, the research's scope is focused on Finland and may not directly extrapolate to other regions or nations. This study does not examine detailed policy analysis or regulatory aspects, which could play a significant role in the actual implementation of green hydrogen projects. Furthermore, the economic analysis is based on current knowledge and may not account for unforeseen market fluctuations. These limitations, while acknowledged, do not undermine the significance and value of the research in contributing to the understanding of green hydrogen production feasibility in Finland.

1.4 Thesis structure

The structure of this thesis has been carefully organized to provide a logical and coherent flow of information for the reader. It consists of several chapters, each contributing distinct aspects to the research effort. Chapter 1, the introductory chapter, acts as the foundation and includes essential sections such as background and motivation, research objectives, an outline of the thesis structure and methodology used for data collection, analysis, and the overall research design to guide the reader through the study's layout.

Chapters 2 and 3 explore the core of the research. Chapter 2 focuses on the technical aspects of industrial-scale green hydrogen production, providing an in-depth examination of electrolyzer technology, energy sources, battery storage, efficiency, and the challenges

faced in large-scale production. Chapter 3 shifts the focus towards economic aspects, including a thorough cost structure analysis, an evaluation of demand and supply dynamics, and the determination of the final hydrogen price.

Chapter 4 examines the specific scenario in Finland, assessing the country's renewable energy resources and conducting an analysis of hydrogen demand and supply. It considers the current situation and offers some projections for the future. Finally, Chapter 5 provides a conclusion, summarizing the main findings and their implications, and it also offers concluding remarks. The thesis is rounded out with the list of all the sources and references used throughout the research.

1.5 Methodology

The methodology employed in this study encompasses an extensive review of existing literature, encompassing academic journals, industry reports, and technical documents. This approach aims to establish a robust foundation for comprehending the technical and economic dimensions of green hydrogen production. Furthermore, quantitative analyses and modeling are employed to examine cost structures and derive estimates for the levelized cost of hydrogen (LCOH).

In conducting the literature review, precise attention has been paid to the selection of the most precise sources through strategic keyword choices. In cases where multiple datasets were available, preference was given to those with the highest frequency of repetition. Furthermore, to enhance accuracy, the approach involved proposing acceptable ranges instead of fixed data where applicable, thereby minimizing potential errors.

In addressing the varied currency denominations used across different literature sources, a consistent standardization approach was adopted. All financial data were uniformly converted to euros at the rate of $1.09 per euro, providing a unified and comparable basis for analysis. This standardized conversion ensures the coherence and clarity of financial information throughout the study.

2 TECHNICAL ASPECTS OF GREEN HYDROGEN

Hydrogen is classified into different colour categories, including green, blue, gray, and some others, based on the environmental impact of its production methods. Green hydrogen, produced mainly from renewable energy sources, is environmentally friendly, while grey hydrogen, derived from fossil fuels, can harm the environment. Blue hydrogen, positioned between green and grey, involves capturing and storing CO_2 to reduce carbon emissions [35]. Hydrogen production methods are divided into those dependent on non-renewable or renewables. Table 1 provides an overview of various hydrogen production methods.

Table 1. Well-known hydrogen production pathways [6–8, 35, 36].

Energy Source	Category	Technology
Non-Renewable Sources	Reforming methods	Steam methane reforming (SMR)
		Partial oxidation of methane (POM)
		Autothermal reforming (ATR)
		Partial oxidation (POX) of oil products
		Plasma reforming
	Gasification	Coal gasification (CG)
	Desulfurization	Desulfurization
	Pyrolysis	Hydrocarbon pyrolysis
Renewable Sources	Biomass	Steam gasification of biomass
		Supercritical water gasification (SCWG) of biomass
		Bio-photolysis
		Photo fermentation
		Dark fermentation
		Dark-photo co-fermentation
	Electrolysis	Conventional water electrolysis methods - Alkaline water electrolysis (AWE) - Proton exchange membrane water electrolysis (PEMWE)
		High-temperature electrolysis - Solid oxide water electrolysis (SOWE)
		Anion exchange membrane water electrolysis (AEMWE)
	Thermolysis	One-step water thermolysis
	Thermochemical cycles	Sulfur-iodine (SeI) cycle
		Copper-chlorine (CueCl) cycles
		Two-step metal oxide cycles
	Photo-electrolysis	Photo-electrolysis
	Plasmolysis	Plasmolysis

Renewably sourced hydrogen can be utilized for various purposes including energy storage, electricity generation, fueling transportation, producing chemicals, and industrial applications like steel making. It can be transformed into power and transportation fuel using fuel cell systems, while its reactions with substances like nitrogen and carbon dioxide yield ammonia, methanol, and more. Beyond its role as fuel, hydrogen acts as both an energy carrier and storage medium, capitalizing on renewable resources. Its significance extends to sectoral decarbonization, essential for achieving net-zero CO_2 emissions by 2050 [36].

2.1 Electrolysis technology

Water, an abundant and endlessly available resource on our planet, serves as a vital raw material to produce H_2 using various water-splitting methods such as electrolysis, thermolysis, and photo-electrolysis [37]. Among these methods, electrolysis stands out as a well-established and efficient technique for water splitting. However, this process is notably energy-intensive, necessitating an input of electricity to drive the reaction [38].

The fundamental design of an electrolysis setup, as depicted in Fig. 3, comprises a cathode, an anode and an electrolyte. However, it should be noted that the type of electrolyte may vary depending on the type of electrolyzer. Upon the application of an electric current, water undergoes division, leading to the release of hydrogen at the cathode and the release of oxygen at the anode. The distinct gases formed at their respective electrodes can be effortlessly isolated, yielding pure hydrogen and oxygen. The utilization of water to generate hydrogen offers a distinct advantage, enabling its widespread implementation without being constrained by local reserves of fossil fuels or biomass.

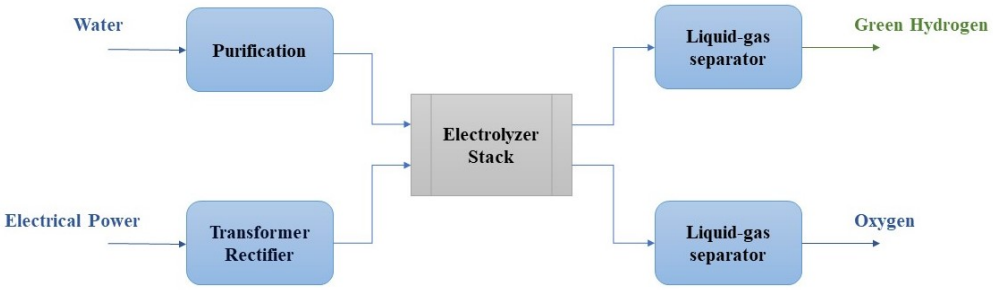

Figure 3. Flow diagram of the water electrolysis process [7].

Water electrolysis requires an electrolyzer and can be classified into different types based on the electrolytes used: alkaline water electrolyzer (AWE), proton exchange membrane water electrolyzer (PEMWE), solid oxide water electrolyzer (SOWE), and anion exchange membrane water electrolyzer (AEMWE). While AWE and PEMWE systems are commercially established, current attention is shifting toward SOWE and AEMWE solutions, believed to be closer to industrial use. Not all electrolyzer technologies are suitable for coupling with intermittent renewable energy sources, and their performance involves trade-offs in factors like cost, noble metal usage, technology readiness, and flexibility. This section will offer a detailed overview of available electrolyzer types, discussing their advantages and limitations, particularly in the context of research and development.

Water electrolyzers are organized into three key levels: the cell, the stack, and the system level. The cell, the foundational unit, houses the electrochemical process. Moving to the stack, multiple cells are interconnected, utilizing spacers, seals, frames, and end plates. Finally, at the system level, components such as cooling equipment, hydrogen handling processes, electrical transformers, water treatment, and gas management ensure the overall functionality and optimization of the water electrolyzer system.

2.1.1 Principle of operation

In the electrochemical process of water electrolysis, a water molecule undergoes a transformation, leading to the separation of water into its constituent gases, hydrogen, and oxygen. This crucial process relies on the application of electricity to affect the conversion of hydrogen and oxygen into their gaseous states, as captured by Eq. 1.

$$\mathrm{H_2O_{(\ell)}} + \text{Energy} \rightarrow \mathrm{H_{2(g)}} + \frac{1}{2}\mathrm{O_{2(g)}} \tag{1}$$

Water electrolysis requires a crucial energy input from a direct current (DC) power supply. In normal room temperature conditions, water's natural tendency to split itself is quite low, producing only about 10 moles per liter. This low amount mainly happens because pure water doesn't conduct electricity well. To fix this issue, an acid or a base is added to improve the electrolyte's conductivity [39].

A water electrolysis cell consists of two electrodes separated by an electrolyte, facilitating the transfer of chemical charges between them. In alkaline electrolyzers, this transfer is achieved through a concentrated potassium/sodium hydroxide (KOH or NaOH) solution and a porous inorganic diaphragm. In contrast, PEMWE, AEMWE, and SOWE use a solid electrolyte to separate electrons and enable proton or anion transport depending on technology. These systems eliminate the need for a liquid electrolyte solution, as transport occurs directly within the respective components. Fig. 4 illustrates the principles of all commercially available electrolysis types [40].

- Cell voltage

In the context of water electrolysis, two key voltage parameters are essential for energy calculations: the reversible cell voltage and the enthalpy voltage. The reversible cell voltage represents the minimum voltage necessary for water decomposition. Meanwhile, the enthalpy voltage, also known as the thermo-neutral voltage, is associated with the

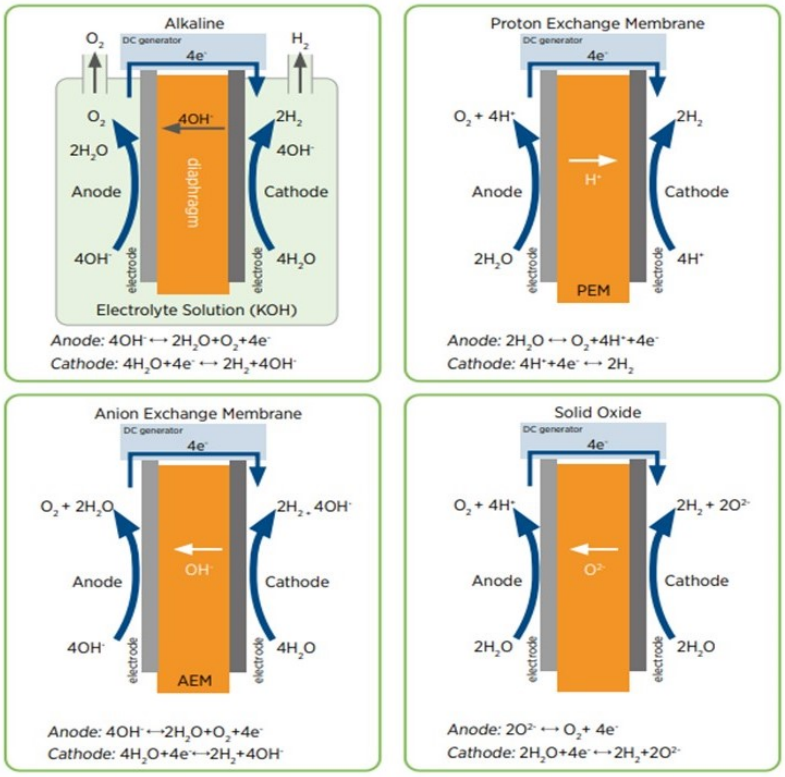

Figure 4. Principles of all commercially available types of water electrolyzers [40].

enthalpy of the reaction and signifies the minimum voltage required for the process of water electrolysis [39].

The determination of the required cell voltage for this electrochemical process relies on thermodynamic principles. The free reaction enthalpy (ΔG) as described in Eq. 2 can be computed using the reaction enthalpy (ΔH), temperature (T), and reaction entropy (ΔS) [41]:

$$\Delta G = \Delta H - T \cdot \Delta S \tag{2}$$

The reversible cell voltage (U_{rev}) Eq. 3 is determined by dividing the free reaction enthalpy (ΔG) by the product of the number of exchanged electrons ($z = 2$) and the Faraday constant ($96,485\,\text{C mol}^{-1}$) [41]:

$$U_{\text{rev}} = -\frac{\Delta G}{z \cdot F} \tag{3}$$

The thermoneutral voltage (U_{th}) as defined in Eq. 4 depends on the reaction enthalpy (ΔH), which is composed of the free reaction enthalpy (ΔG) and irreversible thermal

losses ($T\Delta S$):

$$U_{\text{th}} = -\frac{\Delta H}{z \cdot F} \tag{4}$$

Under standard conditions of $25\,^{\circ}\text{C}$ and 1 bar pressure, the free reaction enthalpy (ΔG) for water splitting is $237\,\text{kJ mol}^{-1}$ and the reaction enthalpy (ΔH) is $286\,\text{kJ mol}^{-1}$, resulting in a reversible cell voltage of $-1.23\,\text{V}$ and a thermoneutral voltage of $-1.48\,\text{V}$. Since the free reaction enthalpy is positive under standard conditions, water splitting is considered a non-spontaneous reaction [12].

The actual cell voltage in an operational electrolysis cell exceeds the theoretical reversible cell voltage determined by thermodynamics. This difference arises due to the necessity for additional voltage to overcome the innate irreversibilities originating from factors such as reactant products, transportation, charge transfer, and resistance within the electrolyte and electrodes during the electrolysis process. These various factors collectively elevate the practical voltage requirement beyond the theoretical estimate [42].

The voltage of the electrolytic cell, denoted as U_{cell}, is determined by combining the reversible voltage (U_{rev}) with the additional overvoltages generated within the cell. These additional overvoltages consist of the ohmic resistance (U_{ohm}), activation overvoltages (U_{act}) arising from limitations in anode and cathode reaction kinetics, and concentration overvoltages (U_{con}):

$$U_{\text{cell}} = U_{\text{rev}} + U_{\text{ohm}} + U_{\text{act}} + U_{\text{con}} \tag{5}$$

The concentration overvoltages are typically observed at elevated current densities, where mass transfer limitations come into play. This occurs when the available water supply within the stack is insufficient to adequately support the reaction kinetics involved in the production of hydrogen and oxygen at the electrode surface [43].

- Efficiency

Energy efficiency in the water electrolysis process is defined as the energy of hydrogen output per unit of electrical power supplied. This efficiency, denoted as η, is contingent on the electrical power utilized for electrolysis [39]:

$$\eta = \frac{\Delta H \cdot F_{\text{H}_2} \cdot LHV}{P_E} \tag{6}$$

In this context, ΔH represents the enthalpy change of the reaction, F_{H_2} indicates the outflow rate of hydrogen gas, LHV stands for the lower heating value, and P_{E} signifies the electrical power supply.

In certain other literature sources, efficiency is characterized with respect to the hydrogen outflow rate, electrical power input, heat delivered to the heat exchanger, and supplementary heat requirements, including electricity generation efficiency [44–46]:

$$\eta = \frac{F_{\mathrm{H_2}} \cdot HHV}{\frac{P_E}{\eta_{\text{electric}}} + E_{HE} + E_{\text{red}}} \tag{7}$$

Here, HHV stands for the higher heating value, η_{electric} represents the electricity generation efficiency, E_{HE} denotes the energy input to the heat exchanger, and E_{red} signifies the redundant energy required.

Electrical efficiency spans a wide range, from 25% to 80%, and is independent of the electrolysis cell system. In addition, the overall efficiency of a hydrogen production plant can be calculated, encompassing power input from water treatment, hydrogen production, hydrogen drying, pump power, and hydrogen purification. To facilitate comparisons among various electrolysis systems, it is crucial to maintain consistent operating pressures and boundary conditions. Under room temperature conditions and without accounting for additional heat, voltage efficiency is conveniently measured based on HHV. Voltage efficiency is the ratio of enthalpy voltage to the actual cell voltage [39]:

$$\eta_{\text{Voltage}} = \frac{V_{\text{th}}}{V_{\text{real}}} \tag{8}$$

Eq. 8 holds true when the process adheres to or assumes adherence to Faraday's law of decomposition. However, during the process, maintaining the Faraday assumption can be challenging due to gas diffusion, current behaviors within the cell, and gas leakage into the surroundings. These disturbances diminish the actual hydrogen production rate compared to the ideal calculated production rate. Consequently, Faraday efficiency (current efficiency) quantifies these losses:

$$\eta_{\text{Faraday}} = \frac{F_{\mathrm{H_{2,real}}}}{F_{\mathrm{H_{2,ideal}}}} = \frac{F_{\mathrm{H_{2,real}}}}{I \cdot (z \cdot F)^{-1}} \tag{9}$$

Thus, the total cell efficiency (excluding losses from peripheral device power consumption) is the product of voltage efficiency and current efficiency:

$$\eta_{\text{cell}} = \eta_{\text{voltage}} \times \eta_{\text{Faraday}} \tag{10}$$

To assess the comprehensive performance of an electrolyzer system, essential data regarding the configuration, such as the quantity of cells arranged in series and/or parallel per stack, as well as the number of stacks per unit, is indispensable. The rated voltage for an electrolyzer stack is determined by the quantity of cells connected in series, while the total cell area determines the current density, directly influencing hydrogen production. The total power output can be straightforwardly calculated as the product of the current and voltage [12].

2.1.2 Alkaline water electrolyzer

With over 120 years of history, alkaline water electrolysis stands as the oldest and most widely adopted technology for water electrolysis. Historically, it thrived in areas with low electricity costs, unfavorable fossil source production, and expensive hydrogen transport to consumers Among the available methods, alkaline electrolysis is the most developed and has the most economic potential [9].

Using electric energy, alkaline water electrolysis separates water into the gases oxygen and hydrogen. The equations 11-13 provide the chemical processes. At the cathode, water molecules are reduced by electrons to hydrogen and negatively charged hydroxide ions. Hydroxide ions are oxidized to produce oxygen and water at the anode while releasing electrons. In general, a water molecule reacts 2:1 with hydrogen and oxygen [41].

$$\text{Cathode:} \quad 2\mathrm{H_2O_{(\ell)}} + 2\mathrm{e^-} \rightarrow \mathrm{H_{2(g)}} + 2\mathrm{OH^-_{(aq)}} \tag{11}$$

$$\text{Anode:} \quad 2\mathrm{OH^-_{(aq)}} \rightarrow 0.5\mathrm{O_{2(g)}} + \mathrm{H_2O_{(\ell)}} + 2\mathrm{e^-} \tag{12}$$

$$\text{Overall reaction:} \quad \mathrm{H_2O_{(\ell)}} \rightarrow \mathrm{H_{2(g)}} + 0.5\mathrm{O_{2(g)}} \tag{13}$$

The product gases are created in the electrolysis stack when the electrolyte is poured through it. Although gas covering of the electrode surface can raise the necessary cell voltage and hence increase the operating expenses, spontaneous convection can be a more affordable option. In order to keep the electrolyte within an ideal temperature range, the majority of alkaline water electrolyzer systems also include a temperature control [47].

The liquid electrolyte and product gas, in two-phase mixtures, exit the electrolysis cell and move into subsequent gas separators. Typically, phase separation occurs in large tanks with extended residence times. The product gas undergoes demisting and drying processes before being purified to the desired level. Meanwhile, the liquid electrolyte is directed out of the gas separator and pumped back into the electrolysis stack [48].

Since the product gases dissolve in the electrolyte solution, combining both electrolyte cycles leads to losses and heightened gas impurities. An alternative approach involves utilizing partly separated electrolyte cycles with an equalization line to balance liquid levels in both vessels. In such a setup, electrolyte concentration increases on the cathodic side due to water consumption and decreases on the anodic side owing to water production. To maintain optimal electrolyte conductivity, occasional mixing of the electrolyte becomes necessary in separated cycles [14, 49].

The design of the electrolysis stack depends on the manufacturer; however, some general similarities can be observed. The AWE cell design involves two half-cell compartments separated by a permeable porous diaphragm facilitating hydroxide ion movement while preventing substantial gas crossover. Common electrode substrates include perforated metal sheets, woven metal meshes, or expanded metal sheets coated with an electrocatalyst. Electrodes, placed close to the diaphragm in a sandwich-like configuration, minimize distance, reducing ionic resistance and enhancing gas bubble evolution for improved cell efficiency. A traditional assembly with a predetermined space between the two electrodes was employed in earlier alkaline water electrolyzers. Subsequently, this idea was replaced by the zero-gap assembly, which minimizes ohmic losses caused by the electrolyte by pressing the electrodes directly into the separator [41]. Modern alkaline electrolyzers often adopt the zero-gap diaphragm electrode assembly (DEA) design [12, 13].

The diaphragms, exemplified by Zirfon Perl UTP, require high thermal, chemical, and electrochemical resistance. Innovative approaches, such as woven stainless-steel meshes, promise cost reductions. Electrode materials, chosen for corrosion resistance and electrochemical activity, include pure nickel, stainless steel, or mild steel substrates. Commercial AWE cell designs incorporate various electrocatalysts, adapted from the chlor-alkali industry, to enhance activity and corrosion resistance [50].

In today's commercial systems, cells operate at pressures ranging from atmospheric to 30 bar, with temperatures between 40 and 90 °C. Diaphragms made from diverse materials, including fiberglass-reinforced polyphenylene sulfides, offer alternatives. Despite innovations, challenges persist, such as testing under industrial conditions and addressing issues like gas purity. Electrodes, crucial for long-term resistance against corrosion in high pH environments, favor materials like pure nickel, stainless steel, or mild steel substrates. Commercial AWE cell designs incorporate diverse electrocatalysts, tailored to specific half-cell reactions. Common coatings include Raney-nickel, Rutheniumdioxid (RuO_2), or other Mixed Metal Oxides (MMO's) and Molybdenum (Mo). The use of nickel oxides and nickel and cobalt-based mixed oxides further enhances anode electrochemical

activity [50].

Materials for half-cell compartments, bipolar plates, spacers, and elastic elements predominantly consist of nickel or nickel-coated steel, providing corrosion protection from the alkaline electrolyte. A schematic of a typical alkaline water electrolyzer cell design for both tiny gap and zero gap is depicted in Fig. 5.

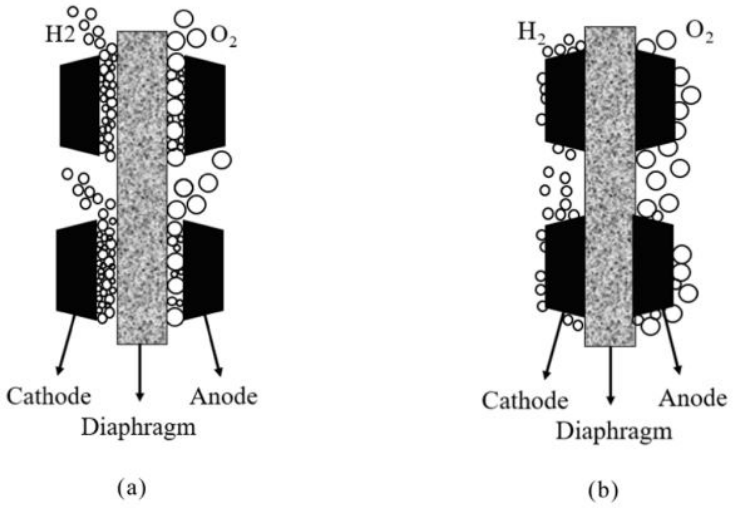

Figure 5. Structure of an AWE cell: (a) tiny gap and (b) zero gap [51].

The hydrogen production capacity of a cell depends on its current density and size. Connecting multiple cells in series forms a stack, where one cell's cathode becomes the adjacent cell's anode. In this bipolar stack design, only the end plates require electrical contact. However, a drawback is that if one cell is defective, the entire stack may fail, though some designs allow for electrical bypassing of a faulty cell. Pressurized AWE stacks utilize long rods, advantageous for improved gas evacuation due to smaller bubbles at higher pressures, resulting in a more compact design compared to stacks operating at atmospheric pressure.

The electrolyzer system comprises various process components, instrumentation, and control devices. Power electronics, including a transformer and rectifier, convert incoming alternating current (AC) into regulated direct current (DC) current applied to the stack contacts. Gases evolve from electrodes, carrying the electrolyte in a two-phase flow to spatially positioned gas/water separators above the stack. Depending on the system design, heat-exchangers and baffles cool the electrolyte and reduce aerosol content. In conventional stack designs, a two-phase mixture exits cells towards a liquid/gas separator.

Some atmospheric designs integrate liquid/gas separation within cells, saving an external separator. Gases then pass through demisters to retain fine droplets, with control valves regulating system pressure. Contamination risks arise from mixed electrolyte streams after separators, particularly at slower KOH circulation and higher system pressure. Adequate control is crucial, achieved through natural convection in conventional systems, limiting part-load operation to less than 20%. However, newer AWE systems can operate down to 10%, necessitating forced circulation for rapid gas evacuation and heat dissipation. The product gas quality ranges from 99.5–99.9% for H_2 and 99–99.8% for O_2, potentially exceeding 99.999% through catalytic gas purification. Pressurized operation requires a cell design and a balanced lye system, maintaining a small pressure difference between the anode and cathode. Control valves regulate pre-pressure and follow hydrogen pressure, while a feed water system with a pump ensures constant alkaline solution concentration. Deionization guarantees feed water quality, and additional heat exchangers cool electrolyte and gas, often complemented by a low-pressure hydrogen gas reservoir to manage pressure fluctuations without mechanical compression [50].

2.1.3 Proton exchange membrane water electrolyzer

The design of a proton exchange membrane water electrolyzer cell closely resembles that of a PEM fuel cell. Employing perfluorinated sulfonic acid (PFSA) membranes like Nafion® or fumapem® with a thickness of 100-200 µm, the membranes ensure high proton conductivity and prevent gas mixing during the two half-cell reactions in separate anode and cathode chambers. However, gas permeability, especially under differential pressure, presents challenges, addressed by applying Pt nanoparticle-containing membranes to reduce hydrogen crossover [52]. PFSA membranes also face swelling issues during water absorption, leading to undesirable wrinkling and potential damage in compressed cells [53].

The membrane and electrodes, forming the membrane electrode assembly (MEA), utilize platinum as a catalyst for efficient hydrogen production on the cathode and metals like iridium for oxygen production on the anode [54]. The catalyst layers on both sides are only a few micrometers thick. Between the MEA and the bipolar plates' flow channels, porous transport layers (PTL) ensure uniform electric current distribution. PTL characteristics include high electrical and thermal conductivity, as well as gas and water permeability. Carbon-based materials like carbon paper or nonwovens are suitable on the hydrogen side, while titanium, due to its high conductivity and corrosion resistance, is exclusively used on the oxygen side. The flow field plates, usually made of titanium or coated steel,

must be corrosion resistant. While carbon composite materials are an option on the hydrogen side, the cost-effective use of single-layered titanium sheets for bipolar plates is more common, often integrated with flow structures for water and gas transport [50]. A schematic of a typical PEMWE cell design is depicted in Fig. 6. Similar to AWE stacks,

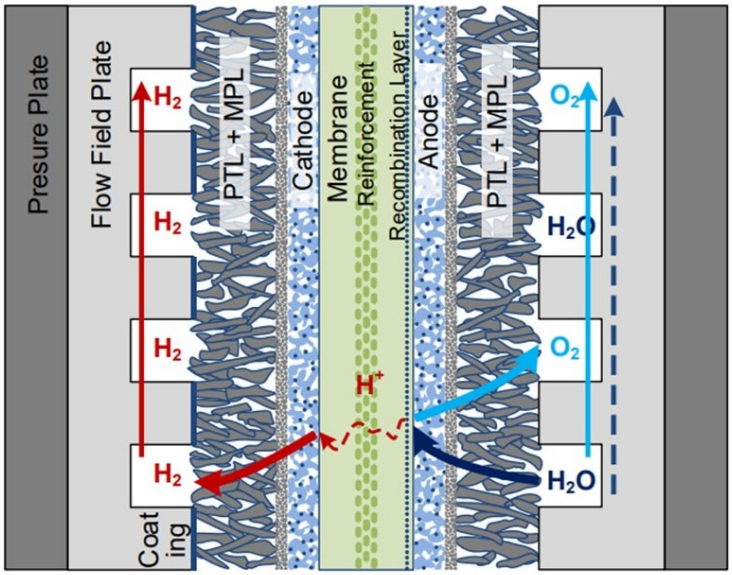

Figure 6. Structure of a PEMWE cell [50].

PEMWE stacks connect multiple single cells electrically in series and hydraulically in parallel, with bipolar plates separating adjacent cells to enhance hydrogen production. The current PEMWE stacks consist of 30-220 cells with an active area up to 1,500 cm², and ongoing development includes prototypes exceeding 2,000 cm². Despite a lower active cell area (5 to 10 times less) compared to AWE stacks, PEMWE stacks achieve a comparable gas production rate due to higher current density. PEMWE stacks generally feature a more compact design, leveraging an ionomer as a solid electrolyte and an electrode arrangement on the ionomer/membrane to effectively prevent mass transport limitations across various current densities. Proton exchange membrane water electrolyzer stacks are predominantly designed for pressurized operation, to ensure gas tightness under high pressures, robust steel end plates are commonly employed within the stack.

The PEMWE system shares a foundational structure with alkaline counterparts but offers simplicity without liquid electrolyte. Varied layouts exist among manufacturers, with pressurized PEMWE falling into balanced pressure and differential pressure systems. Balanced pressure resembles AWE, while in differential pressure, only the hydrogen side operates under pressure, allowing cost-effective components on the oxygen side. A rectifier

supplies DC current, and a circulation pump moves reactant water on the anode side, dissipating heat with a heat exchanger. Heavy metal ions are captured by an ion exchanger to prevent water quality degradation. The gas-water separator removes oxygen, and a demister separates water droplets. A smaller gas-water separator returns water to the anode side. Reactant water is purified for use, and a feed water pump increases pressure. External recoolers cool the anode circuit, and a compression refrigeration machine cools hydrogen. Drying and oxygen removal are vital, with a deoxidizer reactor and pressure or temperature swing adsorption commonly used [55].

2.1.4 Solid oxide Water electrolyzer

Solid oxide electrolyzers operate at elevated temperatures (500-1000°C), allowing for advantageous kinetics with cost-effective nickel electrodes. The high temperatures offer benefits such as decreased electricity demand, utilizing waste heat, and potential reversibility, enabling operation as both a fuel cell and electrolyzer. Moreover, SOWEs can perform co-electrolysis of CO_2 and water to produce syngas, a fundamental chemical industry building block. However, challenges arise from thermochemical cycling, leading to faster degradation, particularly during shutdown/ramping periods. Stack degradation issues include sealing challenges at higher differential pressures, electrode contamination by sealant silica, and additional contaminants from piping, interconnects, and sealing. Presently, SOWEs are deployed at the kW-scale, with some ongoing projects reaching 1 MW. To enhance efficiency, SOWEs can be integrated with heat-producing technologies, leveraging endothermic electrolysis at higher temperatures. This setup allows for reduced energy demand and the utilization of external heat sources, such as waste heat or concentrated solar power, for water vaporization in the electrolysis process. The prospect of coupling SOWEs with concentrated solar power presents a fully renewable option capable of supplying both electricity and the necessary heat for the electrolysis process [40].

2.1.5 Anion exchange membrane water electrolyzer

The latest technology in electrolysis is Anion Exchange Membrane, currently commercialized by only a few companies with limited deployment. AEMWE combines the less harsh environment of alkaline water electrolyzers with the simplicity and efficiency of PEMWE, allowing the use of non-noble catalysts, titanium-free components, and operation under differential pressure. Despite its potential, AEMWE faces challenges such as chemical and mechanical stability issues, resulting in unstable lifetime profiles. Perfor-

mance is slowed down by low AEMWE conductivity, poor electrode architectures, and slow catalyst kinetics. Performance enhancement methods, such as tuning membrane conductivity or adding supporting electrolytes, may compromise durability. AEMWEs share system design concepts with PEMWE, but due to the technology's early stage, there is limited information on challenges related to high differential pressure operation. Anticipated improvements include enhanced mechanical stability, gas purity, and the ability to withstand high pressure differentials, positioning AEMWE as a promising option with a greater power range than alkaline systems, albeit still narrower than PEMWE. The limitation lies in the sizing of the balance of the plant rather than the stack itself [40].

2.1.6 Comparison

Electrolyzers play an important role in the growing hydrogen economy, each technology grappling with unique challenges and offering distinct advantages. The AWE is renowned for its reliability in large-scale hydrogen production for stationary applications. Operating at temperatures between 40-90°C and pressures from 1-30 bar, it utilizes potassium hydroxide as an electrolyte, boasting an efficiency range of 60-77%. AWE's commercial history is marked by its enduring performance, thanks to robust components like a ZrO_2 stabilized with polyphenylene sulfide (PPS) mesh separator and nickel-coated stainless steel electrodes. On the other hand, PEMWEs excel in compactness and quick response, functioning at 50-130°C and pressures below 70 bar with a PFSA membrane. With efficiency ranging from 60-83%, PEMWE's use of iridium oxide and platinum nanoparticles on carbon black electrodes makes it ideal for dynamic applications and integration with renewable energy sources. AEMWEs, operating at 50-70°C and pressures under 35 bar, blend AWE and PEMWE benefits. With efficiency ranging from 50-70%, AEMWEs use high surface area nickel or NiFeCo alloys and nickel foam for oxygen and hydrogen electrodes, respectively, offering an environmentally friendly alternative with broader application potential. Lastly, solid oxide electrolyzers operate at very high temperatures (500-1000°C) and atmospheric pressure, providing versatility as both electrolyzers and fuel cells with an efficiency of up to 100%. While still in early deployment stages, they show promise for integration with heat-producing processes, albeit facing challenges related to thermo-chemical cycling, limiting current prevalence to smaller-scale applications.

Factors influencing the choice of electrolyzer include efficiency, scalability, operating conditions, and cost-effectiveness. AWE remains the preferred choice for established large-scale applications, PEMWE excels in compactness and responsiveness, AEMWE offers an environmentally friendly alternative, and SOWE present high-temperature op-

eration with potential integration into heat-producing processes. Ongoing research continues to optimize each technology for diverse applications as the hydrogen economy evolves. In this landscape, competition and innovation play important roles in driving down costs and enhancing the overall efficacy of electrolyzer technologies. Table 2 offers a comparison of various electrolyzer parameters, while Table 3 outlines the key advantages and disadvantages associated with them.

Table 2. Comparison parameters of different electrolyzers [10, 12, 50, 51, 56–58].

Parameter	AWE	PEMWE	AEMWE	SOWE
System efficiency (%)	60-77	60-83	55-70	Up to 100
Hydrogen purity (%)	> 99.5	99.9999	99.99	$94 < p < 99$
Operating temperature (°C)	40-90	50-130	50-70	500-1000
Current density (A/cm^2)	0.2-0.6	0.6-2.5	0.5-1.5	0.3-2
Operating pressure (bar)	< 30	< 70	< 35	< 15
Cell voltage (V)	1.8-2.4	1.8-2.2	1.8-2.2	0.7-1.5
Stack energy consumption (kWh/Nm^3)	4.2-5.9	4.2-5.5	4.3-5	> 3
Capital cost (USD/kW)	880-1650	1540-2550	714-2000	> 2000
Stack lifetime (kh)	60-120	60-100	5-30	8-20
System lifetime (y)	20-30	10-20	< 20	-
Cold start time (min)	$15 < t < 60$	< 15	< 20	> 60
Degradation per annum (%)	2-4	2-4	-	17
Minimum load (% of design capacity)	15-40	0-10	10-20	> 3

Table 3. Advantages and disadvantages of different electrolyzers [50, 58–60].

Electrolyzer Type	Advantages	Disadvantages
AWE	Mature & developed technology	Slow cold start-up time
	Large system size available (MW range)	Potential electrolyte leakage
	Non noble catalysts	Low partial load range (high minimal load)
	Cost effective (low capital cost)	Low current density
PEMWE	High current density	High cost of components (membrane and catalyst)
	Low minimal load	Medium system size
	Compact system design	Acidic corrosive environment
	Fast cold start-up time and rapid system response	Prone to CO poisoning
AEMWE	Potential to use cheap and abundant materials	Low technological maturity
	Compact designs and small footprint	Medium lifetime
	Suitable for high pressure operation	Extreme sensitivity to CO_2 intrusion
	Reduced energy consumption	High minimal load
SOWE	Efficiency up 100%	Immature technology
	Non noble catalysts	Low durability (brittle ceramics)
	High pressure operation	Bulky system design
	Low minimal load	Low production capacity available

2.2 Energy sources

The selection of energy sources is a crucial aspect in the establishment of an industrial-scale green hydrogen production system. The transition to sustainable hydrogen production involves a careful consideration of various renewable energy technologies to power the electrolysis process. The integration of the energy sources not only influences the environmental sustainability of the process but also affects the economic viability and overall efficiency of hydrogen production. The subsequent subsections will explore specific energy sources, including wind power, solar power, battery energy storage systems (BESS), and the innovative Battolyzer technology. Each energy source brings its unique set of attributes to the table, addressing challenges such as intermittency and enhancing the overall reliability of the green hydrogen production process.

2.2.1 Wind power

Wind power, among the various renewable energy generation technologies, is an ideal one for green hydrogen production due to its abundance, maturity and competitive costs. Wind energy is derived from the movement of air that is caused by air pressure differences and transformed into available kinetic energy. This power is obtained through wind turbines that transform kinetic energy of the wind into mechanical energy. This rotational energy is in turn converted to electrical energy using a generator. Wind energy is one of the most widely spread renewable energy sources nowadays; it is responsible for significant growth of industry. The global production potential for wind energy has seen a gigantic increase, this increase being attributable to the improvements in wind energy conversion systems and developments in power electronic converters.

The power produced by wind turbines is collected by the wind farm collection system and delivered to a central collection point (CCP). Power is sent from the CCP to the main grid via the transmission system. Either AC or DC can be used with this collection system. Power electronic converters still need to be improved upon for DC collection and transmission systems, even with the proven AC collecting methods [61].

- Wind Power

Fundamentally, the main formula of wind power shows the energy possessed by the wind. In this context, wind power can be defined as the speed at which wind energy moves

through a certain region. Th flow rate of the wind could be defined as [62]:

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \rho A U \tag{14}$$

When ρ is air density, A is an area of interest, and U is the velocity.

The kinetic energy of an air stream with mass m and velocity U can be expressed as:

$$E_{\mathrm{K}} = \frac{1}{2} m U^2 \tag{15}$$

By substituting equation 14 into equation 15, the power of wind could be defined as:

$$P = \frac{1}{2} \rho A U^3 \tag{16}$$

This basic principle of wind power demonstrates the dependence between the speed of the wind and the level of power that is produced. Due to the terrain complexity that differs from one terrain type to another, wind speed is largely dependent on roughness [62].

- Wind turbine

A wind turbine is a type of a device that is used to convert wind energy into electricity. There are two main types based on the orientation of their axes: horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) are the two broad categories. HAWTs are conventionally preferred by large and medium power plants because of their high efficiency. VAWTs are mainly employed for domestic and personal purposes and small-scale energy supplies. They are figuring in a low cost, compact and easy-to-install design in comparison with HAWTs [63]. The direction of the rotor with a VAWT is perpendicular to the direction of the wind, therefore allowing it to spin and generate electricity, even at reduced wind speeds. No effort is needed for service or maintenance for VAWTs than for HAWTs. On the other hand, the VAWTs are inept in the sizeable energy generation [64]. Among the advantages of VAW idea over HAWT include the fact that this type of turbine can generate electricity at ground level and its installation is relatively simple.

The horizontal axis wind turbines have been the most common of the large-scale wind turbines for electricity production, as they are the more expensive and require larger installation space when compared to the vertical axis wind turbines. HAWTs have their

rotational axis of the wind direction aligned parallel to the wind while generating more electricity [64]. The wind turbines require lofty towers and large blades, and 20 % of the equipment cost is associated with transportation. Constructing of a HAWT needs a very skilled workforce. However, once the inital investment is made, the cost per electricity unit declines when output is high. HAWTs are better than VAWTs and are hence preferable for areas near the seashore and hills [65]. The vertical axis and horizontal axis wind turbine are shown in Fig. 7 a and b respectively.

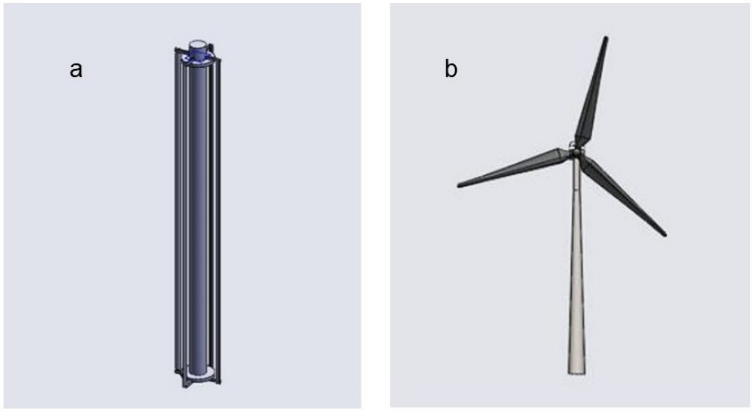

Figure 7. Wind turbine: a. vertical axis, b. horizontal axis [65].

In 2022 the global wind power generation was 77 percent compared to the previous year. 6 GW, resulting in 906 GW power installed capacity and it is 9% more than the last year installment. Additionally, the largest markets contributing to the new installations in 2022 come after in order of China, the United States, Brazil, Germany, and Sweden. Jointly, that number of countries constituted the 71% of world installations, showing a little decrease by 3% [66].

The unpredictability and intermittency of wind power affect wind farm installations [67]. So, as a solution, storage alternatives are taken into account. The use of battery storage through electrochemical mechanisms is already there, yet the issues of long-term capacity, safety, and recycling still need to be solved. One of the examples is compressed air energy storage which is a mechanical energy storage. It is effective, but it needs to be examined in view of safety and efficiency as it has a problem of heat generation and supply demands. Pumped hydro storage, which is the most used one has the main disadvantage of the limited positions to place the underground reservoirs and low efficiency. Lastly, hydrogen storage includes electrolysis to generate H_2 element, which possesses remarkable energy storage capacity and benefits, but more advancement is needed [68].

Wind power storage in the hydrogen reservoir is a very promising choice because of high energy density and environmental benefits. To take advantage of this capability, the process would be that of electrolyzing water to produce H_2 using the electricity produced. As regards the offshore wind farms, the link to water electrolysis for hydrogen production and storage is a matter of the thorough investigation. Different researches, in turn, have focused on this issue to show the best methods to optimize the use of offshore wind energy [69].

In the near future, there will be a trend toward the implementation of novel schemes for the capture of renewables and development of green hydrogen. A hydrogen farm idea can be seen as a solution that should be used to take advantage of the resources that are readily available to produce green hydrogen. Among others, this initiative has three main objectives, namely, to provide long-term solutions and meet the energy needs of different industries and their systems [70].

Recently, research has been conducted in the field of optimizing power-to-hydrogen systems to increase H_2 production and improve profitability. Methods such as linear programming and net present value analysis have been employed to examine the effects of expanding wind farms on the optimal design of these systems [71]. Additionally, other studies have utilized MATLAB simulations to assess the performance of turbines, temporary backup batteries, and electrolyzers. These investigations have identified important points regarding system efficiency under various grid connection conditions by examining different designs of batteries and electrolyzers. Among the interesting observations made, the significant impact of storage on the levelized cost of hydrogen and the importance of scalability factors such as increasing the scale parameter for improving hydrogen production and reducing costs have been highlighted [72]. Furthermore, sustainability studies in specific regions have looked into the effectiveness of various wind turbine models for hydrogen production, providing significant insights for local energy strategies [73].

Wind power for green hydrogen production represents a promising convergence of renewable energy technologies. By leveraging wind energy to produce hydrogen, a sustainable, carbon-free energy carrier can be created, addressing both energy and environmental challenges. While there are obstacles to overcome, the potential benefits make this a pivotal area for future energy strategies. As technology advances and costs decrease, the integration of wind power and green hydrogen will play a crucial role in the global transition to a sustainable energy future.

2.2.2 Solar power

Solar power, a key renewable energy source, holds promise for large-scale green hydrogen production by converting sunlight into electricity through photovoltaic cells. This electricity powers electrolyzers, initiating hydrogen production. The pursuit of affordable, abundant, and environmentally friendly energy is crucial for enhancing quality of life. As global attention shifts from depleting fossil fuels, solar power, currently at less than 4.5% of global electricity production [74], emerges as a promising solution. Despite its current higher cost, solar energy is seen as practical for decentralized power generation, especially in remote regions. Projections from the International Energy Agency suggest solar photovoltaic (PV) systems could contribute up to 16% of global electricity by 2050 [75]. Fig. 8 illustrates passive and active solar energy technologies, utilizing sunlight and heat directly or converting solar energy, respectively. Solar cells, utilizing the photoelectric effect in

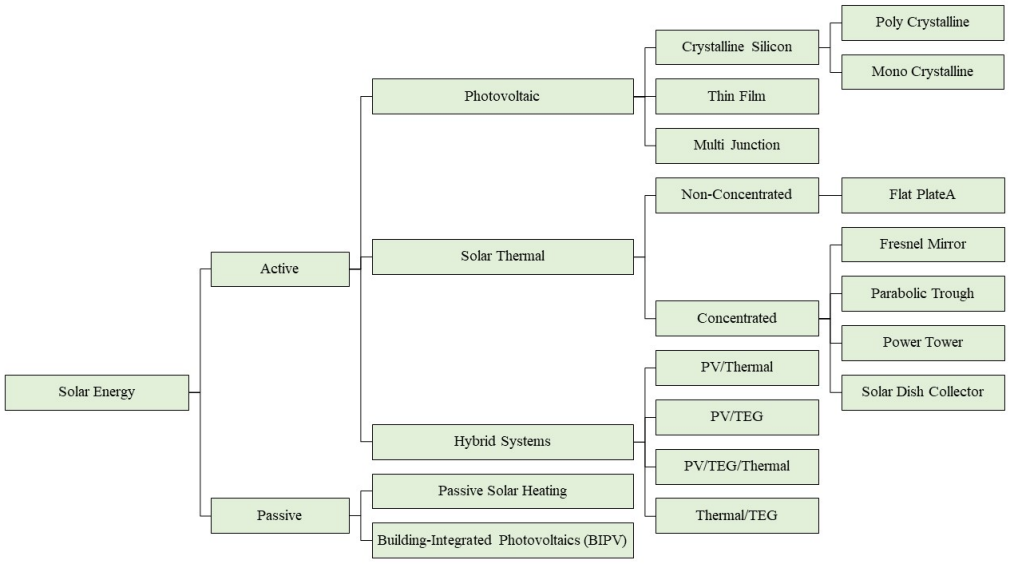

Figure 8. Most available solar energy technologies [76–79].

semiconductors like silicon and selenium, convert sunlight into electricity. Commercial photovoltaic cells typically achieve 16-26% efficiency under optimal conditions [80, 81]. Photovoltaic systems operate on the principle of the photovoltaic effect, where sunlight creates an electric current. Solar panels consist of interconnected cells arranged in series and parallel configurations to increase voltage and current.

To overcome the impractical voltage of a single PV cell (0.5V), cells are connected in series, and multiple series are grouped in parallel for increased current capacity [65]. The solar PV system includes essential components: a PV module, maximum power

point tracking (MPPT) technology, DC-DC converter, and inverter. Maximum power point tracking optimizes power extraction, and a DC-DC converter addresses intermittent power. Storage elements like batteries enhance consistent power supply. An inverter converts DC to AC for AC loads and grid connections [82]. Challenges include low conversion efficiency and dependency on atmospheric conditions, but suitable converters and MPPT techniques can improve overall system performance [83]. The solar PV system configuration is depicted in Fig. 9. Concerns about hydrogen, including lower en-

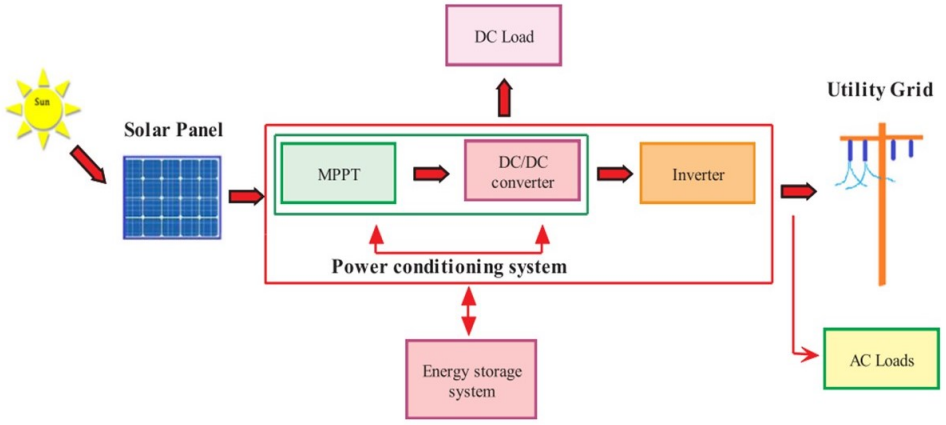

Figure 9. Solar PV system configuration [84].

ergy density, high costs, infrastructure investments, and greenhouse gas emissions during manufacturing, are being addressed by the decreasing cost of solar electricity [85].

In the quest for sustainable energy, harnessing solar power for hydrogen generation has emerged as a promising avenue. Researchers have explored diverse approaches to integrate renewable solar energy with hydrogen production, emphasizing the economic feasibility of transitioning to solar PV-generated electricity through grid-connected alkaline water electrolysis [86]. Additionally, the integration of wind energy and solar PV systems for water electrolysis has been studied, highlighting the location-specific nature of efficiency analyses [87]. Various renewable-based hydrogen production techniques have been compared, incorporating both solar PV and solar thermal energy [88]. Insights into hydrogen utilization from different technologies have contributed to a broader understanding of this evolving field [89, 90].

Solar hydrogen production relies on decoupled PV-electrolysis systems, with silicon-based PV cells, the majority of current production, becoming more cost-effective. However, the estimated cost of green hydrogen from silicon-based PV-electrolysis remains relatively high, ranging from €2.2 to €6 per kilogram, influenced by various factors.

Despite approaching the efficiency limit, silicon PV cells' efficiency impacts solar hydrogen production, posing challenges for widespread commercial deployment. Nevertheless, PV-based hydrogen production remains environmentally friendly, with no greenhouse gas emissions or noise pollution and simplified maintenance [91].

2.2.3 Battery energy storage system

In the domain of green hydrogen production, which heavily relies on intermittent renewable sources like wind and solar, the integration of battery energy storage system emerges as an important solution. The challenges posed by the intermittency of renewable energy can be effectively mitigated by BESS, which stores excess energy during periods of high renewable output and releases it during low output, ensuring a consistent and reliable power supply for hydrogen production processes [92, 93].

Beyond addressing intermittent energy management, the incorporation of BESS into green hydrogen production facilities offers additional advantages. Acting as a buffer during peak demand periods, BESS provides grid support, reducing stress on the electrical grid. Through the process of peak shaving, BESS optimizes energy consumption, ensuring the efficient operation of green hydrogen production facilities.

The enhancement of electrolysis, a crucial process in green hydrogen production, is another facet where BESS proves invaluable. By providing a stable and continuous power supply, BESS ensures that electrolyzers operate at their optimal efficiency, ultimately leading to reduced energy consumption associated with hydrogen production. This optimization is particularly significant in positioning green hydrogen as a competitive alternative to traditional, carbon-intensive hydrogen production methods.

The synergy between battery energy storage system and green hydrogen production extends to the concept of hybrid energy systems. The integration of BESS with renewable energy sources and electrolysis facilities creates a holistic approach to energy management. Moreover than efficiency, through the optimization of energy use, reduction of grid stress, and improvement of overall system stability, BESS contributes significantly to a smaller carbon footprint associated with green hydrogen production [94].

In parallel, efforts to address power availability concerns involve the hybridization of electrolyzer power supply technologies, combining wind and solar PV to enhance the electrolyzer load factor. This approach minimizes power supply variability, diminishing the

need for expensive intermediate hydrogen storage. Configurations incorporating energy storage systems, as demonstrated in various studies, highlight the potential for low-cost PV and batteries to eliminate the necessity for wind electricity in specific regions for green ammonia production depending on the cost structures involved. While the future role of BESS in green hydrogen production remains uncertain, ongoing studies explore various joint configurations of solar PV, energy storage, and electrolyzer systems, often in microgrid contexts. These endeavors aim to maximize hydrogen production efficiency. The utilization of hybrid PV-BESS electrolyzer systems not only ensures reliable electrolyzer power but also contributes to grid stability and economic operation, aligning with green hydrogen criteria. Despite the traditional reliance of green hydrogen on exclusive on-site renewable energy sources, future plants connected to the grid should avoid grid energy purchases to maintain their green status [94].

2.2.4 Battolyzer

Electrolyzer technology currently grapples with high costs and is not optimized for intermittent operation [94]. In response to these challenges, researchers are exploring a promising alternative known as the battolyzer. Functioning initially as a battery, the battolyzer stores electricity until fully charged and then transitions to hydrogen gas production. This innovative device, capable of seamlessly generating both electricity and hydrogen, holds the potential to enhance economic viability in the energy sector.

The integrated battery and electrolyzer concept operates by leveraging the battery's functionality for electricity storage. During periods of surplus renewable electricity, the battery charges efficiently, and during deficits, it discharges. This approach allows for the direct storage of electricity with high power-to-power efficiency. Once the battery reaches its designed capacity, excess electricity is used to produce hydrogen, eliminating capacity restrictions. While hydrogen storage incurs efficiency losses compared to battery storage, it becomes indispensable for seasonal energy storage, providing a compelling case for integrating short-term battery storage with long-term hydrogen fuel storage [95].

The practical implementation of the battolyzer involves a high-level concept illustrated in Fig. 10. The device comprises an electrochemical cell with electrodes and a separator. The electrolyte, common or different for electrodes based on cell chemistry, circulates for battery action and to remove electrolysis products. The separator, while preventing plate contact, also ensures there is no cross-contamination of hydrogen and oxygen. Despite their potential, battolysers are still in their early stages, with limited research since their

2017 inception [96].

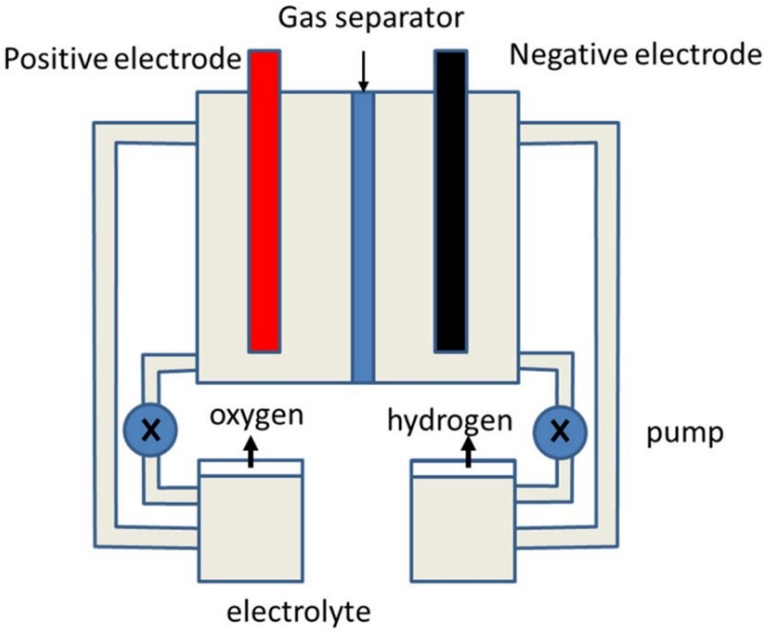

Figure 10. Schematic view of a battolyzer [97].

Integrating batteries and electrolyzers into single units offers the advantage of reducing grid infrastructure burden and enabling more flexible power management at a singular site. Battolyzers can effectively respond to electricity fluctuations caused by renewable generation or consumer demand, accommodating various charge and discharge rates. Operating continuously, they efficiently store surplus electricity and produce hydrogen or electricity during deficits. The device outperforms separate battery and electrolyzer units in terms of utilization and capacity factor. While independent units face low utilization, the battolyzer, using a single system, proves economically favorable [95].

2.3 Efficiency in green hydrogen production

The efficiency of a green hydrogen production facility, measured in kilowatt hours per kilogram of hydrogen, is influenced by the performance of its cell, stack, and balance of plant components. The cell's efficiency decreases linearly with higher load levels, and prolonged operation results in reduced efficiency due to degradation. The cell voltage, a key performance indicator, is inversely related to stack efficiency. AWE and PEMWE technologies operate at different power density ranges, affecting their respective footprints.

The balance of plant, which includes components like cooling, purifiers, and gas separation, also plays a role in overall power consumption. Strategies to minimize efficiency losses involve a comprehensive facility design, the use of commercially available components, and optimization for specific applications. Rectifiers, crucial in the balance of plant, demonstrate improved efficiency at higher loads, suggesting the potential use of a single rectifier for multiple stacks to enhance overall efficiency, especially in facilities of 20 MW or larger.

Efficiency dynamics display unique characteristics, with low efficiency at very low loads, a progressive increase up to a 30% load, and subsequent decline. This differs from thermal power plants, underscoring the need for a tailored operational strategy. Operating at a lower-than-design load offers higher efficiency in some technologies (this does not apply to AWE), but reduces hydrogen production, creating a tradeoff between capital and operational costs. Compressors, storage, and subsequent stages in the hydrogen supply chain have an impact on overall efficiency, highlighting the importance of minimizing conversion stages for higher efficiency in converting renewable power to consumed hydrogen.

The efficiency of electrolysis techniques varies based on the specific process employed. Alkaline water electrolyzer, for instance, is influenced by factors like electrolyte concentration and system temperature. It typically operates with an efficiency ranging from 70% to 80%, implying that approximately 20% to 30% of the energy input dissipates as heat. In contrast, proton exchange membrane water electrolyzer can attain efficiencies of up to 85%. Additionally, the efficiency of green hydrogen production hinges on operating conditions and scale [10, 51].

When it comes to the efficiency of green hydrogen production as a whole, many things are taken into consideration, including hydrogen production, hydrogen storage and transfer, and hydrogen utilization. For instance, in a recent study [98], researchers investigated the efficiency of transforming renewable energy into electricity using hydrogen as an energy carrier. They analyzed various stages of the process, from electrolysis to hydrogen utilization in power plants. Findings revealed that alkaline water electrolysis achieves an efficiency of about 70%, while proton-membrane systems can reach up to 85%. Additionally, the study highlighted the challenges of utilizing hydrogen as a fuel in power plants and proposed solutions, such as using hydrogen-methane mixtures. Finally, the study estimated the real efficiency of transforming renewable energy via hydrogen in combined cycle power plants to be approximately 38%, highlighting potential avenues for enhancing system efficiency.

3 ECONOMIC ASPECTS OF GREEN HYDROGEN

This chapter investigates the economic aspects of large-scale hydrogen production, emphasizing not just technical considerations. Despite PEM and alkaline water electrolyzers being established in the market, their significant costs, both in terms of initial investment and operational expenses, pose challenges compared to fossil fuel-based methods. PEMWE, in particular, are 50%-60% pricier than alkaline counterparts, hindering market adoption. AEMWE and SOWE face even greater cost barriers, with limited commercialization and experimental components. The analysis explores the cost structure, identifies crucial factors, and proposes cost reduction strategies for industrial-scale green hydrogen production. Attention is also given to hydrogen supply and demand dynamics, contributing to a comprehensive understanding of market forces. The examination calculates the LCOH and final price, assessing the economic feasibility and competitiveness of large-scale green hydrogen production. The chapter concludes with a global perspective on major electrolyzer manufacturers, with a primary focus on AELWE and PEMWE due to their maturity and available data.

3.1 Cost components

Research indicates notable diversity in the expenses associated with electrolyzer systems, underscoring the difficulty in identifying representative figures for both capital and operational costs [92]. Consequently, these costs are established by amalgamating the anticipated total costs of green hydrogen with estimates delineating the breakdown of electricity costs, capital expenditures (CAPEX), and operating expenditures (OPEX). Fig. 11 provides a visual representation of the current cost breakdown estimates for green hydrogen for operational hours in the range of 5000 to 6000 h/a.

Presently, the predominant factor influencing system expenses continues to be the stack, constituting 40%-50% of the total costs in both AWE and PEMWE. This proportion is significantly contingent on factors such as design, manufacturing approach, business rationale, and customer specifications. The primary cost drivers for electrolyzers encompass:

Stack: The stack, the primary cost driver for available electrolyzer technologies (AWE and PEMWE), primarily comprises cell units, porous transport layers, bipolar plates, end plates, and various smaller components (e.g., spacers, seals, frames, and bolts) [94]. The

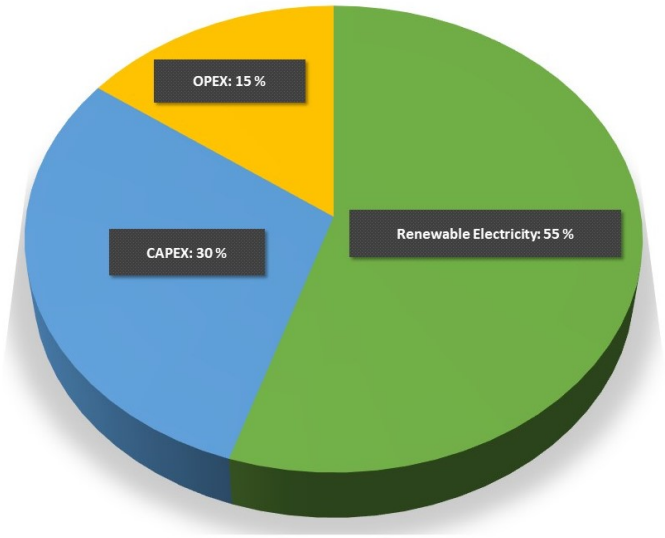

Figure 11. Cost breakdown estimates for green hydrogen [40, 58, 99].

cell unit itself, essential for the core electrochemical process of water splitting, typically includes the membrane with catalyst layers coated as electrodes (in PEMWE) and electrodes with diaphragms (in AWE).

Power electronics: Power electronics involve the application of solid-state electronics for controlling and converting electric power. While generally used for connecting renewable energy systems to the grid, in electrolyzer systems, the main role is to convert alternating current from the network to the direct current required by the electrolysis cell stack [100]. The hydrogen yield from a water electrolyzer corresponds directly to the average DC current applied to its electrodes. Industrial-scale systems require kiloampere-range currents at relatively low voltages, necessitating robust high-power rectification units to convert AC grid electricity. These units, which represent a significant cost component, highlight the pivotal role of power electronic converters in this domain. Exploring higher voltage operation could improve both energy and cost efficiency. Multi-pulse thyristor rectifiers serve as the standard choice for high-power, high-current AC-DC conversion, despite drawbacks such as low power factor and harmonic generation. These rectifiers are essential for linking electrolyzer systems to the AC grid and enabling power flow control. However, this study does not address the performance and modeling of alternative topologies, such as the 6-pulse thyristor rectifier, 12-pulse thyristor rectifier, and IGBT-based buck-rectifier, commonly used in industrial-scale applications [101].

Gas conditioning and separation: Gas conditioning in electrolyzers involves mechanically compressing gas to a specified storage pressure and drying the gas to purify raw hydrogen. Gas separation, on the other hand, is a critical process to remove impurities

and separate hydrogen from other gases such as oxygen and nitrogen, ensuring the hydrogen meets purity standards. Depending on technological advancements, hydrogen is purified to 99.5–99.9999% and compressed to over 50 bar for facilitated storage [102]. Despite its crucial role in the hydrogen generation process, this stage appears to be the least costly among the four main components in each of the reviewed electrolyzer types.

Balance of plant: The balance of plant system constitutes the remaining portion of key electrolyzer costs. Typically encompassing components such as heat recovery and rejection equipment, material transport systems (e.g., pumps, valves, and piping), control and safety systems, waste collection and disposal systems, equipment for maintenance and repair, as well as heating, cooling, ventilation, air conditioning, power supply, and distribution [103].

In alkaline water electrolyzers, as depicted in Fig. 12, electrodes and diaphragms within the stack contribute to over 50% of the overall costs, a notable contrast to the 25% allocated to the catalyst-coated membrane (CCM) in proton exchange membrane water electrolyzers. The manufacturing of electrodes incurs substantial expenses, wherein the principles of learning-by-doing, process automation, and economies of scale play important roles in potential cost reduction. In contrast, bipolar plates in AWE stacks constitute a minor portion of the stack costs, contrasting with PEMWE stacks where they surpass 50%. This discrepancy is attributed to the simpler design, uncomplicated manufacturing processes, and cost-effective materials, such as nickel-coated steel, employed for bipolar plates in alkaline stacks [104, 105].

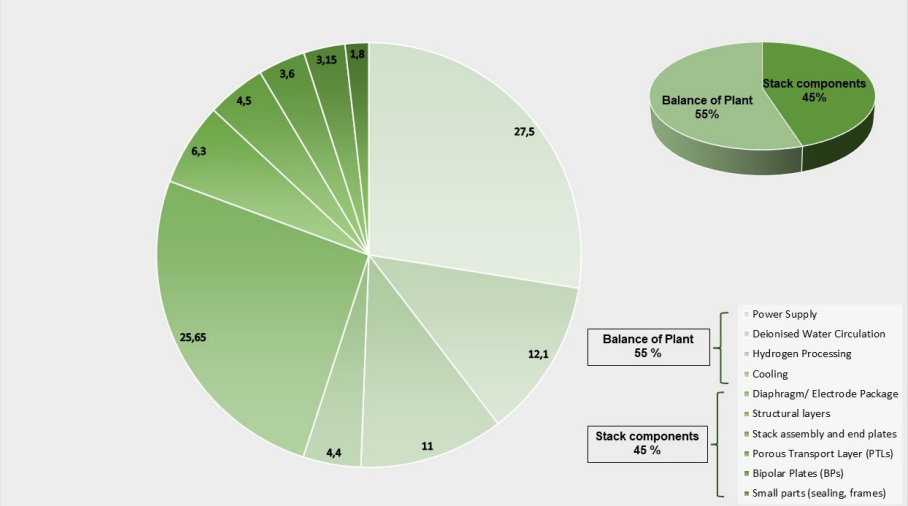

Figure 12. Cost breakdown for 1 MW AWE [40].

In PEMWE stacks, bipolar plates emerge as a significant cost factor, often designed to

serve multiple functions and necessitating advanced materials like iridium or platinum-coated titanium [106]. This aspect presents an opportunity for innovation to contribute to both performance and durability enhancements, along with potential cost reductions. Ongoing research focuses on substituting titanium with more economical materials, relying on the coating to retain its functional characteristics while mitigating costs. Within the stack's core, the CCM incurs notable costs, primarily due to rare metals. However, when viewed in the broader perspective, these metals constitute less than 10% of the total cost of a proton exchange membrane water electrolyzer system. Notably, for iridium, there is a potential bottleneck in scaling up PEMWE manufacturing if a significant increase in iridium supply is not concurrently realized [40]. Fig. 13 shows cost breakdown for a 1 MW PEMWE.

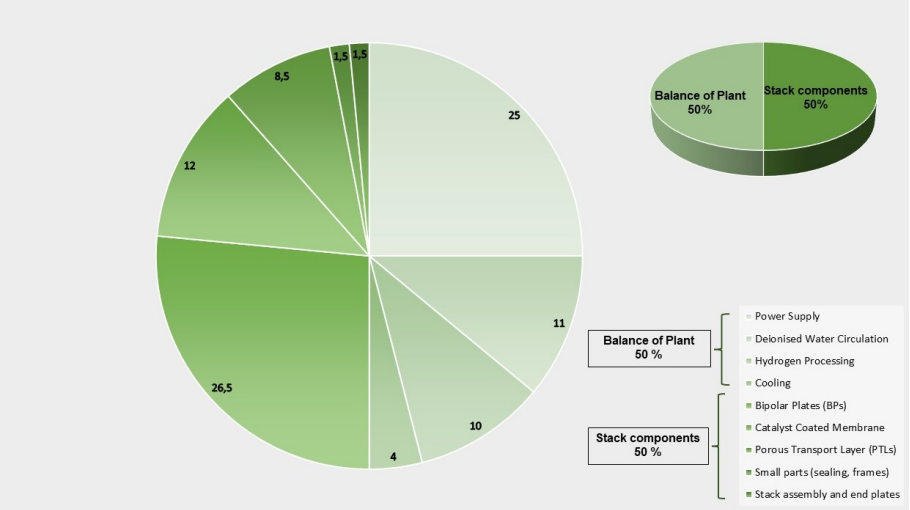

Figure 13. Cost breakdown for a 1 MW PEMWE [40].

In some other analyses, the cost structure has been compared according to the capacity of the electrolyzer. With the escalation of electrolyzer capacity from 1 MW to 100 MW, there is a consistent rise in the contribution of the stack. Conversely, the proportion of other cost components exhibits a diminishing trend. The alterations in the distribution of components for alkaline and proton exchange membrane water electrolyzers are visually depicted in Fig. 14 and Fig. 15 respectively.

3.2 Cost reduction options

While a significant decrease in the cost of electricity utilized for electrolysis is generally recognized as the primary requirement for enhancing the competitiveness of 'green' hy-

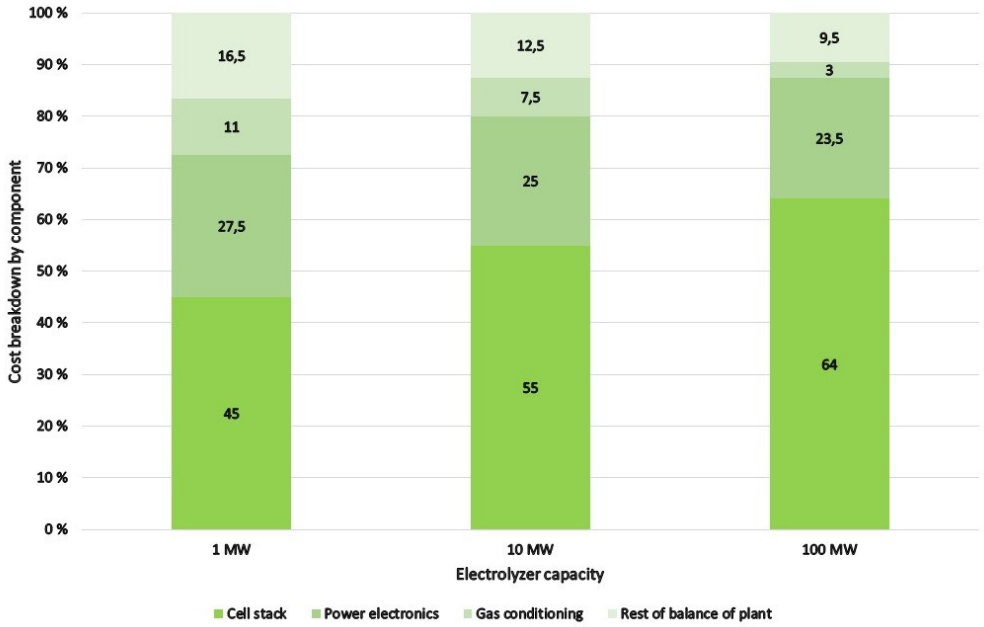

Figure 14. Cost breakdown by major component for different capacities of AWE [58].

drogen, it should not be regarded as the sole factor in the overall cost reduction process essential for power-to-hydrogen technologies to effectively rival hydrocarbon-based H_2 production [107]. Currently, the costs of green hydrogen are at least two or three times higher than those of blue hydrogen. Although the progressively declining costs of renewable power contribute to narrowing this disparity, careful consideration should be given to further reducing the costs associated with electrolyzers; the second most substantial expense (Table 4).

Table 4. Potential improvement for AWE and PEMWE technologies [3, 58, 108–110].

Goals			AWE	PEMWE
Decreased energy consumption per unit	KWh/kgH_2	Current	50–78	50–83
		Aimed	< 45	
Increased stack lifetime	h	Current	60-10000	50-90000
		Aimed	> 100000	100000-120000
Increased module and stack size	MW/unit	Current	5-10	1-5
		Aimed	10-100	5-10
Broadened load range (lower minimum and higher maximum load)	%	Current	15-100	5-120
		Aimed	5-300	5-300
Minimization of the use of scarce materials	-	Current	Pt, Ru, W	Ir & Pt
		Aimed	Elimination	Minimization
Typical start-up time (cold)	min	Current	30–60	15-28
		Aimed	< 30	< 15
Increased scale of production of electrolyzers	GW/year	Current	> 0.04	0.01-0.04
		Aimed	> 1	
Decreased average stack cost	€/kW	Current	295-490	435-950
		Aimed	100	

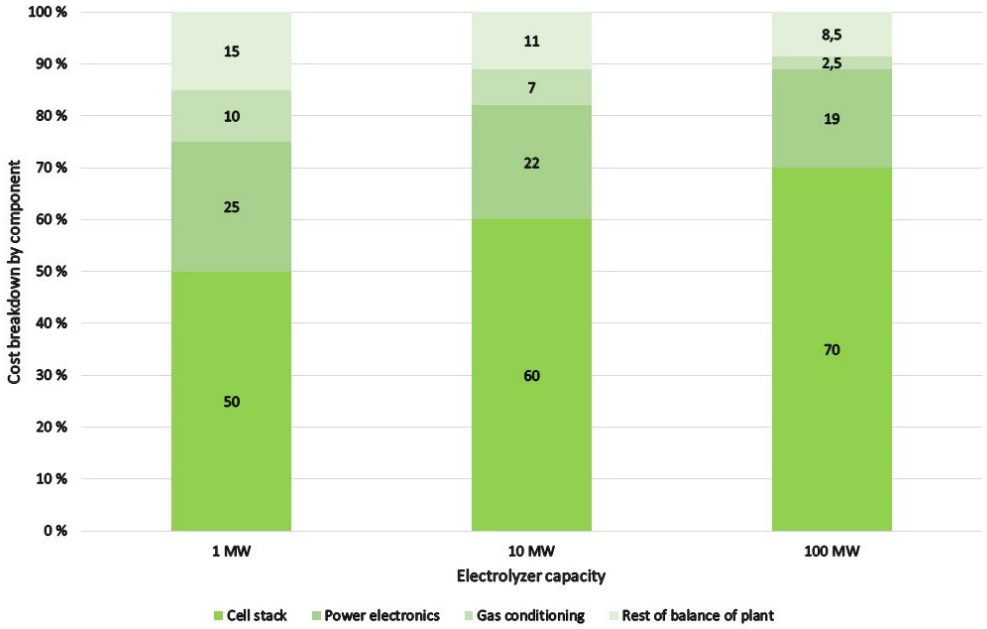

Figure 15. Cost breakdown by major component for different capacities of PEMWE [58].

3.2.1 Cost reduction in long term

Electricity constitutes the primary expenditure in on-site green hydrogen production, and strides are being taken to usher in a era of more affordable renewable energy. It is important to redirect attention towards addressing the second most substantial cost factor: electrolyzers. By concurrently diminishing costs associated with both electricity and electrolyzers, while enhancing efficiency and extending operational lifetimes, there lies the potential for achieving a noteworthy 80-85% reduction in the overall cost of hydrogen. The visualization in Fig. 16 illustrates the significant prospect of cutting up to 85% of production costs for green hydrogen in the foreseeable future [3, 40].

Cost-cutting approaches encompass a spectrum of measures, spanning from the foundational design of the electrolyzer stack to more expansive system-wide components.

3.2.2 Opportunities for cost reduction

While technological progress has been actively pushing down the costs of renewable electricity for a number of decades, the full potential for reducing the costs of electrolyzers in a similar way is yet to be properly estimated. There are several technical aspects, improving which could make electrolyzers, and consequently green hydrogen, more competitive on

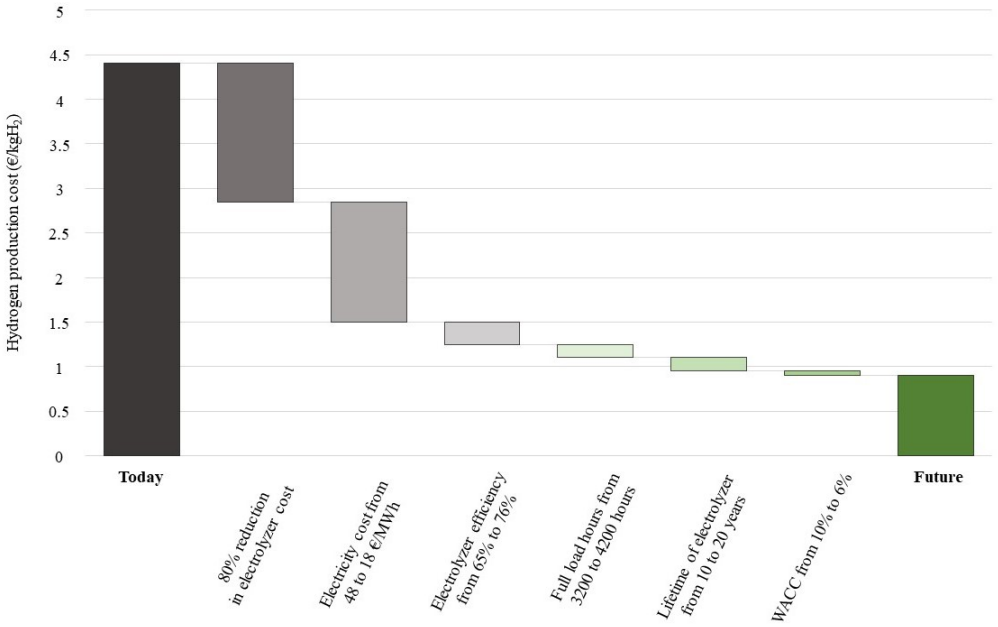

Figure 16. Cost reduction for green hydrogen production in long term [40].

a global market. These aspects generally include energy consumption per unit of production, stack lifetime, stack size, load range, start-up time, electrolyzer's scale of industrial production, and use of scarce materials. Given that each electrolyzer technology is currently at a different stage of improving these features, it is useful to compare their current characteristics with the ultimate targets.

- Energy consumption per unit of production

Reducing the share of electricity costs in 'green' hydrogen production, which can be as high as 73%, is crucial for cost reduction. Enhancing the electrical efficiency of electrolyzer systems is key to lowering the energy consumption per unit of hydrogen produced. While it's challenging due to energy-intensive processes, optimizing efficiency is vital. Alkaline water electrolyzers, with energy consumption between 50 and 78 kWh per kg of H_2, generally outperform proton exchange membrane water electrolyzers. High-pressure AWEs, though saving energy by eliminating the need for an external H_2 compressor, may compromise gas purity and require additional energy for pressurization. PEMWEs, operating at higher pressures, offer safety benefits but consume more electricity per kg of hydrogen. Improving the electrical efficiency of PEMWEs could lead to further cost reduction [111, 112].

- Stack lifetime

Extending the lifespan of electrolyzers is crucial for reducing the cost of hydrogen production. AWEs currently lead in durability, with a stack lifetime of 60,000 to 100,000 hours and proven system longevity exceeding 30 years. Factors affecting their lifespan include gas permeation, nickel alloys, and water impurities. Addressing these factors would enhance durability, positively impacting the cost of 'green' hydrogen. PEMWEs, with a reported lifespan of 50,000 to 90,000 hours, lag behind alkaline systems due to factors like operating conditions, variable load, and gas permeation. Overdesigning stacks to handle these challenges increases PEMWE costs, highlighting the need for cost-efficient improvements to promote wider adoption of PEMWE technology.

- Load range

Renewable energy sources, like wind and solar power, exhibit significant daily and seasonal variations. Electrolyzers operating in intermittent load conditions must have a wide load range to accommodate changes affecting temperature and pressure. Each electrolyzer type has optimal temperature and pressure characteristics, and using variable power that cannot sustain these conditions reduces the efficiency of hydrogen production. This challenges the competitiveness of green hydrogen against fossil-based systems, leading to increased costs [113].

Lower loads result in heat underproduction, making it difficult for electrolyzer to reach optimal temperature. Balancing plant components, with constant energy demand, contributes to higher energy consumption per kg of H_2 at loads below 30% of nominal power. Electrolyzer systems with greater tolerance to lower loads are more suitable for power-to-hydrogen production, as they experience fewer efficiency losses [114].

Currently, alkaline water electrolyzers, with a minimum acceptable load of around 15%, require further improvement in load range compared to the more favorable proton exchange membrane water electrolyzers, which tolerate a minimum load of around 5%. Most AWEs, due to their relatively high minimum load, need complete shutdown, depressurization, and flushing when insufficient electricity is provided, unlike PEMWEs [115].

- Start-up time

Alkaline electrolyzers, having been in existence for around a century, are the most established power-to-hydrogen technology among various water electrolysis systems. Originally designed for stationary applications with grid connections, they faced challenges with the increasing use of intermittent power sources from renewable energy. To address this, pressurized alkaline electrolyzers were introduced [116].

Despite improvements, alkaline water electrolyzers still face limitations for low-load operation compared to proton exchange membrane water electrolyzers. PEMWE, which require only a few minutes to reach optimal operating temperature, have a notable advantage in terms of quick start-up time. However, it is important to note that PEMWE cools down faster than AWE, which impacts their performance under variable power supply conditions [117].

- Procurement of materials

Material procurement presents a challenge for electrolyzer cost and scale-up, especially with scarce resources. The current production of iridium and platinum for PEMWEs supports only an estimated annual manufacturing capacity of 3 GW-7.5 GW, falling significantly short of the projected 100 GW requirement by 2030. AWE manufacturers are addressing this challenge by eliminating the need for scarce materials. Moreover, technologies exist to significantly reduce material requirements in PEMWEs. In contrast, AEMWEs do not rely on scarce materials from the outset.

- Scaling-up (sizing-up) of components

In the domain of electrolyzer systems, the strategic scaling up of components, particularly through enlarging module sizes, profoundly influences economic considerations. Challenges tied to increasing stack size, such as leakage and manufacturing constraints, highlight its limited scalability [3]. In contrast, the balance of plant demonstrates strong economies of scale, exemplified by the cost-effectiveness of larger components like compressors. Scaling stack production to GW-scale facilities yields substantial cost reductions, with the stack's contribution diminishing at higher production rates. Standardizing components and plant design emerges as a vital strategy for cost efficiency. Embracing economies of scale, enlarging stack size or mass-producing standard-sized stacks holds promise for reducing the unit cost of hydrogen production. Estimates suggest notable cost reductions through plant scaling, particularly benefiting the balance of plant, power electronics, and gas conditioning components [58]. However, technological limitations associated with increased stack size present challenges, creating a pronounced economy of scale effect for remaining components. In essence, the complex dynamics of scaling up components play a crucial role in shaping the economic viability of electrolyzer systems.

- Increasing production volumes (numbering-up)

Expanding electrolyzer plant production cuts costs significantly. Higher volumes reduce building and equipment costs, making automation cost-effective. Scaling from

10 MW/year to 1 GW/year yields a 70% reduction in stack cost. Full automation at 2 GW/year offers a 90% cost reduction, with advanced coating technologies playing a crucial role. Frame manufacturing sees an 85%-90% cost reduction at 1 GW/year. Components with rare materials achieve a 45%-55% cost reduction, dominated by platinum, iridium, membrane, titanium, and gold costs. In the balance of plant, a production increase from 10 MW/year to 1 GW/year leads to a 40% cost reduction. Deionized water circulation and cooling systems achieve the most significant reductions (50%-60%), while power supply and hydrogen processing costs only reduce by about 30% [58].

- Efficiency and flexibility in operations

Low-load efficiency losses in power supply restrict system flexibility economically. To overcome this, a modular plant design with multiple stacks and power supply units is recommended. In addition, compression may pose a flexibility bottleneck, as it might not adjust its production rate as swiftly as the stack. An alternative solution involves an integrated plant design with sufficient capacity, optimized for handling production variability through integrated electricity and hydrogen storage [50].

- Learning rate

The concept of learning-by-doing, synonymous with innovation through production and market competition, impacts the cost decrease in green hydrogen production. The learning rate signifies the cost reduction percentage when production doubles. To enhance this rate, strategies include standardization, specialization, and simplification in electrolyzer technologies. Electrolyzers, complex systems with varying learning rates for each component, affect cumulative learning rates for power-to-hydrogen systems [118]. Alkaline water electrolyzer leads with learning rate of 16±8% (8-24%), while proton exchange membrane water electrolyzer lags slightly at 9±2% (7-11%). No electrolyzer technology excels in all categories, but AWEs and PEMWEs, with average stack costs of 295-490 €/kWh and 435-950 €/kWh, respectively, are closer to competitiveness for green hydrogen production [119].

3.3 Demand and supply

Growing hydrogen applications will drive future demand. Currently vital for the chemical industry, hydrogen is used in ammonia, methanol, and refineries. To decarbonize, zero carbon hydrogen from electrolysis and carbon capture must replace steam methane

reforming (SMR) and autothermal reforming (ATR) produced hydrogen. New industrial uses, especially in hard-to-abate sectors like steel, will further boost sustainable hydrogen demand. In mobility and industrial heating, adoption depends on technological developments, regulations, and subsidies. While battery electric vehicles dominate, hydrogen may play a role in heavy goods vehicles. Sustainable hydrogen's role in heating hinges on political intervention and subsidies, competing with other alternatives [59].

The EU's July 8, 2020, hydrogen strategy aims for a climate-neutral Europe. Targets include 6 GW and 40 GW electrolyzer capacity by 2024 and 2030, respectively, with production goals of 1 million and 10 million tons of renewable hydrogen per year. Reaching these targets requires significant investments and potential importation. Hydrogen is viewed as a key vector, with the clean hydrogen alliance facilitating collaboration and project pipelines. The "next generation EU" recovery plan prioritizes hydrogen investment, contributing to economic growth and leadership goals, with a total fund of EUR 750 billion [40].

3.4 LCOH and final hydrogen price

Determining the cost of a kilogram of green hydrogen is complex and hindered by limited production disclosure. Analysts use models focusing on signed contracts or public data, often overlooking storage and transportation expenses. Factors like electrolyzer type and energy source influence pricing, with lower costs tied to Chinese alkaline electrolyzers. However, applicability in Western markets is constrained by limited Chinese exports. While models offer centralized views on daily hydrogen costs using market prices, individual production costs vary among companies, complicating price calculations.

3.4.1 Calculation method

Many studies have conducted LCOH calculations, and although the fundamental principles guiding these scenarios have remained consistent, each study has utilized its own methodology.

In one model [120], which considers an off-grid green hydrogen production system consisting of an alkaline water electrolyzer, a battery energy storage system, and solar PV and wind installations for renewable power generation, the economic performance of the hydrogen production plant has been evaluated using the levelized cost of hydrogen. The

LCOH is calculated as the total annualized cost divided by the annualized hydrogen production:

$$\text{LCOH} = \frac{\sum_{i=1}^{N} \frac{I_i + O_i - R_i}{(1+r)^i}}{\sum_{i=1}^{N} \frac{m_{H_2,i}}{(1+r)^i}} \tag{17}$$

In this model, I_i represents the total investments, O_i the total operational costs, R_i the revenue income, $m_{H_2,i}$ the total hydrogen production, and r the discount rate. Each term is calculated for each year i over a simulation period of $N = 30$ years. The discount rate is set at a reasonable 3%. The costs of replaced components are allocated to the annualized investment costs in the year the replacement occurs. Both the solar PV and wind power generation installations are assumed to have a lifetime of 30 years.

In another model, which only considers a system consisting of an alkaline electrolyzer and a solar PV system, the LCOH has been determined by summing the electricity and electrolysis costs and dividing by the utilization rate. [121]:

$$\begin{aligned} \text{LCOH} = & \frac{\text{CAPEX}_{\text{PV}} + \frac{\text{InvRepl}}{(1+\text{WACC}_{\text{nom}})^{0.5\times N}} + \sum_{t=1}^{N} \frac{\text{OPEX}_{\text{PV}}(t)}{(1+\text{WACC}_{\text{nom}})^t}}{\eta \times \sum_{t=1}^{N} \frac{\text{Yield}(0)\times(1-\text{Degr})^t}{(1+\text{WACC}_{\text{real}})^t}} \\ & + \frac{\text{CAPEX}_{\text{el}} + \frac{\text{StackRepl}}{(1+\text{WACC}_{\text{nom}})^{20}} + \sum_{t=1}^{N} \frac{\text{OPEX}_{\text{el}}(t)}{(1+\text{WACC}_{\text{nom}})^t}}{\eta \times \sum_{t=1}^{N} \frac{\text{FLH}(0)\times(1-\text{Degr})^t}{(1+\text{WACC}_{\text{real}})^t}} \end{aligned} \tag{18}$$

In the given context, where N represents the economic lifetime of the system and t denotes the year number ranging from 1 to N, the variables are defined as follows: CAPEX_{PV} is the capital expenditure of the PV system at $t = 0$ in €/kWp, InvRepl is the cost of inverter replacement made at $t = \frac{N}{2}$ in €/kWp, $\text{OPEX}_{\text{PV}}(t)$ is the operation and maintenance expenditure of the PV system in year t in €/kWp, $\text{Yield}(0)$ is the initial annual PV yield in year 0 in kWh/kWp without degradation, Degr is the annual degradation of the nominal power of the system, η is the electrolyzer efficiency, CAPEX_{el} is the capital expenditure of the electrolyzer system at $t = 0$ in €/kW, StackRepl is the cost of electrolyzer stack replacement made at $t = 20$ in €/kW, $\text{OPEX}_{\text{el}}(t)$ is the operation and maintenance expenditure of the electrolyzer in year t in €/kW, $\text{FLH}(0)$ is the initial annual electrolyzer full load hours in year 0 in hours without degradation, WACC_{nom} is the nominal weighted average cost of capital per annum, and $\text{WACC}_{\text{real}}$ is the real weighted average cost of capital per annum.

3.4.2 Estimated LCOH

Multiple studies have assessed diverse factors and variables, including CAPEX, stock and plant lifetime, efficiency, annual hydrogen production, and electricity cost, to establish a price range for three scales: small (1 MW), medium (20 MW), and large (100 MW) (see Fig. 17). The calculated LCOH ranges from around 2.2 €/kgH_2 to just under 6 €/kgH_2, depending on scenarios and locations worldwide. Moreover, the LCOH for AWE is lower than that for PEMWE.

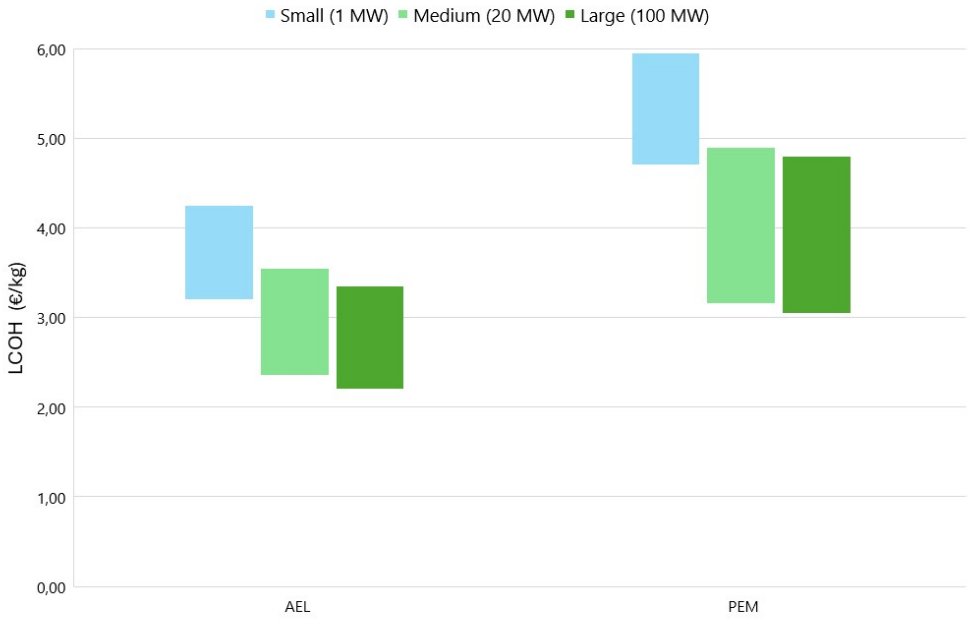

Figure 17. Levelized cost of hydrogen in different scenarios [120–124].

As shown in Fig. 17, current costs render green hydrogen less competitive than natural gas. However, rapid changes are anticipated as the costs of solar electricity, wind energy, and water electrolysis decrease, and considerations for CO_2 emissions become integrated into the analysis. By 2030, there's an expectation for a substantial reduction in the LCOH of green hydrogen, positioning it competitively on a global scale against natural gas-derived hydrogen with CCS. The potential for further cost reductions exists with increased electrolyzer production. Presently, high demand and limited manufacturing capacity contribute to elevated electrolyzer prices, but future trends anticipate lower prices with growing volumes and competition from Asian manufacturers, paralleling developments in the PV industry [121]. Similar advancements are expected in the wind sector, further contributing to cost reduction efforts.

3.5 Well known manufacturers

The surge in installed electrolyzer capacity is notably evident in recent years, as illustrated in Fig. 18. The period from 2022 to 2023 witnessed a substantial increase in installed capacity across all types of electrolyzers.

To capitalize on this trend, companies actively engaged in electrolyzer production have endeavored to boost their manufacturing capabilities. Some companies have strategically entered or expanded their presence in the burgeoning electrolyzer market by diversifying their applications. Fig. 19 provides insights into the leading 20 electrolyzer manufacturers in 2023, ranked by production capacity.

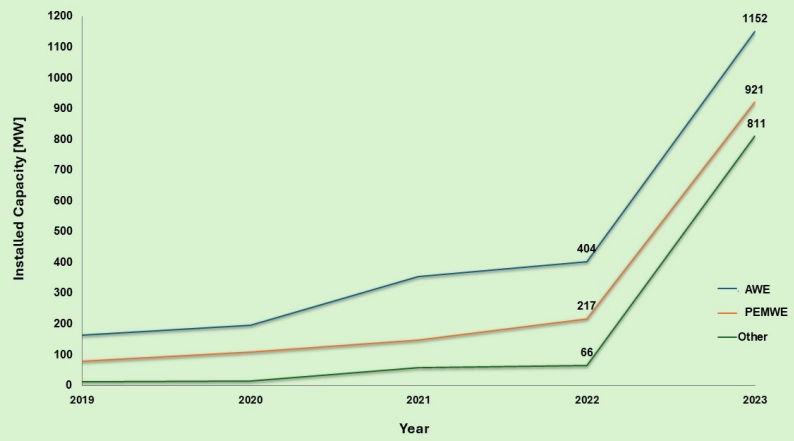

Figure 18. Installed capacity for all types of electrolyzers [125].

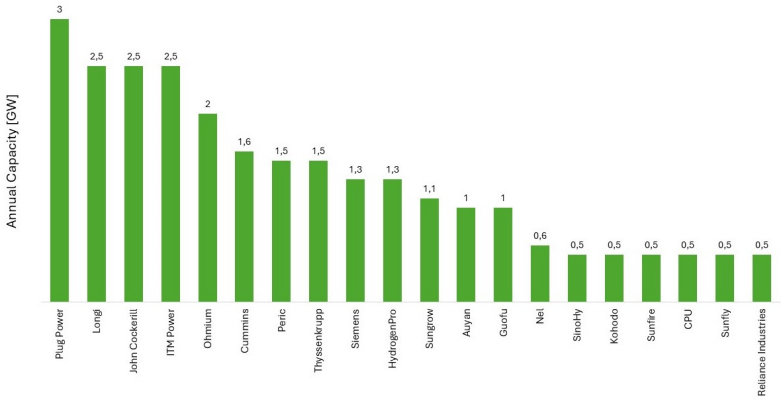

Figure 19. Production capacity of 20 electrolyzer manufacturers in 2023 [126].

Concurrently, there has been a gradual uptick in attention towards proton exchange membrane water electrolyzers. Over recent years, numerous companies have intensified their

involvement in PEMWE production. Table 5 compiles the top 5 producers of both AWEs and PEMWEs, reflecting the evolving landscape of electrolyzer manufacturing.

Table 5. Top 5 producers of AWE and PEMWE [126].

Rank	AWE			PEMWE		
	Company	Country	Annual capacity (GW)	Company	Country	Annual capacity (GW)
1	Longi	China	2,5	Plug Power	USA	3
2	John Cockerill	Belgium	2,5	ITM Power	UK	2,5
3	Thyssenkrupp	Germany	1,5	Ohmium	USA	2
4	Peric	China	1,5	Cummins	USA	1,6
5	Hydrogen Pro	Norway	1,3	Siemens Energy	Germany	1,3

4 GREEN HYDROGEN PRODUCTION IN FINLAND

Finland, mirroring the trend observed in several European nations, has initiated strategic investments in the field of green hydrogen. Various studies project a significant upswing in green hydrogen production in Finland by 2030. This chapter conducts a concise examination of renewable energy sources in Finland, exploring the potential for hydrogen production based on renewable energy. Furthermore, the chapter delves into the dynamics of hydrogen supply and demand in the Finnish context. While the determination of a definitive price for green hydrogen in Finland falls outside the purview of this study, relevant literature on the subject has been reviewed and synthesized. Concluding the chapter is a succinct SWOT analysis pertaining to green hydrogen production in the Finnish context.

4.1 Assessment of renewable energy resources in Finland

Finland, an industrialized nation with significant energy needs, is at the forefront of global efforts to combat climate change. Committed to achieving carbon neutrality by 2035, the country has become a leader in utilizing renewable energy sources (RESs) to reduce greenhouse gas emissions. In 2022, RESs accounted for 40% of Finland's energy consumption, encompassing bioenergy, hydropower, wind power, ground heat, and solar power. The national energy and climate strategy aims to raise this share to over 50% by 2030. This aligns with the government's commitment to making wind and solar energy the primary sources of electricity, fostering a competitive environment for these RESs. The strategic goal is to transition to a carbon-free electricity system by leveraging technological progress and implementing mechanisms that ensure the dominance of renewable energy in Finland's energy landscape [127].

Examining wind speed, average temperature, and solar irradiance across the entirety of Finland may result in the loss of specific information or obscure variations between different geographical locations. To mitigate this, the analysis focuses on a specific geographic location, southeastern Finland, for these three categories of data. Fig. 20, Fig. 21, and Fig. 22 depict the monthly averages of wind speed, global radiation, and recorded temperature, respectively, within the selected location.

Finland's distinct geographical position and climate pose specific challenges for harnessing solar energy. The seasonal variation in solar radiation results in significantly lower

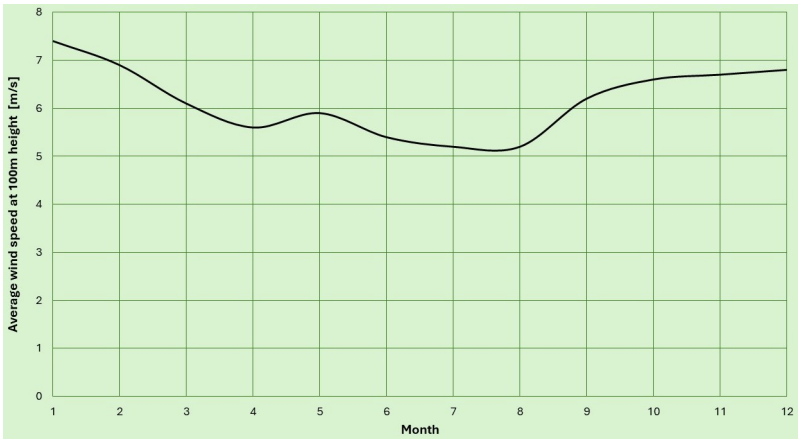

Figure 20. Average monthly wind speed in southeastern Finland in 2022 [128].

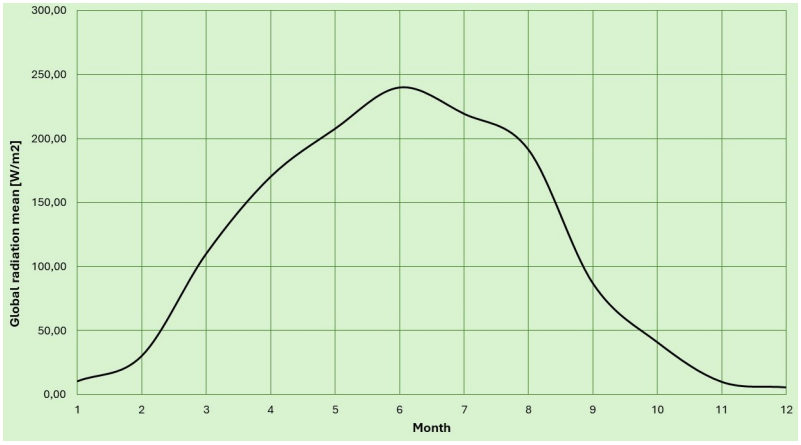

Figure 21. Average monthly global radiation in southeastern Finland in 2022 [128].

sunlight during winter compared to summer. Conversely, the winter months experience higher wind speeds than the annual average, presenting the potential to enhance energy production in the country during these periods.

Since 2019, the capacity linked to the primary grid has consistently grown by approximately a hundred megawatts each year. However, in 2022, this growth more than doubled. According to the Finnish energy authority, solar power production in 2022 reached nearly 635 megawatts, marking a substantial increase of over 240 megawatts compared to the preceding year. In 2022, Finland fulfilled 12% of its electricity demand through wind and solar power generation, with wind energy accounting for around 11% and solar energy around 1% [127]. The country's abundance of windy coastlines makes wind power a particularly cost-effective investment in RESs. Fig. 23 illustrates the annual power generation from wind and solar energy in Finland in 2022.

It's important to note that the primary concentration of wind energy production in Finland

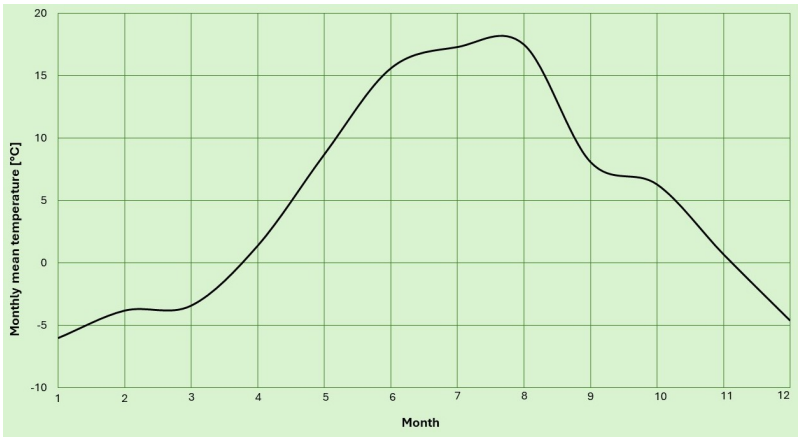

Figure 22. Average monthly ambient temperature in southeastern Finland in 2022 [128].

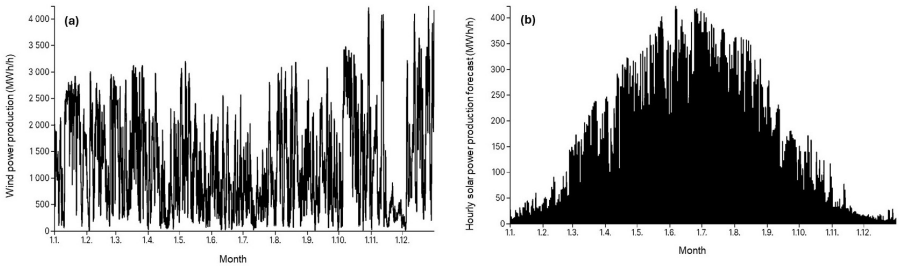

Figure 23. Power generation in Finland in 2022: (a) wind power and (b) solar power [129].

is found in the western regions of the country. In contrast, the central and eastern areas do not align with the representation in Fig. 23. To effectively design and construct a green hydrogen production plant, a thorough examination of energy sources specific to the chosen location should be conducted after its determination.

Evaluating the radiation and wind speed conditions in southeastern Finland, alongside the wind and solar generation trends in Finland, it becomes evident that employing a hybrid system for green hydrogen production is more favorable than relying solely on one energy source. Moreover, recognizing the significance of achieving a higher full load for cost reduction in hydrogen production, a hybrid system that integrates both wind and solar energy into the grid emerges as a superior option.

4.2 Hydrogen demand and supply in Finland

Finland's hydrogen sector exhibits a blend of dedicated production and by-product generation, with the refining, biofuel, chemical, and mining industries being the main consumers. Estimated total dedicated hydrogen production annually ranges from 140,000 to

150,000 tons, predominantly originating from steam reforming or partial oxidation of fossil fuels, with less than 1% derived from water electrolysis. A significant contributor to the hydrogen supply is by-product hydrogen from sodium chloride electrolysis, amounting to 22,000–24,000 tons annually. Hydrogen is also a by-product of oil refining, although its significance lies within the refining process, and pertinent data remains undisclosed [130].

The primary consumer of dedicated hydrogen is the oil refining and biofuel sector, representing 88% of usage, particularly in hydro-cracking and hydro-treating processes. Other consumers include the chemical industry (7% for hydrogen peroxide production) and the mining and ore refining sectors (5% for hydrogen sulfide and metal reduction). Notably, Finland's steel sector utilizes a limited amount of hydrogen for preventing steel oxidation. The UPM BioVerno production plant in Lappeenranta is the second-largest hydrogen consumer, with an estimated biofuel production capacity equivalent to 7,800 tons of hydrogen annually.

By-product hydrogen, notably from NaCl electrolysis, serves various purposes such as generating process steam, district heat, and, to a lesser extent, electricity. The prospect of redirecting hydrogen, currently vented into the atmosphere, to more valuable applications is recognized, offering opportunities for optimization. Fig. 24 illustrates the current utilization of hydrogen in Finland, encompassing both dedicated production and by-product hydrogen.

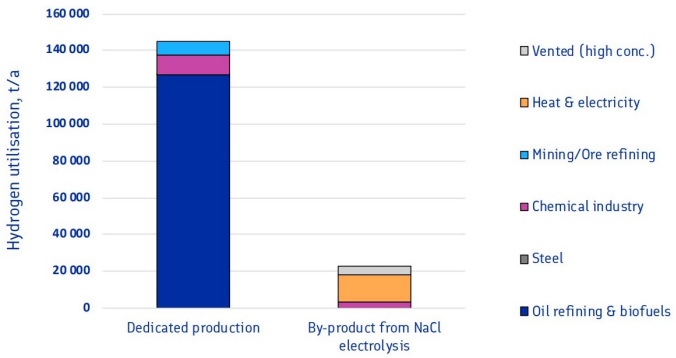

Figure 24. Present applications of hydrogen in Finland [130].

In terms of production sites, Finland features a limited dozen dedicated hydrogen production sites, with Neste Oyj refineries in Porvoo and Naantali standing out as major players. The Naantali refinery exclusively relies on by-product hydrogen from dehydrogenation and aromatization, rendering dedicated production unnecessary. However, Neste has announced the forthcoming closure of the Naantali site [130].

Geographically, hydrogen consumption is concentrated in south to south-eastern Finland, while potential production sites for new wind power are mainly located in the west coast . This spatial misalignment raises concerns about transmission distance, losses, and grid capacity shortages, as highlighted by RED II regulations. Effectively addressing these challenges is important for cultivating a sustainable and efficient hydrogen ecosystem in Finland. Fig. 25 provides an overview of the geographical distribution of hydrogen production plants and their annual hydrogen outputs.

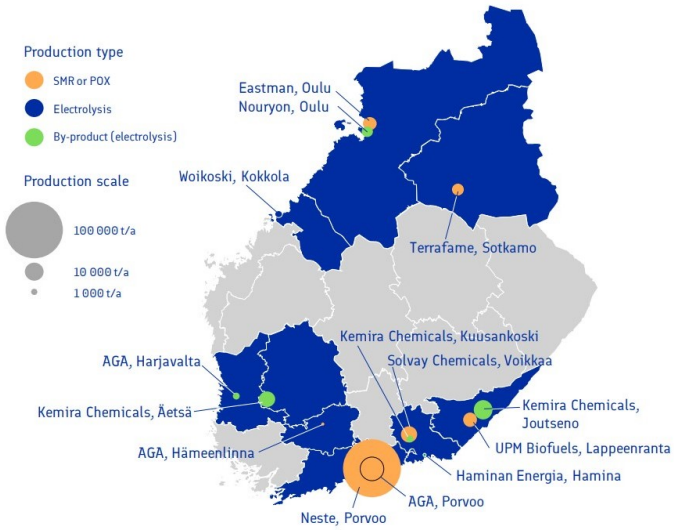

Figure 25. Geographical distribution of hydrogen production sites [130].

4.3 Estimated LCOH in Finland

The primary cost factor in electrolysis is the expense of clean electricity, along with the critical role of the electrolysis capacity factor in determining the cost of low-carbon hydrogen. Upscaling, process optimization, and material substitution in electrolysis technologies are expected to reduce specific investment costs. Effective integration of power-to-x side-streams is crucial for profitable plant operation.

Recent studies indicate a significant decrease in the Levelized Cost of Hydrogen over time. It is projected that the cost of hydrogen will fall below 2 €/kgH_2 before 2030 and approximately 1.7 €/kgH_2 by 2040. This reduction is driven by decreasing component prices and improved efficiency in production technologies. A detailed economic model using a 3% discount rate shows that LCOH is highly sensitive to discount rates, with higher rates accelerating cost reductions over the years. Notably, with a 1% discount rate, LCOH remains below 2 €/kgH_2 for all projected installation years [120]. An analysis

of an off-grid green hydrogen production system in southeastern Finland reveals that the optimal configuration relies primarily on wind power and an alkaline water electrolyzer until 2035. The addition of solar PV and battery energy storage systems becomes economically viable only after 2035, further enhancing the efficiency and reducing energy curtailment. This system optimization underscores the importance of strategic integration of renewable energy sources and storage solutions to achieve cost-effective hydrogen production [120].

4.4 SWOT analysis

Finland possesses strengths such as a robust electric grid, renewable wind power potential, and a complete hydrogen production value chain with extensive industrial experience. However, challenges arise from geological formations, though the country's innovation and financial capabilities can potentially address these issues.

Despite optimistic hydrogen roadmaps, uncertainties exist that could pose threats, particularly those beyond Finland's control. On a positive note, numerous opportunities abound, paving the way for Finland to integrate low-carbon hydrogen into its energy system. Balancing these strengths and opportunities with awareness of weaknesses and potential threats is crucial for a successful transition. Fig. 26 illustrates a SWOT analysis focused on the expansion of green hydrogen production and utilization.

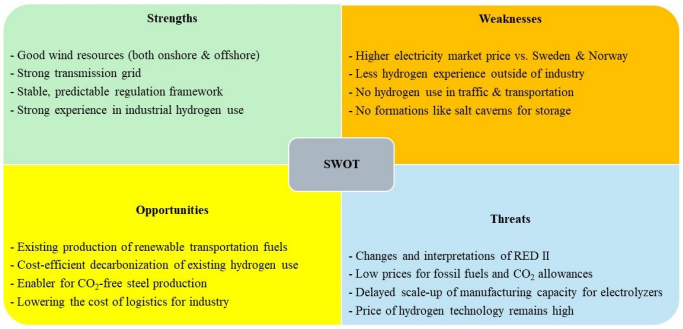

Figure 26. SWOT analysis for green hydrogen production in Finland [130].

4.5 Investement in green hydrogen in Finland

Currently, alkaline electrolyzers dominate green hydrogen production due to their reliability, mature technology, and availability. In Finland, they align well with sustainability

goals, offering a robust and economically viable solution. However, advancements in PEMWEs pose a potential challenge to this dominance, despite higher initial costs. Continuous technology developments in PEMWEs could shift market dynamics, necessitating vigilance and adaptability.

Finland's renewable energy landscape presents challenges for solar-based green hydrogen due to low solar full load hours, while wind energy shows promise and the synergy between wind power and alkaline electrolyzers is compelling. Hybrid systems integrating various renewable sources, energy storage methods, and smart grid technologies are crucial for cost-effective green hydrogen production. Optimizing these dynamic components is necessary to maximize efficiency. Advances in energy storage technologies, like battery systems, offer additional opportunities for enhancing reliability and stability. Addressing high production costs requires innovation in materials science, process engineering, and industrial-scale production. Replacing expensive materials with cost-effective resources and scaling up production can yield economies of scale, significantly reducing costs. Proper system sizing is key, with hybrid PV-wind systems increasing electrolyzer full load hours. While PEMWEs present cost reduction potential, material availability remains a concern.

Finland's prospects for expanding clean hydrogen production are promising due to robust wind resources, a strong electricity grid, an established hydrogen value chain, and decades of industrial hydrogen experience. Despite the lack of cost-effective underground storage, natural gas pipelines can be adapted for hydrogen transport. Finland's regulations allow higher vehicle mass for cost-effective hydrogen transport by truck, and the heavy long-distance transport sector offers opportunities for hydrogen-powered fuel cells [130].

As electrolyzer technology matures, perceived investor risk decreases, lowering investment WACC rates. Direct electrification solutions are generally more cost-effective and efficient, but applications in long-distance marine and aviation transport, chemicals, and steel making are expected to drive green hydrogen demand. A holistic approach involving technological progress, optimized energy systems, and collaboration across industries, academia, and policymakers is essential. Investor sentiment in Finland is neutral to slightly positive, peaking in 2020 and 2021 after Finland's hydrogen strategy publication. Discussions focus on general hydrogen topics and transport applications, with hydrogen fuel cell trucks receiving more positive attention. Investment aid is crucial for green hydrogen projects, addressing high initial costs and infrastructure gaps, similar to early wind power development. Green electricity prices significantly impact electrolysis profitability, leading companies to secure long-term wind power contracts and adopt cooperation

schemes to manage risks and costs [131].

A recent sensitivity analysis indicates that using a wind farm as the sole power source for an off-grid alkaline system is cost-effective until 2035–2040. Incorporating Solar PV and BESS increases full-load hours and reduces electricity curtailment below 8% but is currently not economically viable due to component costs and southeastern Finland's climate. Projections suggest hydrogen costs could be reduced to 2 €/kgH_2 by 2030 [120].

5 CONCLUSION

This master's thesis has investigated the feasibility of implementing industrial-scale green hydrogen production in Finland, examining both technical and economic dimensions. The significance of green hydrogen as a key catalyst in steering the transition towards a zero-emission future has been revealed. Notably, the exploration of electrolyzer technologies has revealed the prevalence of alkaline water electrolyzers (AWEs) in large-scale applications, driven by their cost-effectiveness and technological maturity, despite the advantages of proton exchange membrane electrolyzers (PEMWEs) for their compatibility with volatile renewable energies.

The business cases clarify the crucial significance of the quality of renewable energy sources, highlighting Finnish wind energy as a more promising avenue than solar for competitive hydrogen production. Projections suggest a significant decrease in the anticipated levelized cost of hydrogen (LCOH) in Finland by 2030, currently ranging from 2.7 €/kgH_2 to 3.4 €/kgH_2, thereby establishing the economic viability of green hydrogen.

Analyzing cost structures, which include electricity price, capital expenditures (CAPEX), and operating expenses (OPEX), highlights the need to focus on CAPEX elements such as the stack, power electronics, gas conditioning, and balance of plant. Key strategies for cost reduction include scaling up components, technological advancements at the cell and stack levels, increasing production volumes, improvements in production technologies, and learning-by-doing.

The urgency of transitioning from fossil fuels, particularly natural gas, for hydrogen production has been emphasized. Electrolyzer technologies are nearing large-scale development, aligning with ambitious EU targets of achieving 40 GW of electrolyzer capacity by 2030. Among the electrolyzer options, AWEs emerge as the mature and cost-effective choice, followed by PEMWEs and solid oxide water electrolyzers (SOWEs).

Looking forward, the author expresses strong confidence in the pivotal role that Power-to-X and hydrogen applications will assume in the coming years. The escalating presence of renewable electricity sources necessitates critical energy storage mechanisms, and green hydrogen production emerges as a facilitator for the heightened integration of renewable energy into national energy schemes.

Looking ahead, the future trajectory of research in the field of green hydrogen production should encompass a comprehensive exploration of several key areas. First and foremost,

optimizing the entire plant's performance is important for maximizing efficiency and minimizing environmental impact. Investigating novel approaches to integrate and fine-tune various components, from electrolyzers to energy storage systems, can significantly enhance the overall effectiveness of green hydrogen production facilities.

Furthermore, a detailed analysis of diverse energy resources is warranted, focusing on the synergistic utilization of wind, solar, grid, and hybrid systems. Understanding how these sources can complement each other and contribute to a reliable and resilient energy supply for green hydrogen production is essential. This research could unveil innovative strategies to balance the intermittent nature of renewable resources and ensure a consistent output of green hydrogen.

In the domain of materials science, ongoing research and development efforts should be dedicated to finding cost-effective alternatives to the expensive metals currently employed in electrolyzer technologies. Exploring new materials with enhanced durability, conductivity, and efficiency could lead to substantial cost reductions and increased sustainability in the production process.

Addressing barriers against scale-up is another crucial avenue for future research. Investigating the challenges associated with expanding green hydrogen production from pilot projects to industrial-scale operations will be vital. This includes overcoming technical hurdles, optimizing logistics, and navigating regulatory frameworks to facilitate the seamless transition to large-scale, commercially viable production.

Finally, an emphasis on interdisciplinary research is recommended to foster collaboration between engineers, economists, policymakers, and environmental scientists. This collaborative approach can yield holistic solutions that not only consider technical feasibility but also account for socio-economic factors, policy implications, and public acceptance.

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