Louvain School of Management

Modelling green hydrogen production costs: Focus on areas with high renewable energy potential facing water stress.

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Declaration

During the preparation of this master’s thesis, the authors utilized

- Chat GPT for language improvement.
- Scribbr for the citation of sources and the bibliography.

After using Chat GPT and Scribbr, the authors diligently reviewed and edited the content produced by the tool. We take full responsibility for the final content presented in this thesis. By signing this declaration, we affirm that the content of this master’s thesis reflects our original work, augmented by the responsible use of AI.

28 May 2024

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Acknowledgement

This thesis marks the culmination of five years of academic journey, starting with a bachelor's degree in business engineering and advancing to a double master's in business engineering and international management at the Louvain School of Management. Both passionate about energy and innovation, we were thrilled to conduct research on such a fascinating and timely topic as green hydrogen. This experience has not only deepened our knowledge but also fuelled our interest for innovative technologies in the energy sector.

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List of Abbreviations and Acronyms

IEA	International Energy Agency
PV	Photovoltaic
IRENA	International Renewable Energy Agency
EU	European Union
CCUS	Carbon Capture Utilisation and Storage
CCS	Carbon Capture and Storage
SMR	Steam Methane Reforming
CO_2e	CO_2 equivalent
UNESCO	United Nations Educational, Scientific and Cultural Organization
ESMAP	Energy sector Management Assistance Program
OECD	Organisation for Economic Co-operation and Development
LCOH	Levelized Cost of Hydrogen
PVOUT	Power output generated per unit of installed PV capacity
GHI	Global Horizontal Irradiance
GPS	Global Positioning System
NASA	National Aeronautics and Space Administration
GHI	Global Horizontal Irradiance
CAPEX	Capital Expenditures
OPEX	Operational Expenditures
ASTM	American Society for Testing and Materials
WACC	Weighted Average Cost of Capital
PEM	Polymer Electrolyte Membrane or Proton-Exchange Membrane
ARENA	Australian Renewable Energy Agency
SWRO	Sea Water Reverse Osmosis
RO	Reverse Osmosis
MSF	Multi-Stage Flash Distillation
MED	Multi-Effect Distillation
EPC	Engineering, Procurement and Construction

List of variables and parameters

Variable	Description	Units
LCOH	Levelized cost of hydrogen	\$/kg
t	Year of operation of the plant	Year
T	Total years of operation of the plant	Year
h	Hours of a year ($h = 1, \ldots, 8760$)	hour
$Electrolyser_t$	Total cost of electrolyser in year t	\$
$CE_{lifetime}$	Total lifetime cost of electricity	\$
$Mass_t^{H2}$	Mass of hydrogen produced in year t	kg
$WACC$	Weighted Average Cost of Capital, discount rate	%
C^{elec}	Capacity of the electrolyser	kW
$CAPEX_t^{elec}$	Capital expenditures for the electrolyser in year t	\$
$OPEX_t^{elec}$	Operational expenditures for the electrolyser in year t	\$
Stack_t	Capital expenditures for the stack in year t	\$
GC_t	Capital expenditures for the gas conditioning in year t	\$
PE_t	Capital expenditures for the power electronics in year t	\$
BoP_t	Capital expenditures for the Balance of plant in year t	\$
ω	Proportion of operational costs relative to capital costs for the electrolyser	%
Min power	The minimal power input to operate the electrolyser	%
Max power	The maximal power input to operate the electrolyser	%
SEC^{elec}	The specific electricity consumption to produce one kilogram of hydrogen via electrolysis	$\frac{kWh}{kg_{H2}}$
E_h^{elec}	The energy allocated to the electrolyser	kWh
E_h^{DW}	The energy allocated to the desalination unit	kWh
E_h^{cons}	The energy consumed by the electrolyser	kWh
CE_t	Cost of electricity in year t	\$
$LCOE^S$	Solar levelized cost of electricity	\$/kWh
$CAPEX_t^S$	Solar capital expenditures in year t	\$
$OPEX_t^S$	Solar operational expenditures in year t	\$
E_t^S	Solar electricity generation in the year t	kWh
E_h^S	Solar electricity generation in the hour h	kWh

z	Number of solar PV modules of the solar farm	/
C^S	Nameplate capacity of a solar PV module	kWp
IC^S	Installed costs of a solar PV module	\$/kWp
OC^S	Operating costs of a solar PV module	\$/kWp
GHI_h	Global horizontal irradiance in hour h	Wh/m²
A	Total area covered by PV modules	m²
η	Conversion efficiency of the PV modules	/
PR	Performance ratio of the PV modules	/
$LCOE^W$	Wind levelized cost of electricity	\$/kWh
$CAPEX_t^W$	Wind capital expenditures in year t	\$
$OPEX_t^W$	Wind operational expenditures in year t	\$
E_t^W	Wind electricity generation in the year t	kWh
E_h^W	Wind electricity generation in the hour h	kWh
τ	Number of wind turbines of the wind farm	/
C^W	Nameplate capacity of a wind turbine	kWp
IC^W	Installed costs of a wind turbine	\$/kWp
OC^W	Operating costs of a wind turbine	\$/kWp
$v_{h,i}$	Wind speed at height i in period h	m/s
ρ	Air density	kg/m^3
R	Area swept by the rotor of wind turbines	m²
d	Diameter of the rotor of the wind turbines	m
C_p	Power coefficient of wind turbines	/
i,j	Hub height of wind turbines	m
α	Power law exponent, depends on factors such as surface roughness, wind speeds, and temperature	/
v_{min}	The minimum cut-in wind speed at which wind turbines begin to generate power	m/s
v_{max}	The maximum cut-out wind speed at which wind turbines are shut down	m/s
CW	Cost of water	\$/kg_{H2}
LCOW	Levelized cost of water	\$/m^3
FW_{cons}	Freshwater consumption	L/kg_{H2}

UW_{cons}	Ultrapure water consumption	L/kg_{H2}
DW_{Cons}	Desalinated water consumption	L/kg_{H2}
SEC^{DW}	Specific energy consumption of the desalination unit per kg of hydrogen	$\frac{kWh}{kg_{H2}}$

Currency conversion

Exchange rates (2020-2024 average)	**1 € equals**
US dollar ($)	1.1148

Source: (European Central Bank, 2024)

Outline of the master thesis

Chapter 1, "*Introduction*," addresses the challenge of climate change and the significant impact of the energy sector. It delves into the specificities of the hydrogen molecule, with a particular focus on green hydrogen. The chapter concludes by introducing the research question and setting forth the objectives of the study.

Chapter 2, "*Methodology and Scope of the model*", defines the overall approach of the thesis. It explains the methodology used to construct the model, details the system setup and the scope of costs considered. Chapter 2 also lists the selection criteria used to identify the specific areas chosen as case studies for applying the model.

Chapter 3, "*Levelized Cost of Hydrogen Model*", begins by introducing the general formula of the model. It then delves into the equations that form the foundation of the model, followed by a discussion of the optimization objectives and constraints.

Chapter 4, "*Parameter values*", justifies the LCOH parameters via five steps: analysing the project's cost of capital, assessing electrolyser costs, detailing power generation plant specifications, evaluating water requirements, and determining electrolyser efficiency, which is essential for accurate hydrogen production calculations.

Chapter 5, "*Results and Discussion*," presents the results of the model and further discusses the findings about the production cost of green hydrogen in the three sites. The chapter ends with a critical examination of the research's limitations.

Chapter 6, "*Conclusion*," synthesizes the key findings of the study. It offers a comprehensive summary, highlights the contributions to the literature and proposes directions for future research.

Chapter 1 Introduction

1 Overall Context

1.1 Climate Change

In 2023, record temperatures have been monitored in many parts of the world, endangering human health and biodiversity. According to data collected by the Copernicus satellite constellation, 2023 was the warmest year on record, by a margin close to 1.5 °C above pre-industrial level *(World Meteorological Organisation, 2024)*. Climate change is having a profound effect on our planet, disturbing ecosystems, causing sea levels to rise, and intensifying extreme weather events such as hurricanes, floods, and droughts (*Scientific Consensus - NASA Science*, 2022).

The Paris Agreement, agreed by world leaders at the United Nations Climate Change Conference in 2015, sets long-term goals to tackle climate change and its negative impacts. The first objective to reduce the risks of climate change is to substantially reduce global greenhouse gas emissions to keep the rise in global temperature below 2°C over pre-industrial levels and pursue efforts to limit it to 1.5°C (*Key Aspects of the Paris Agreement | UN*, n.d.).

The Intergovernmental Panel on Climate Change confirmed in their *Sixth Assessment Report* that anthropogenic greenhouse gas emissions, such as the ones released by burning fossil fuels, are the main cause of global warming. According to the International Energy Agency (IEA) report on CO_2 emissions, global energy-related CO_2 emissions increased by 1.1% in 2023, reaching a new record high of 37.4 billion tons. Emissions from coal accounted for more than 65% of the increase (IEA, 2023). Out of the total world greenhouse gas emissions, the majority are related with energy-related activities, encompassing, power generation, industrial processing, and energy use in buildings (Ritchie et al., 2024). An essential facet of the climate change problem is rooted in energy, necessitating improvements in both energy production and consumption, as introduced in the next subsection.

1.2 Increasing the share of renewables

As published in the report "*CO2 Emissions in 2023, A new record high, but is there light at the end of the tunnel?*" by the IEA, the pace of emission growth witnessed over the past decade has been slower compared to historical trends. In the decade before 2023, global emissions grew around 0.5% per year, the slowest rate since the Great Depression in 1929. Although the rate of emissions growth is slowing down, greenhouse gas emissions continue to grow relentlessly. The goal is to reduce emissions in absolute terms, meaning that this is not the right trajectory (IEA, 2023).

In pursuit of a sustainable future, energy production from carbon-intensive resources needs to be reduced and let space for the deployment of renewable energies (IEA, 2023). According to the IEA, wind and solar photovoltaic (PV) capacity worldwide reached 540 giga-watt (GW) in 2023, up 75% from 2022 levels. However, numerous challenges remain to increase the use of renewable energies. These include incorporating low-carbon energy into heavy industries, addressing the intermittency of wind and solar power, integrating energy grids, and building up energy storage capacity. Reports like "*The World Energy Transitions Outlook 2023, 1.5°C Pathway*" published by the International Renewable Energy Agency (IRENA) underscore the need for innovative solutions to address the climate emergency (IRENA, 2023).

The IEA employs integrated modelling frameworks to generate and construct future energy projections and scenarios. These scenarios are not predictions but serve as tools for readers to compare various potential outcomes. They offer insights into the potential trajectory of the global energy mix by illustrating the key levers and actions shaping each scenario. For instance, the *Net Zero Emissions by 2050 Scenario* outlines a pathway for the global energy sector to achieve net zero CO_2 emissions by 2050, with the aim of limiting the global temperature rise to 1.5°C (IEA, 2023). In these scenarios, green hydrogen emerges as a crucial component for decarbonization. It emits only water vapor and can support diverse industrial applications, which are further detailed in section 2.

1.3 European Strategy

In recent years, the European Union (EU) has introduced two important policies, outlining the future strategy of the EU: the European Green Deal and the REPowerEU plan. The European Green Deal Europe is an ambitious roadmap towards a sustainable future, aiming to achieve carbon neutrality by 2050. The European Commission also introduced the REPowerEU plan which supports the ambitious EU goal of achieving at least a 55% reduction in net greenhouse gas emissions by 2030. Recently, European electricity and energy prices have risen sharply after the reduction of Russian gas imports, encouraging energy savings and investments in renewable energy (International Monetary Fund, 2022). Therefore, one of the pillars of REPowerEU consists of increasing the resilience of the EU energy system, by decreasing the dependence on fossil fuels and diversifying energy supplies at European level (*The REPowerEU Plan Explained*, 2023).

As part of the RePowerEU plan, the EU plans to increase the importations of renewable energy sources and hydrogen. Moreover, the European Commission introduced the "European green hydrogen strategy" aiming for a climate neutral Europe. This seeks to boost the clean production of hydrogen to be used as a feedstock, fuel, energy carrier, and storage alternative for European renewables (IRENA, 2020; European Commission, 2020). The strategy targets an annual generation of 10 Mt of renewable hydrogen by 2030, with an additional 10Mt to be imported from outside the EU (Thomas et al., 2023). In light of these hydrogen importation targets, regions endowed with abundant renewable energy resources find themselves strategically positioned to export green hydrogen to the EU.

2 Hydrogen

Hydrogen has an important role to play in a net zero economy as it emits no carbon emissions at the point of use. Today, this molecule is already in use in several industries, but the production processes emit significant amounts of greenhouse gases. The next section dives into the basics of the hydrogen molecule, the different production methods, and its current use cases.

2.1 The molecule

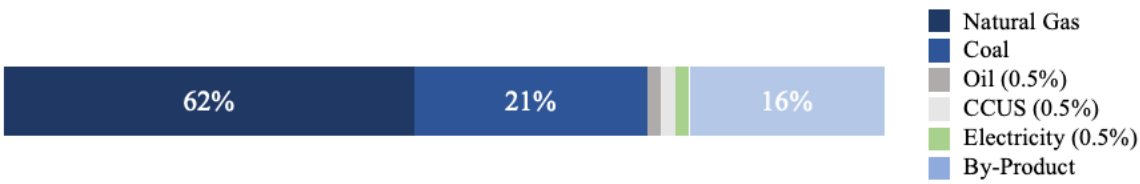
Hydrogen (H) is the first atom in the periodic table and its nucleus consists of just one proton and one associated electron, therefore, it is also the lightest chemical element. It is colourless, odourless, tasteless, flammable and it is the most abundant element in the universe (Jolly, 2024). In this report, the term "hydrogen" refers to dihydrogen (H_2), a gas composed of two hydrogen atoms. Dihydrogen exists as a gas under normal pressure and temperature conditions. For storage, hydrogen must be compressed to around 350 to 700 times atmospheric pressure, it can also be liquefied by cryogenically lowering its temperature to -253°C (The Royal Society, 2021).

Hydrogen has a high energy density of 33.3 kilowatt-hour (kWh) per kg, which is almost three times as much as natural gas (12.5 kWh per kg). Hydrogen is an effective and lightweight energy transporter since it holds a significant quantity of energy in one kilogram. However, the volumetric energy of 3.5 kWh/m^3 under ambient conditions, is very low compared to other fuels and energy carriers (Zivar et al., 2021; Demaco Holland B.V., 2023). In simple terms, hydrogen is a dense energy source per kilogram, but it requires a lot of space compared to other fuels. Due to these properties, hydrogen is liquified under pressure for its storage and transportation (Carbone4, 2022; IEA, 2019).

2.2 Current production methods

Today, hydrogen consumed in the industry is mainly produced from fossil sources. The molecule is produced both in dedicated processes and as a by-product of other industrial activities such as crude refining and petrochemical industry processes. Hydrogen as a by-product accounted for 16% of global production in 2022 while dedicated production represented the remaining 84% of production. For the dedicated production, hydrogen is almost entirely produced from fossil resources via coal gasification and steam reforming of natural gas. The total production of hydrogen in 2022 amounted to 95 megatons (Mt) (IEA, 2023).

Figure 1: Production of hydrogen by source in 2022



Source: Adapted from IEA, 2023.

In 2022, hydrogen production accounted for 830 Mt of CO_2 emissions (IEA, 2023). Currently, hydrogen has a relatively high average carbon footprint of around 15 kgCO_2e per kg of H_2 for dedicated hydrogen production, placing it among the energy carriers with the highest carbon footprint compared to coal, natural gas, diesel, and oil (carbone4, 2022). This high carbon footprint is linked to the important share of gas and coal in the production of hydrogen. The literature distinguishes four main types of dedicated production based on the feedstock used and often assigns a colour code summarized in the underlying table (Table 1).

Gas-based hydrogen “grey hydrogen” is by far the most important dedicated production method with 62% of global production in 2022. Grey hydrogen emits around 9-12 kg of CO_2e per kg of hydrogen by reforming natural gas through steam methane reforming (SMR) and cost around $1.95 per kg of hydrogen produced. The main advantages of this mature technology are its low cost and large-scale production. Its key disadvantage is the harmful emission of CO_2 and a vulnerability to future carbon taxes. Coal based “brown” hydrogen, represents 21% of the global production. Regarding emissions, brown hydrogen, produced through coal gasification, is the most polluting method with around 19 – 25kg of CO_2e per kg of hydrogen. The average cost of brown hydrogen arounds $3 per kg of hydrogen.

Coal or gas based “blue” hydrogen represents 0.6% of total production. The blue hydrogen production process is the same as for grey or brown hydrogen but with carbon capture, utilization, and storage (CCUS) or carbon capture and storage (CCS) on top. The carbon dioxide (CO_2) that would normally be released is captured, used, or stored underground. Therefore, it emits less CO_2, around 1.8 – 4.3 kg of CO_2e per kg of hydrogen for SMR CCS and coal CCS respectively. The cost of production for blue hydrogen is therefore between $1.5 – 2.5/kg. By leveraging on current infrastructures, blue hydrogen can help build up the demand for clean hydrogen.

Finally, electrolysis based “green” hydrogen that uses renewable electricity only represents a small fraction of the total production (0.1%). Green hydrogen splits water molecules into hydrogen and oxygen through electrolysis using renewable electricity. According to the literature, it only emits around 1.34 – 4.47 kg of CO_2e per kg. This technology is not used on a large scale yet and the production of green hydrogen was still below 100 kilotons (kt) in 2022 with production costs ranging between $3.00 – 6.60/kg. Low-emission, blue and green hydrogen represented less than 0.7% of global production.

Table 1: Literature estimate for dedicated hydrogen production

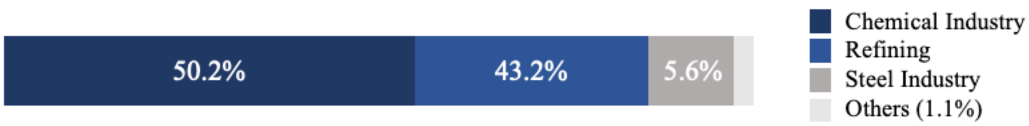
Feedstock	Colour code	Emissions (kg CO_2e / kg H_2)	Costs ($/kg H_2)	% of Total Production
Natural Gas	Grey	9 – 12	1.95	62
Coal	Brown	19 – 25	3	21
Gas or coal with CCS	Blue	1.8 – 4.3	1.5 – 2.5	0.6
Renewable Energy	Green	1.34 – 4.47	3.00 – 6.60	0.1

Sources: (The Royal Society, 2021; Farhana et al., 2024; IEA, 2019; Moberg and Bartlett 2022; IEA, 2023; Zang et al., 2024; Al-Qahtani et al., 2021; Hjeij et al., 2022; Ajanović et al., 2022; Burchart-Korol et al., 2022; Kumar & Lim, 2022).

2.3 Current use cases of hydrogen

Global hydrogen demand reached 95 Mt in 2022. Due to its properties, hydrogen is frequently used as a reactant in chemical processes. Traditional use cases of hydrogen are the chemical industry (47.7 Mt), refining (41 Mt), the steel industry (5.3 Mt), and to a lesser extent electronics, glassmaking, and metal processing (1 Mt) (IEA, 2023).

Figure 2: Hydrogen use by sector in 2022.



Source: Adapted from IEA, 2023

The chemical industry is the main traditional application of hydrogen and uses it to produce ammonia (NH_3), methanol (CH_3OH) and other chemicals. Ammonia is produced via the Haber-Bosch process where hydrogen is mixed with nitrogen (N_2) (Darmawan et al., 2022). Ammonia is used in the production of fertilisers which are essential in our modern agricultural system. Ammonia accounts for around 420 Mt CO_2 emissions per year constituting up to 2% of the annual global greenhouse gas emissions. (The Royal Society, 2021).

Today, refineries mainly use hydrogen for hydrocracking and desulfurization to transform crude oil into more valuable products. In 2022, about 80% of the hydrogen used in refining was produced onsite, both through dedicated production and as a by-product. The production of hydrogen used in refining resulted in 240 – 380 M tCO_2 emitted in the atmosphere in 2022 (IEA, 2023).

Traditionally, the steel industry produces steel from iron ore by burning coal, which is highly carbon intensive. However, an alternative process called direct reduced iron utilizes hydrogen as a reducing agent to produce steel from iron ore. Today, the use of coal, grey hydrogen and brown hydrogen in steel production contributes significantly to carbon emissions.

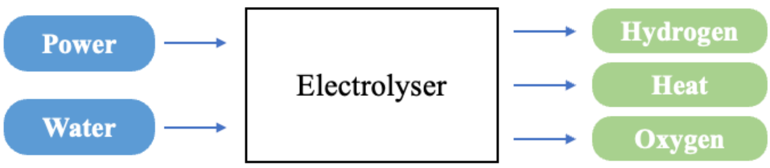
3 Green hydrogen

Green hydrogen and the vast array of opportunities that it offers have a critical role to enable countries reduce the carbon intensity of their energy mix. Since the 2015 Paris agreement, public authorities committed to a future sustainable energy mix, included low-carbon hydrogen into their energy strategies. According to the *Global Hydrogen Review 2023*, if all announced projects are realized, the annual production of green hydrogen, could reach 38 Mt in 2030. However, only 4% of those potential projects have taken a final investment decision. Under the more optimistic IEA's Net Zero Emission scenario, hydrogen demand is expected to grow further in traditional and new applications, hitting 150 Mt by 2030.

3.1 Electrolysis

In this report, low-carbon hydrogen, low-emission hydrogen, and green hydrogen is referred to as hydrogen produced though electrolysis with a renewable energy source.

Figure 3: Simplified electrolysis process



Source: Adapted from International Solar Alliance

By powering the electrolyser with electricity, the water molecule (H_2O) is separated in dihydrogen (H_2) and oxygen (O_2). Besides the separation of those molecules, heat is released. The chemical reactions involved in water electrolysis, happen in the stack. The two main types of electrolysers used are the Alkaline electrolyser and the Polymer Electrolyte Membrane (PEM) electrolyser. In the PEM electrolyser used in this research, two electrodes (an anode and a cathode) are separated by an electrolyte known as a polymeric membrane, which is immersed in water, as shown in Appendix 1. When an electric current passes through water, it ionizes into gaseous molecules, with hydrogen accumulating on the cathode and oxygen accumulating on the anode (Jonsson & Massgard, 2021).

The chemical process of electrolysis is described by the following reactions:

Total reaction:	$2\,H_2 0 + Energy \rightarrow 2\,H_2 + O_2$
Anode Reaction:	$2\,H_2 0 \rightarrow O_2 + 4e^-$
Cathode Reaction:	$4H^+ + 4e^- \rightarrow 2\,H_2$

While this process could enable the production of low-carbon hydrogen, the electricity consumed in the electrolysis must have a carbon content lower than $60gCO_2e/kWh$ to be considered as "low-carbon hydrogen". Considering that 55 kWh of electricity is needed to produce 1 kg of hydrogen through electrolysis, this translates to 3.33 kg of CO_2e emitted per kg of hydrogen produced (carbone4, 2022). Similarly, the EU delegated acts state that, for hydrogen to be considered low-carbon, its life-cycle emissions must be lower than 3.38 kgCO_2e per kg of hydrogen. This is 70% lower than the production from natural gas without CCUS (De Temmerman & Thomas, 2023).

3.2 Applications of green hydrogen

The push for decarbonization is expected to drive the adoption of green hydrogen in novel applications, particularly in sectors where emissions are hard to abate (IEA, 2023). Low-carbon hydrogen can also enhance grid stability by storing excess renewable energy, thereby mitigating the intermittency of sources like wind and solar. That hydrogen can then be turned back into electricity via fuel cells when renewable sources are insufficient. However, the round-trip efficiency of power-to-hydrogen-to-power systems is around 30-40% due to the combined losses in electrolysis, storage, and fuel cell conversion. Approximately 60% of the original electricity is lost when converting electricity to hydrogen and back, whereas lithium-ion batteries lose only about 15% in a storage cycle (IEA, 2019). This low efficiency means hydrogen should be used where direct electrification is not feasible.

Carbone 4 conducted prospective research in its report *Low carbon hydrogen*, on the applications of the molecule to highlight the most efficient uses of low carbon hydrogen to respond to the climate emergency. The report elaborates on the utilization of hydrogen for applications such as ammonia production, heavy-duty transportation, and steel manufacturing.

3.2.1 Ammonia

Ammonia (NH_3) is the largest consumer of hydrogen in the chemical sector and more than 80% is used to produce synthetic fertilizers for agriculture (Carbone4). The world average impact of ammonia is of $2.4\ tCO_2e/tNH_3$ (IEA, 2019). Low carbon hydrogen has the potential to decrease the environmental impact of the refining and production of ammonia. Moreover, ammonia has a considerable potential to help reduce the greenhouse gas emissions for power, transport, heat, and energy storage due to its higher volumetric energy than hydrogen. Thanks to its stability for low pressure storage at 10 times the atmospheric pressure, as well as its suitability for long-term storage and transportation, the properties of the molecule fulfil the requirements for efficient energy storage across time and space (Aziz et al., 2020). Ammonia can be directly used in high temperature solid oxide fuel cells to produce electricity or indirectly by being "cracked" back to hydrogen. Under the more optimistic IEA's NZE scenario, low-emission hydrogen demand for ammonia production amounts to 3.5 Mt in 2030. This represents a share of 15% of low-emission hydrogen in the total sectoral demand.

3.2.2 Transport

Further, low-carbon hydrogen can be used to reduce the greenhouse gas emissions of the transport industry by serving as a fuel. According to a report published by the IEA, hydrogen holds promise as a clean energy carrier for various modes of transportation, including vehicles and ships (IEA, 2020). Hydrogen converted into ammonia has for example been proposed as a potential carbon-free fuel for maritime shipping due to its high energy density and ease of liquefaction (Laursen et al., 2022). Ammonia-powered ships could offer a pathway to decarbonize the shipping sector, which is currently a significant contributor to global emissions (Royal Society, n.d.).

3.2.3 Steel

Steel production, responsible for about 9% (1.8 Gt) of global CO2 emissions due to coal use, could be decarbonized with hydrogen (European Parliamentary Research Service, 2020). However, the cost of producing low-carbon hydrogen today is too expensive to compete with traditional more polluting resources, replacing coal with hydrogen would increase the price per ton of steel produced by 30%. Transitioning from grey or brown hydrogen to green hydrogen in direct reduced iron and gradually replacing coal-based plants with green hydrogen offers for example a promising solution to reduce emissions in this industry (European Parliamentary Research Service, 2020).

3.3 Production costs

Green hydrogen has not been used at scale, due to competition from cheaper incumbent fossil fuels. As seen earlier, green hydrogen production costs remain 1.54 to 3.38 times more expensive than grey hydrogen (Table 1). According to the IRENA, the main factors influencing cost of production are electricity costs, investment cost, fixed operating costs and the number of operating hours of the electrolyser facilities. Investment costs are related to the electrolyser and include the procurement of components and the construction of the electrolyser facility (IRENA, 2020).

When operating hours are low, the largest cost component is the investment cost, as it is spread over a smaller output of hydrogen. On the contrary, with increasing operating hours, investments cost per unit of hydrogen decreases and the electricity cost dominates. On average, although subject to variations of specific projects, the cost of electricity accounts for the largest cost component in green hydrogen projects (IRENA, 2020). According to a study by Lazard, for electrolysers of 20 MW or more, electricity represents on average 40 – 70% of the levelized cost of hydrogen (Lazard, 2021).

As highlighted by the IRENA, low electricity prices are decisive to achieve cost competitiveness of green hydrogen production. In favourable conditions characterized by cheap renewable electricity, low investment costs, and extensive operating hours, green hydrogen could reach cost parity with its fossil-derived counterparts. It is worth mentioning that around 3000 – 4000 operational hours per year are enough to decrease the fixed costs per kg of hydrogen produced. Achieving these operating hours is feasible with large-scale hybrid photovoltaic-wind farms in prime locations in the world, where operations can exceed 5000 hours (IRENA, 2020).

According to the IRENA, green hydrogen production costs are almost competitive in regions with favourable conditions, although these areas tend to be distant from demand hubs. For instance, wind power can nearly achieve a 50% capacity factor in Patagonia, with electricity costs ranging from $25 to $30 per MWh. This could yield a production cost of approximately $2.5 per kg of hydrogen, close to the cost range of blue hydrogen (IRENA, 2020).

A way to reduce electricity expenses and consequently lower overall production costs involves tapping into inexpensive renewable power from regions with high renewable energy potential. Another leverage point is to reduce electrolyser's costs or to enhance the efficiency of the electrolyser, thereby reducing the amount of electricity needed to produce one kilogram of hydrogen.

3.4 Water supply

Another important aspect in green hydrogen production encompasses a sustainable water sourcing, since water is an essential feedstock for the electrolysis. According to a report from IRENA, more than 35% of the global operational and planned green and blue hydrogen projects are in regions facing water stress (IRENA, 2023).

The aqueduct water risk atlas defines water stress as:

> The water stress measures the ratio of total water demand to available renewable surface and groundwater supplies. Water demand include domestic, industrial, irrigation, and livestock uses. Available renewable water supplies include the impact of upstream consumptive water users and large dams on downstream water availability. Higher values indicate more competition among users (Aqueduct Water Risk Atlas, n.d.).

Understanding the dynamics of water in hydrogen production is primordial to account for the environmental sustainability of the technology. According to the European Environment Agency, water stress occurs when the demand for water exceeds the available amount during a certain period or when poor quality restricts its use. Water stress causes deterioration of freshwater resources in terms of quantity and quality (European Environment Agency). Moreover, water stress poses significant risks to humans and environmental well-being and is a proxy measure for local water competition between sectors (World Resources Institute, n.d.).

Along with carbon emissions, the growing pressure of humanity on water resources is a big concern for the decades to come. A report from UNESCO published in 2023 states that 2 billion people worldwide do not have a safe drinking water access (UNESCO, 2023). There are several factors contributing to water shortage, such as population expansion, intensive agriculture, and climate change. Adding to these challenges, the energy sector emerges as the most significant consumer of water among all industrial sectors (IRENA, 2023). States must therefore reconsider water policies when developing low carbon energy projects since they are essential to maintaining the stability of regions (Eyl-Mazzega, 2022).

All current hydrogen production methods require water as a production input and as a cooling agent. While green hydrogen technology consumes the least amount of water compared to other hydrogen production methods, it remains essential to scrutinize its water usage to ensure sustainable consumption practices (IRENA, 2023). While some argue that the water usage to meet hydrogen targets will not significantly impact global water resources (World Economic Forum, 2024), it is imperative to consider local water contexts, particularly in regions facing chronic water risks like water stress, when planning hydrogen projects.

The production of hydrogen via electrolysis requires a stable supply of water, which raises issues to produce green hydrogen at scale in regions facing water risks. Additionally, unsustainable water sourcing could affect communities, agriculture, and the environment by intensifying the water stress locally (Eyl-Mazzega, 2022). In this context, seawater desalination emerges as a promising solution to the development of hydrogen production facilities in regions with water risks since it marginally affects local freshwater resources.

3.5 Conclusion

In conclusion, the chapter highlights the escalating urgency of combating climate change and the need for a substantial reduction in greenhouse gas emissions. Among the solutions, green hydrogen has the potential to decarbonize various industries. The production of green hydrogen, primarily through electrolysis using renewable energy, emits significantly less CO_2 compared to traditional methods like steam methane reforming (grey hydrogen) and coal gasification (brown hydrogen). In the chemical industry, green hydrogen can significantly reduce emissions in ammonia production, a key component in fertilizers. In the transportation sector, hydrogen-powered vehicles and ships offer a clean energy alternative. The steel industry can also benefit from hydrogen as a reducing agent, replacing carbon-intensive coal processes. Despite its promise, the widespread adoption of green hydrogen faces cost challenges. Lowering production costs requires access to cheap renewable electricity, efficient electrolyser technology, and extensive operational hours. Additionally, sustainable water sourcing is crucial, especially in regions facing water stress, with desalination presenting a potential solution. This research focuses on the economic competitiveness of green hydrogen, with the next section introducing the research question and objectives.

4 Research Question and objectives

With the urgent need to scale up green hydrogen production, it is crucial to identify levers to improve the economic competitivity of its production costs. This begs the following question: how can cheap and low carbon hydrogen be produced? As seen in subsection 3.2, low production costs can be achieved by decreasing the electricity cost. This includes finding places endowed with a high potential for renewable energy where electricity production is cheap. Pinpointing these areas is essential to bring this energy vector one step closer to large scale adoption. Consequently, this research will focus on regions with abundant solar and wind resources. The core objective of this thesis is to compare the green hydrogen production costs in different locations with high solar and wind energy potential.

Hydrogen production relies on fresh water as a feedstock, making a reliable supply of water imperative. It is crucial to source this freshwater in a manner that does not harm local communities or the environment. To address this concern, this thesis focuses on coastal areas, where desalinated seawater can be used as feedstock. This ensures that green hydrogen production aligns with environmental and social sustainability goals, particularly Sustainable Development Goal 6: "Ensure availability and sustainable management of water and sanitation for all" (UN, n.d.). This approach underscores that safeguarding natural resources and community well-being is a prerequisite for responsible energy generation. As a result, the locations analysed in this research face water risks, prompting the need for a seawater desalination unit at the hydrogen production facility.

Therefore, this research develops a model that assesses green hydrogen production costs given the wind and solar conditions of a specific site where the focus lays on water stress regions with high renewable power potential. The following research question is formulated:

Modelling green hydrogen production costs:
Focus on areas with high renewable energy potential facing water stress.

4.1 Contribution of the research

This thesis contributes to the existing literature on the economic feasibility of green hydrogen production by introducing a location-specific cost model. It particularly focuses on regions experiencing water stress that also possess strong wind and solar resources, recognizing that water is a critical input in hydrogen production and that producing in regions with abundant renewable energy can potentially lower production costs. The aim is to develop an adaptable model which computes the production costs of green hydrogen at specific spots in water-stressed regions with high renewable energy potential.

A joint report from the World Bank, ESMAP, the OECD, the Hydrogen Council and Global Infrastructure Facility, states that the literature lacks sufficient information concerning the cost of clean hydrogen to effectively inform and guide policymaking and investment decisions (ESMAP, 2024). Additionally, an adaptable model to compute the economic cost of green hydrogen production at a particular spot in the world depending in the renewable energy potential is not available in the literature.

Modelling production at different spots allows to compare costs and assess where production is the most attractive. This is a crucial step for the technology's large-scale implementation in the industry. This thesis provides policymaker, investors, and other industry stakeholders with a useful instrument to evaluate the viability and attractiveness of green hydrogen projects. Designed to be applied across different sites, this model gives decision-makers the ability to evaluate the economic feasibility of green hydrogen production in diverse locations, promoting informed decision-making for green hydrogen projects.

Consequently, this research is an attempt to address these gaps by constructing a transparent, flexible, and adaptable model for computing the cost of production of green hydrogen in a specific location. The model's adaptability lies in the ability of users to easily adjust parameter values for specific technical requirements, geographic locations, scales, levels of efficiency, and others. The model transparently details its boundaries and the assumptions that were made based on documented research.

Chapter 2 Methodology and Scope of the research

The first section of this chapter, "*Overall approach*", describes the big picture surrounding the model. The second section discusses the methodology used in this thesis. The third section, "*Outline of the model*", comprises three distinct subsections: "*System Setup*", "*Area selection*", and "*Data*". "*System Setup*", covers the high-level boundaries of the analysed system and introduces the three components of the facility: the power generation plant, the desalination unit, and the electrolyser. In the " *Area selection* " subsection, the criteria used to select areas that aligns with the research question are outlined, followed by an explanation of the suitability of the three selected site. The "*Data*" subsection discusses the source of data used in the model.

1 Overall Approach

As mentioned in Chapter 1, this research aims to answer the research question by computing the production cost of hydrogen in water-stressed places with high renewable potential, and subsequently comparing the results with each other. In this study, the metric employed to compare costs across different sites is the cost per kilogram of hydrogen, which is obtained through Levelized Cost of Hydrogen (LCOH) calculations. This ratio serves as a reference metric to compare different projects in feasibility assessments studies and investment decisions. It should again be noted that this research focuses solely on production costs of green hydrogen and does not address any downstream activity such as transportation or final use.

The approach involves deconstructing the LCOH formula into smaller components to address each element independently. Afterwards, these components are integrated back into the LCOH formula to determine the cost per unit of hydrogen produced. The overarching objective of this research is to develop an adaptable LCOH model to compare different sites. The same facility setup is applied across different sites to ensure the comparability of the results. In this report, the model is applied in three different locations by plugging local weather data in. The results of the three sites are analysed and compared with each other in chapter 5.

2 Methodology

The research adopts a methodical approach to secure conclusive outcomes from the modelling process. The first step, discussed in section 3 of this chapter, involves setting the main assumptions regarding the system and the configuration of the facility. Some general economic assumptions are also set, defining the scope of costs to be considered within the model. These high-level assumptions are the same for all the selected sites.

In the second step**,** the model is written down by carefully putting up the formulas that govern the relationships among the different parameters and variables. This is done in chapter 3 with the aim of simulating the operations of the facility and the climatic conditions of the chosen sites as best as possible. The local climate impacts the operating hours of the electrolyser, significantly influencing production costs. To obtain a calculated LCOH that is truly location specific, the model is built on wind speed and solar irradiation data of the chosen site.

The third step, described at the end of chapter 3, defines the objective function and constraints of the optimization. The model minimizes the levelized cost of hydrogen by optimizing the number of wind turbines and solar panels. This optimization process hinges upon two key factors: the size of the electrolyser and local weather data. Given the size of the electrolyser and local climatic conditions, the model dynamically adjusts the size of the wind and solar farms to minimize the LCOH. The number of solar modules and wind turbines dictate the renewable energy output, the amount of hydrogen produced for a given electrolyser's capacity, and the volume of water consumed.

In the fourth step, addressed in chapter 4, the model is prepared to be applied to specific locations through a set of assumptions. At this stage, default values of economic and technical parameters are determined based on literature research. As for high-level boundaries, parameter assumptions are consistent across selected sites. The parameters related to the electrolyser, the power generation plant, and the desalination unit are uniform across sites.

In the fifth step, the results of the model in three different locations are computed and analysed. Further, a sensitivity analysis of some influential parameters is carried out.

As just explained, this research relies on a set of assumptions and hypotheses. The transparent approach is essential as LCOH calculations need to be performed consistently to compare different projects. Indeed, as a report by Agora Industry and Umlaut notes, there are significant differences across LCOH studies since the scope of cost estimations is often inconsistent across reports. In some studies, the scope of analysis is even not specified at all. Agora Industry and Umlaut also highlight the gap between theoretical models and real-world projects. The report continues, nonetheless, that some simplifications are justifiable as the influence of certain factors is neglectable and omitting them can significantly reduce the modelling effort. Some modifications and assumptions in the LCOH make sense depending on the focus of the research or project (Agora Industry et al., 2023). Assumptions made in this research aim to strike a balance between the pragmatism and the realism of the research.

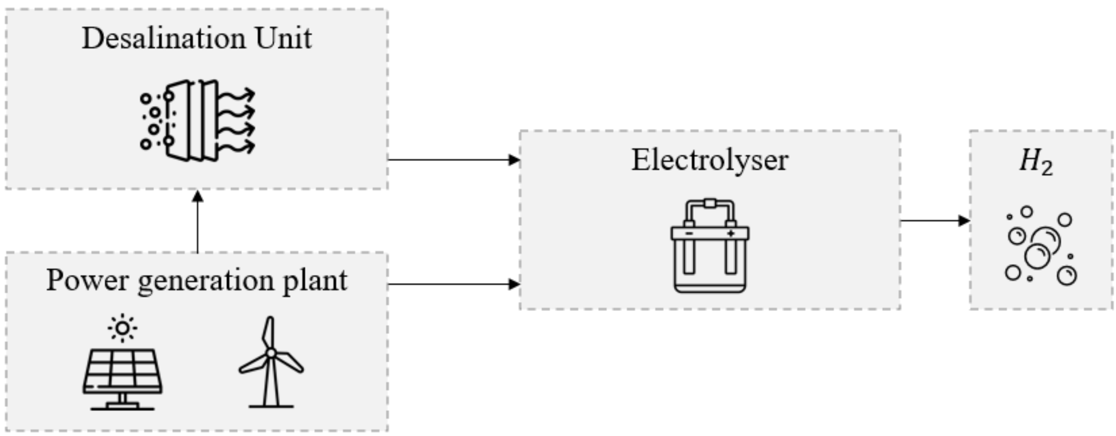
3 Outline of the model

3.1 System setup

The system setup defines the scope of the research and the boundaries of the production facility. The production facility used in this research is fictious but is constructed to be as realistic as possible. The overall production site consists of a power generation plant, a desalination unit, and an electrolyser, where the hydrogen is actually produced. The renewable power is generated using a mix of wind turbines and solar panels, delivering electricity to both the desalination unit and the hydrogen production plant. The production site is located in a coastal area and uses desalinated seawater as feedstock for the hydrogen production plant.

Further, the entire system is treated as a single entity, isolated from the external environment and without storage capacity. This has three implications for our production site. First, the electricity generated from the wind turbines and solar panels is exclusively allocated to hydrogen production, the desalination of seawater and other maintenance operations within the production site. Second, the desalinised seawater is exclusively used as feedstock to produce H_2 and other maintenance operations within the production site. Third, the electricity produced is delivered just-in-time, which leaves surpluses unexploited. The system lacks both a battery for electricity storage and a connection to the grid.

Figure 4: Simplified representation of the system setup



3.2 Scope of costs

This section dives into the scope of the costs considered for the facility. In order to construct a representative model, the major costs of green hydrogen production are tackled based on their level of importance, according to the report from *Agora Industry and Umlaut (2023)*. All the costs, which are labelled as 'to be considered' and 'individual decision' are addressed in this research, except the stack degradation and the cost of buildings. Appendix 2 lists the cost components that are in and out of the scope of the model.

Additional hypotheses regarding the operation of the plant and cost modelling are made:

Hypothesis 1: The model does not account for down time due to maintenance. It means that there is no hydrogen production only when the electricity supply is too low.

Hypothesis 2: Cost related to location, such as the cost of land and other site conditions related costs are omitted.

Hypothesis 3: The balance of plant and equipment necessary for the operation of the power generation plant, desalination unit, and electrolyser is considered. This includes the costs and energy losses associated with inverters in both the power generation plant and the electrolyser. However, installations such as cables, pipes, pumps, and heat exchangers used to transport water or electricity between the electrolyser, the desalination unit, and the power generation plant are not included.

Hypothesis 4: No loss of power and water leaks are assumed in the transportation between the electrolyser, the desalination unit, and the power generation plant.

Hypothesis 5: The analysis excludes costs associated with the electrical grid, contingency, funding, properties, hydrogen transport and storage, and by-product revenues.

3.3 Area Selection

The selection of pertinent regions is based on three main characteristics, the water stress, the proximity to the coast and the potential for renewable energy generation. The regions are chosen without regard for existing land use, such as agricultural areas and natural reserves, or geographical constraints like rough terrain, although sites must be located onshore and near the coast.

3.3.1 Water stress

In the present study, the Aqueduct Water Risk Atlas from the World Resources Institute is used to define regions with water stress. The research concentrates on regions labelled as having high (40-80%) to extremely high (>80%) water stress or regions classified as arid with low water use. The percentage ratio reflects the total water demand to the available renewable surface and groundwater supplies. Regions with water stress levels above medium will most likely need to develop additional water supply capacity to support green hydrogen facilities. Additionally, this research considers regions classified as "Arid and with low water use." These regions have very low water demand and thus score lower in water stress but lack available water resources (Aqueduct Water Risk Atlas, n.d.).

3.3.2 Coast

To secure water availability and avoid exacerbating water stress, the production facilities analysed in this study are located near the coast to incorporate a desalination unit. The facility exclusively consumes desalinated seawater, ensuring a reliable feedstock for the electrolysis process and mitigating the risk of depleting local water resources. The independent sourcing of water is essential for the well-being of local communities and preservation of the environment.

3.3.3 Potential for renewable energy

In this research, selected sites are characterized by favourable wind and solar conditions. The data used to review and assess potential sites comes from the Global Wind Atlas and the Global Solar Atlas, which provide detailed, location-specific data on wind and solar energy potential.

The Global Solar Atlas provides different metrics to assess the solar potential, with the practical PV potential (PVOUT) being used here. The PVOUT measures the power output generated per unit of installed PV capacity, considering diverse factors that affect the conversion of solar resources into electricity by a PV system. Its unit of measurement is kilowatt-hours per kilowatt peak (kWh/kWp). Places with practical PV potential exceeding 4.5 kWh/kWp per day are regarded as excellent conditions for solar panels (ESMAP, 2020). This research considers places with practical PV potential exceeding 4.5 kWh/kWp per day.

The wind speeds published by the Global Wind Atlas are used to assess potential sites. Areas are considered commercially viable for wind energy if they have average annual wind speeds of 6.5 m/s or higher at 80 meters. Generally, land is regarded as windy if the average wind speed is 6.4 m/s or more (Center for Sustainable Systems, 2023; Elliott et al., 2010). This study employs a more rigorous selection criterion, choosing only locations where wind speeds surpass 8 m/s.

3.3.4 Selected Locations

Three selected sites answering to the previous criteria have been selected. The first site is in Australia and is referred to as “Site 1”. The second site is located in Namibia and is referred to as “Site 2”. The third site is located in France and is referred to as “Site 3”. The precise GPS coordinates of the three sites are listed in Appendix 3.

The following table summarizes the wind and solar characteristics of the selected sites along with the water stress levels at each location.

Table 2: Selected sites summary

Site	Daily PVOUT [kWh/kWp]	Wind speeds [m/s]	Water stress
Site 1	5.18 - 5.33	9.10	Arid and low water use
Site 2	5.44 – 5.64	8.94	Arid and low water use
Site 3	4.52	8.09	High

3.4 Data

Now that the system set-up and the selection of the location have been explained, data collection is the last step before going into the model assumptions and justifications. As explained previously, the outcomes of the model largely depend on the weather data of the site analysed. It is therefore crucial to have data from a reliable source.

Hourly wind and solar data are obtained from a data access viewer that provides global meteorological data measured by satellites of the NASA (Stackhouse, n.d.). The interest of this database is that it provides hourly data for any specified coordinate, thus delivering a high degree of accuracy for the chosen site. By definition, the LCOH is calculated over the entire lifetime of the facility. However, data for a single year is collected to run the optimization, with the results being extrapolated to the entire lifespan of the facility. The dataset is deemed a representative sample of the climatic patterns expected at the location.

The solar irradiance data retrieved is the "*CERES SYN1deg All Sky Surface Shortwave Downward Irradiance (Wh/*m^2*)*" dataset and spans over a duration of one year. It provides data for the Global Horizontal Irradiance (GHI) index, which quantifies the total amount of solar irradiation received by a horizontal surface in watt-hours per square meter. The wind conditions are measured by the "*MERRA-2 Wind Speed at 50 Meters (m/s)*" parameter, which quantifies wind speeds in meters per second at an altitude of 50 meters above ground level. The collected data is further downloaded into an Excel file.

After outlining the thesis' overall approach, detailing the system setup, defining the scope of costs considered and selecting sites, the next chapter introduces the general formula of the model and delves into the equations that form the foundation of the model.

Chapter 3 Levelized Cost of Hydrogen

As stated by its title, chapter 3 deals with the Levelized Cost of Hydrogen (LCOH) model. Section 1 of this chapter explains the formulas that govern the relationships among the different parameters and variables. Section 2 presents the objective function and constraints of the optimization. The model is optimized based on data for one year, before extrapolating the results to the whole lifetime of the facility. The LCOH can be computed for a specific site by plugging in local weather data, as described in chapter 4.

1 The LCOH Model

The levelized cost of hydrogen represents the average cost per kilogram of produced hydrogen, levelized over the plant's lifetime, including the years of construction and the years of operation. The LCOH metric is the ratio of all the cost of hydrogen production to the mass of hydrogen produced. In simple terms, it indicates how much it costs to produce 1 kg of H_2, considering the upfront capital investment and the cost of operating the assets involved in its production.

1.1 The LCOH formula

The formula used to model the cost per kg of hydrogen is the following:

$$LCOH = \frac{\sum_{t=0}^{T} \frac{Electrolyser_t}{(1+WACC)^t} + CE_{lifetime}}{\sum_{t=0}^{T} \frac{Mass_t^{H2}}{(1+WACC)^t}} + CW$$

The formula reflects the setup of the facility, which consists of the electrolyser, the power generation plant, and the desalination unit, as described in Chapter 3. Thereby, each component is represented by a term in the numerator: $CE_{lifetime}$ is the Cost of the Electricity (CE) consumed by the electrolyser, while $Electrolyser_t$ covers the investment and operating costs associated with the electrolyser over the lifetime of the plant. The cost of water (CW) represents the costs of desalination, including electricity costs.

The formula involves discounting the mass of hydrogen produced, as done in studies by Tang et al. (2022), Park et al. (2023) and Dogliani et al. (2024). The CE and the CW do not need to be actualised since the Levelized Cost of Electricity and the Levelized Cost of Water are integrated in both terms. The CW is not divided by the mass of hydrogen because it is expressed as a cost per kilogram of hydrogen, as explained later in this section. The formulas associated to these three components are further described in their respective subsections, namely: "*Electrolyser*", "*Cost of electricity*", and "*Cost of water*".

1.2 Electrolyser

The total cost associated to the electrolyser includes both capital expenditures (CAPEX) and operational expenditures (OPEX). The initial CAPEX is substantial due to the purchase of components and the construction of the installation in the first year. Ongoing operational expenses occur throughout the electrolyser's lifespan, and stack replacements are required every seven years, as explained in Chapter 4.

$$Electrolyser_t = CAPEX_t^{elec} + OPEX_t^{elec}$$

The costs of the CAPEX are broken down into the stack, the gas conditioning, the power electronics, and the balance of plant. The OPEX of the electrolyser constitutes a fixed percentage (ω) of the CAPEX.

$$CAPEX_t^{elec} = \mathrm{Stack}_t + \mathrm{GC}_t + \mathrm{PE}_t + \mathrm{BoP}_t$$

$$OPEX_t^{elec} = \omega * CAPEX_0^{elec}$$

The total cost of the electrolyser is obtained by summing the yearly costs during the lifetime of the facility and actualizing them.

1.3 Cost of electricity

To determine the total electricity costs in one year, the levelized cost of electricity (LCOE) for both solar and wind is multiplied by the amount of energy generated from each source.

$$CE_t = \sum_{h=1}^{8760} LCOE^S * E_h^S + LCOE^W * E_h^W$$

The cost of electricity derived from the one-year optimization is multiplied by the facility's operational duration to calculate the total electricity cost over its lifetime:

$$CE_{lifetime} = t * CE_t$$

1.3.1 Solar energy output

Several factors need to be considered to convert the GHI into solar energy output: the modules' efficiency, their orientation and tilt, their surface along with losses due to shading, reflection, temperature, wiring, etc (Sandia National Laboratories, n.d.). There is no single formula that can capture all these factors, but a simplified approach is to use in the following equation (Hoogwijk, 2004; Mahtta et al., 2014):

$$E_h^S = z * A * GHI_h * \eta * PR$$

1.3.2 Solar levelized cost of electricity

The calculation of the levelized cost of electricity from solar source is done using the formula used by the Energy Sector Management Assistance Program (ESMAP, 2020).

$$LCOE^S = \frac{\sum_{t=1}^{T} \frac{CAPEX_t^S + OPEX_t^S}{(1 + WACC)^t}}{\sum_{t=1}^{T} \frac{E_t^S}{(1 + WACC)^t}}$$

where:

$$CAPEX_t^S = z * C^S * IC^S$$

$$OPEX_t^S = z * C^S * \ OC^S$$

The CAPEX is calculated by multiplying the number of solar modules by the installed cost per kWp and the installed capacity of one module in kWp. Similarly, the OPEX is calculated by multiplying the number of solar modules by the operating cost per kWp and the installed capacity of one module in kWp.

1.3.3 Wind energy output

The following formula is used to estimate the energy produced by a wind turbine in one hour (Singh & Santoso, 2011; Kalmikov, 2017):

$$E_h^W = \frac{1}{2} * \rho * R * v_{h,i}^3 * C_p$$

The wind speed data collected from NASA was obtained at a height of 50 m above ground level. However, for this study, wind turbines with hub heights of 100 m are chosen. To adapt the data to these hub heights, the widely accepted power law is employed, as detailed in the following equation (Kamau et al., 2010):

$$\frac{v_{h,i}}{v_{h,j}} = \left(\frac{d_i}{d_j}\right)^{\alpha}$$

The value of α is discussed in chapter 4.

1.3.4 Wind levelized cost of electricity

The calculation of the levelized cost of electricity of wind turbines follows the same methodology as the one used for solar.

$$LCOE^W = \frac{\sum_{t=1}^{T} \frac{CAPEX_t^W + OPEX_t^W}{(1 + WACC)^t}}{\sum_{t=1}^{T} \frac{E_t^W}{(1 + WACC)^t}}$$

where:

$CAPEX_t^W = \tau * C^W * IC^W$

$OPEX_t^W = \tau * C^W * OC^W$

The CAPEX is calculated by multiplying the number of wind turbines by the installed cost per kWp and the installed capacity of one turbine in kWp. Similarly, the OPEX is calculated by multiplying the number of wind turbines by the operating cost per kWp and the installed capacity of one turbine in kWp.

1.4 Cost of water

The electricity consumption of the desalination unit is included in the LCOW. Therefore, it is not accounted for in the cost of electricity. To determine the water cost, the levelized cost of water (LCOW) is multiplied by the volume of desalinated water needed per kilogram of hydrogen. The formula is:

$$CW = LCOW * DW_{Cons}$$

Where LCOW represents the cost to desalinate a specific volume of water. DW_{Cons} is the number of litres of desalinated water required to produce one kilogram hydrogen. The levelized cost of water and the volume of water required are based on literature research and their values are addressed in chapter 4.

1.5 Energy allocation

The energy produced by the power generation plant is allocated to the electrolyser and the desalination unit:

$$E_h^W + E_h^S = E_h^{elec} + E_h^{DW}$$

A fixed proportion of the generated electricity is allocated to the electrolyser and another proportion to the desalination unit. These proportions are determined based on the specific energy consumption (SEC) of each unit. SEC^{DW} is the amount of energy required to desalinate the volume of water needed to produce one kilogram of hydrogen. SEC^{elec} is the amount of energy required to produce one kilogram of hydrogen from that volume of water. The proportion of energy allocated to each unit is calculated as follows:

For the desalination unit:

$$E_h^{DW} = \frac{SEC^{DW}}{SEC^{DW} + SEC^{elec}} * (E_h^W + E_h^S)$$

For the electrolyser:

$$E_h^{elec} = \frac{SEC^{elec}}{SEC^{DW} + SEC^{elec}} * (E_h^W + E_h^S)$$

This ensures that the energy produced is appropriately distributed based on the specific energy needs of the electrolyser and the desalination unit. The parameter values for SEC^{elec} and SEC^{DW} are set in chapter 4.

1.6 Hydrogen production

Not all the energy allocated to the electrolyser is effectively consumed due to its operation within a specific capacity range. Consequently, the allocated energy E_h^{elec} and the effectively consumed energy E_h^{cons} may differ. This relationship is governed by a constraint detailed in section 2 of this chapter. The total mass of hydrogen produced is calculated by dividing the total energy consumed by the electrolyser by its specific energy consumption:

$$Mass_t^{H2} = \sum_{h=0}^{8760} \frac{E_h^{cons}}{SEC^{elec}}$$

2 Optimization

The aim of this section is to determine the optimal composition of the wind-solar farm. This is achieved by changing the number of solar PV modules and wind turbines to minimize the LCOH. The constraints of the problem are related to operational limitations of the wind turbines, PV panels and the electrolyser. As a reminder, the optimization is based on data for one year, before extrapolating the results to the whole lifetime of the facility.

Functionally, the model's architecture is constructed using Microsoft Excel, facilitating the adjustment of parameters to suit different scenarios and configurations. This adaptability enables to fine-tune the model to local specificities and ensuring representative results.

2.1 Objective function

$$min\ LCOH = \frac{\sum_{t=0}^{T} \frac{Electrolyser_t}{(1+WACC)^t} + CE_{lifetime}}{\sum_{t=0}^{T} \frac{Mass_t^{H2}}{(1+WACC)^t}} + CW$$

2.2 Decision variables

The number of wind turbines: τ

The number of solar modules: z

2.3 Constraints

The number of wind turbines and solar modules are natural numbers, implying that the values are discrete and non-negative:

$$z, \tau \in \mathbb{N}$$

The wind turbines only generate energy when wind speeds are between the cut-in and cut-out limits, with production ceasing below and above these thresholds. This operational range is set because wind turbines shut down at high wind speeds to avoid mechanical damage, and they cannot generate power at very low speeds:

$$E_h^W = \begin{cases} 0;\ if\ v_{h,i} < v_{min} \\ \tau * \frac{1}{2} * \rho * R * v_{h,i}^3 * C_p;\ if\ v_{min} \leq v_{h,i} < v_{max} \\ 0;\ if\ v_{h,i} \geq v_{max} \end{cases}$$

The wind farm's energy production is capped by its total installed capacity. For instance, a wind farm counting 10 turbines of 5.5 MW cannot produce more than 55 MWh per hour. At any point in time, the energy generated is either equal to the energy produced by all the turbines together or the wind farm's maximum capacity. The following constraint ensures that the energy generated does not exceed the wind farm's maximum capacity:

$$E_h^W = \begin{cases} \tau * \frac{1}{2} * \rho * R * v_h^3 * C_p;\ if\ \tau * \frac{1}{2} * \rho * R * v_h^3 * C_p < \tau * C^W \\ \tau * C^W;\ if\ \tau * \frac{1}{2} * \rho * R * v_h^3 * C_p \geq \tau * C^W \end{cases}$$

Similarly, the solar farm's energy production is capped by its total installed capacity. At any point in time, the energy generated is either equal to the energy produced by all the panels together or the solar farm's maximum capacity. The following constraint ensures that the energy generated does not exceed the solar farm's maximum capacity:

$$E_h^S = \begin{cases} z * A * GHI_h * \eta * PR; if\ z * A * GHI_h * \eta * PR < z * C^S \\ z * C^S;\ if\ z * A * GHI_h * \eta * PR \geq z * C^S \end{cases}$$

The electrolyser operates within a specific capacity range: it shuts down if energy input falls below a certain threshold and runs at full capacity if input exceeds its installed capacity. Within the working range, its consumption is equal to the combined wind and solar energy available.

$$E_h^{cons} = \begin{cases} 0;\ if\ E_h^{elec} < \text{Min power} * C^{elec} \\ E_h^{elec}; if\ \text{Min power} * C^{electr} \leq E_h^{elec} < \text{Max power} * C^{elec} \\ \text{Max power} * C^{elec}; if\ E_h^{elec} \geq \text{Max power} * C^{elec} \end{cases}$$

The values for Min power and Max power will be set in chapter 4 based on literature research.

Chapter 4 Defining the parameter values

As explained in chapter 2, the values of parameters are consistent across sites. In this chapter, the parameter values for the electrolyser, the power generation plant and the desalination unit of all sites are discussed.

The values for the LCOH parameters are justified through a five-step process. First, this chapter delves into the cost of capital linked to the project development. Second, the cost of the electrolyser, encompassing both capital expenditure (CAPEX) and operational expenditure (OPEX), are examined. Third, the section about the power generation plant describes wind-solar mix, including the parameters of the solar panels and wind turbines. Fourth, the discussion covers the water volume and quality requirements for the electrolyser, alongside an analysis of desalination technology, including its energy consumption and cost. Parameters related to water are established accordingly. Fifth, the specific energy consumption of the electrolyser is determined which is essential to calculate the amount of hydrogen produced.

1 Discount rate

In this study, a single Weighted Average Cost of Capital (WACC) is used to discount the different components of the LCOH formula. The alternative approach is to use distinct WACC values for each component and involves employing a different WACC when discounting costs associated with the electrolyser versus a wind turbine for example. The downside of this second approach is that it implies that the overall project has a different risk profile and financing structure than its individual components.

On the contrary, adopting a single WACC enables a holistic assessment of risk, capturing the risks associated to the entire project. Projects in the energy sector are subject to broad risks such as market fluctuations, regulatory dynamics, and macroeconomic influences. Additionally, the risk profile associated with green hydrogen is unknown or high due to the small-scale deployment of the technology and the immaturity of the green hydrogen market (OECD, 2023). Therefore, a single WACC provides a more nuanced understanding of the project's risk landscape. Further, a single WACC aligns with the holistic evaluation approach typically undertaken by investors when assessing projects. Investors often scrutinize ventures in their entirety, considering the mix of equity and debt financing as well as the overall risk profile of the project. (Investopedia, 2021). Moreover, applying a uniform WACC ensures consistency across components of the project, simplifies the evaluation procedure, and facilitates comparisons with other projects.

In assessing the cost competitiveness of green hydrogen production, the International Renewable Energy Agency employs two distinct WACC values to reflect two risk profiles. On one hand, the best-case scenario utilizes a WACC of 6%, which is similar to financing conditions for renewable energy projects as of 2020. This is indicative of a lower-risk investment environment. On the other hand, the IRENA applied a WACC of 10% in its 2020 average scenario, reflecting a relatively higher risk associated with nascent hydrogen technologies (IRENA, 2020).

A report by the OECD highlights the knowledge gap concerning the range of WACC for green hydrogen projects. This lack of information concerning the WACC of low-carbon assets is primarily due to the confidential nature of financing structures and the absence of disclosed financial details. According to the OECD's analysis, the weighted average cost of capital ranges from 6.4% to 24%. This broad range, with WACC values reaching up to 24%, can partly be explained by the diverse company profiles within the analysed value chain and the uncertainty surrounding green hydrogen (OECD, 2023).

As will be uncovered in the discussion in the Chapter 5, WACC values have a significant impact on the levelized cost of hydrogen, influencing the feasibility and attractiveness of green hydrogen projects. To address this challenge, a sensitivity analysis will be conducted in the results chapter. This analysis will illustrate the influence of varying WACC levels on the project's key metrics, providing insights into the project's resilience under different financing scenarios and enhancing our understanding of its financial viability.

In light of the considerations outlined above, the following WACC value is used as default parameter:

$$\text{Default parameter: WACC} = 8\%$$

2 Electrolyser

The term "Electrolyser" is used to describe the facility that produces the green hydrogen. The electrolyser includes the stack, power electronics, gas conditioning and balance of plant. It is in the stack that the actual electrolysis of water takes place. Analysing the overall cost required to build and operate an electrolyser is essential since it significantly impacts the price of the output. This section about the electrolyser's cost is divided in 4 parts.

The first part discusses two different electrolyser technology in order to select the preferred one for this research. The second part fixes the capacity of the electrolyser, which is important for the rest of the model as the electrolyser's size has many operational and economic implications. The third part delves into the technical characteristics of the electrolyser. The fourth part focuses on the economics of the electrolyser and defines its investment cost and operational expenses.

2.1 Electrolyser – Comparative Analysis

In terms of the adoption of electrolyser technologies, the global cumulative installed electrolysis capacity reached 700 MW in 2022, with alkaline electrolysers representing approximately 60% of the total installed capacity. Polymer Electrolyte Membrane or Proton-Exchange Membrane electrolysers (PEM) constituted the other significant portion of the capacity. These are the two technologies that demonstrate commercial readiness and are available for large-scale production (Hydrogen Council, 2023). This research exclusively employs one electrolyser technology. The underlying paragraphs compare the key advantages and disadvantages of both technologies to determine which one is best suited for this study based on literature research summarized in table 3.

First of all, PEM technology exhibits superior characteristics for intermittent operations which makes it more suitable for off-grid green hydrogen production without battery storage. As explained in the several researches, PEM electrolysis has a better response time than alkaline electrolysis, which enables PEM electrolysis to react faster when shut down (Sayed-Ahmed et al., 2024). The cold start-up time for an alkaline electrolyser typically ranges from 1 to 2 hours, while for a PEM electrolyser, it only lasts 5 to 10 minutes. Consequently, PEM electrolysers better absorb the fluctuations in electricity production, which is valuable when working with intermittent renewable energies (Sayed-Ahmed et al., 2024).

Further, the lower operating temperatures of the PEM electrolyser gives the electrolyser advantages over the alkaline technology. Operating at temperatures ranging from 50-80°C, improves the energy efficiency of PEM electrolysis compared to alkaline processes, which necessitate temperatures of up to 90°C. Additionally, the lower operating temperatures diminish the needs in water for the cooling processes. On average, PEM electrolysers consume

21.4% less water than alkaline electrolysers (IRENA, 2023). This gives a higher flexibility in terms of implementation of electrolysers in water stressed areas.

A drawback of PEM electrolysers is their higher cost, as they require precious platinum-group metals, making them generally 50%-60% more expensive than alkaline technology. This currently represents a barrier for larger market penetration of PEM technology (IRENA, 2020).

Regarding the purity level of the produced hydrogen, PEM electrolysers produce hydrogen with a purity level around 99.999% , while alkaline electrolysers produce a slightly less pure hydrogen (99.5%). The pressure of the hydrogen output varies across electrolyser models and manufacturers, and both technologies are available in atmospheric and pressurized models. In this research, it is assumed that the electrolyser includes gas conditioning that produce hydrogen at a high pressure as discussed in subsection 2.3 "*Technical characteristics*".

In conclusion, the PEM electrolyser emerges as the best choice for this research due to its alignment with the specific requirements of the system setup. It is more adapted for the intermittent renewable energy sources. The low water consumption and higher efficiency at lower operating temperatures, make it a more suitable option for arid areas. Despite its higher initial cost, the PEM electrolyser produces hydrogen at a purity level of around 99.999% further underscores its suitability for the intended application. Therefore, the PEM electrolyser stands out as the preferred technology in this research. A summary of the advantages and disadvantages of those technologies is summarized in the underlying table.

Table 3: High-Level comparison of Alkaline and PEM technologies

	Alkaline	PEM
Advantages	• Lower CAPEX/OPEX • Mature technology in multi-MW size plants	• Short response time in dynamic operation (Cold & warm start-up time) • Lower operating temperature (50 – 80°C) and lower water consumption • Higher Energy Efficiency • High purity level of hydrogen (99.999%)
Disadvantages	• Need hydrogen purification • Long cold start time • Lower purity level (99.5%) • Higher operating temperature (70 – 90°C)	• Higher CAPEX (Precious metals) • Presence of platinum group metals

Sources: (Matute et al., 2019; Schmidt et al., 2017; IRENA, 2020; Verdin, 2018; Radner et al., 2023; Kumar & Lim, 2022)

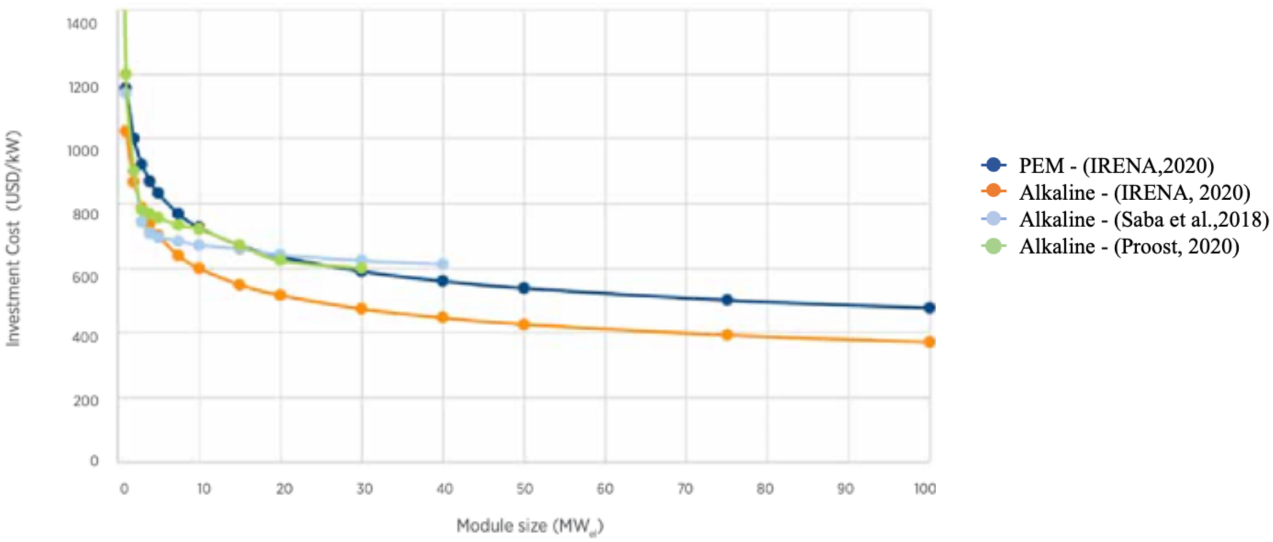
2.2 Electrolyser capacity

An important component of the optimisation problem is the capacity of the electrolyser. The literature argues that the economies of scale in the deployment of the first MW is consequent, this is also called "the scaling-effect". As seen in "*Scaling up Electrolysers to meet the 1.5°C climate goal*" and in "*Cost Projection of Global Green Hydrogen Production Scenarios"*, increasing the scale of the hydrogen plant is predicted to produce significant cost declines. Larger plants, which operate at higher capacities, increase production volumes, enhance equipment utilisation, and yield economies of scales. (IRENA, 2020; Zun & McLellan, 2023)

The underlying figure depicts the scaling effect on a PEM electrolyser. It illustrates a negative correlation between module size expressed in MW and investment cost expressed in $/kW. PEM electrolyser, represented here in bleu, experience a sharp cost decline of around 40% during the expansion of the first 10 MW. Then, scaling from 10 MW to 50 MW decreases investment costs by 25% through the standardisation of components and the design of the plant. To further decrease the investment cost, the capacity of the electrolysers should be considerably augmented, as marginal cost cuts flatten. For example, a doubling of capacities from 50 MW up to 100 MW, only reduces costs by 10%. For this analysis, an electrolyser size of 50 MW, with a cost of $600 per kilowatt, is selected.

Default parameter: $C^{elec} = 50{,}000 \text{ kW}$

Figure 5: Electrolyser investment cost as a function of module size



Source: IRENA 2020

2.3 Technical characteristics

2.3.1 Pressure and purity level

For use in the industry and further down the value chain, the hydrogen must maintain a uniform pressure and purity level. The hydrogen produced from the facility meets the norm ISO 14687-2 and is at a pressure of 30 bar and a hydrogen purity level 5 of 99.999% (Clean Hydrogen Partnership, n.d.). Adequate gas conditioning is part of the electrolyser to achieve those compression and purity levels.

2.3.2 Modular design and load range

Further assumptions are made regarding design of the electrolyser. In this study, a plant design with multiple small stacks is implemented to increase the flexibility of the electrolyser's (IRENA, 2020). This flexibility is an advantage when operating with renewable energy sources, which have variable power outputs. A modular design has two key advantages. First, it reduces the response time after a shutdown since a set of smaller stacks can react more quickly than a single large stack. Second, the modular design allows the electrolyser to function across a wider range of power inputs.

The load range of the electrolyser is constrained by the minimal and maximal power input that the electrolyser can sustain. The upper limit of the working range is materialized by the electrolyser's installed capacity (e.g., maximum 50 MW of power input for a 50 MW electrolyser). The electrolyser also requires a minimum power input to efficiently split water molecules (Egeland-Eriksen et al., 2023). In a modular system, if the available power is less than the minimum required to operate a large, single stack, this power can still be used by turning on only a portion of the smaller stacks. Therefore, the operation limit, or the minimum turndown level can decrease up to 10% (IRENA, 2020). The load range considered in the analysis varies from 10% to 100% of the electrolyser's capacity.

Default parameter: $Min\ power = 10\%$

Default parameter: $Max\ power = 100\%$

2.3.3 Ramp-up time

The model does not account for the ramp-up time and the cold start-up time of the PEM electrolyser. This is the time for the electrolyser to restart producing after having stopped its production. This omission does not affect the results significantly since modern PEM electrolysers can ramp up in less than 10 seconds when they are warm and take between 5 to 10 minutes when they are cold (Sayed-Ahmed et al., 2024). Those number are expected to decrease in the next decade with the significant improvements of the PEM electrolysers (Buttler and Spliethoff, 2018).

2.3.4 Specific energy consumption of the electrolyser

The load factor is the metric that indicates the utilization level of the electrolyser. In this study, the intermittency of renewables and local conditions determine the capacity factor of the electrolyser as there is no battery storage and maintenance time is excluded from calculations.

The model assumes that the electrolyser operates at different load levels, this does not affect the efficiency of production in a consequent way. The efficiency of the electrolyser is the production obtained when powered by the nominal capacity. In this analysis, 55 kWh/kg of H_2 will be set as the electrolyser's specific energy consumption (Clean Hydrogen Partnership, n.d.).

$$\text{Default parameter: } SEC^{elec} = 55\ \frac{kWh}{kg_{H2}}$$

2.4 Cost of electrolyser

This section dives into the costs of the electrolyser where an economic lifetime of 25 years is considered.

$$Electrolyser_t = CAPEX_t^{elec} + OPEX_t^{elec}$$

2.4.1 CAPEX electrolyser

The first element of the equation deals with the upfront investment of the electrolyser, which is considered to costs \$600/kW in this study, for an electrolyser of 50 MW. The breakdown of this investment into the stack, the gas conditioning, the power electronics, and the balance of plant is presented in the following paragraphs.

$$CAPEX_t^{elec} = \text{Stack}_t + \text{GC}_t + \text{PE}_t + \text{BoP}_t$$

Functional and operational details about the stack and other components of the electrolyser were acquired using information from the literature for commercial PEM electrolysis systems. Estimating costs for electrolysers presents two challenges. First, the data is not always publicly available due to its confidential nature and the competitiveness of the market. Secondly, it's challenging to compare the results across studies due to inconsistent boundaries in cost estimates or sometimes the lack of specified boundaries altogether. To deal with those issues, this research establishes a range of values from the literature and selects the most appropriate estimate for a 50 MW electrolyser.

Table 4: Electrolysis system parameters cost for a PEM electrolyser (50MW)

Component	Value	Unit
Stack	300	\$/kW
Gas conditioning	60 (60 – 145)	\$/kW
Power electronics	120 (100 - 217.5)	\$/kW
Balance of plant	120 (100 - 217.5)	\$/kW
CAPEX in year 0	**600**	\$/kW
Stack replacement (every 7 year)	300	\$/kW

Sources**:** (Hydrogen Europe, 2022; Hydrogen Europe, 2023; Clean Hydrogen Partnership, n.d.; Matute et al., 2019; Böhm et al., 2019; Ionomr Innovations Inc., 2020; IRENA, 2020; Mayyas et al., 2019; Zun & McLellan, 2023; Kumar & Lim, 2022)

Delving further into the details of the electrolyser, the primary cost driver is the stack**.** The stack consists of multiple cells connected in series, along with insulation and the opposite electrodes. The cell unit is the central component that actually splits water into hydrogen and oxygen. This is where the actual electrolysis takes place within the stack. The stack represents around 60% of the total electrolyse cost for a 10 MW electrolyser. However, by scaling the capacity of the PEM electrolyser, the percentage cost of the stack can be reduced by up to 30% of the total cost (IRENA, 2020). For a 50 MW electrolyser, this study considers that the stack has an average cost of 300 \$/kW which represents 50% of the total cost.

Stack replacement is a critical aspect of electrolysis system maintenance. The stack has a degradation of 0.12% per 1000 hours (Clean Hydrogen Partnership n.d.), and an estimated lifetime of 80 000 hours (Matute et al., 2019). The progressive stack degradation has an impact on the efficiency rate of electrolyser, which decreases concurrently. When the efficiency value falls below 90%, the stack must be changed. Therefore, the electrolysis plant may require one or more stack replacements during its lifetime. The model assumes that the stack deteriorates each year and loses 1% of efficiency per year. Therefore, after 7 years the membrane is replaced. The cost related to the stack replacement is considered to be equal to the total cost of the stack (300 \$/kW).

Stack replacement: every 7 years

Other cost components necessary for the well-functioning of the electrolysis system are power electronics, gas conditioning, and the balance of plant. Power electronics play a pivotal role as they utilize solid-state electronics for the conversion and control of electric power. This component ensures the efficient and effective operation of the electrolyzer, as it facilitates the transformation of electrical energy into the required form for electrolysis processes. In fact, power electronics account for approximately 15 – 20% of the total costs associated with electrolysers (Böhm et al. 2019). This highlights their significant contribution to the overall cost structure of the electrolyser.

Gas conditioning involves compressing hydrogen for its transport or storage and purifying it to a level of 99.5% to 99.999% to insure safe use in industrial applications. The cost for gas conditioning constitutes around 15% of the total cost for alkaline systems and falls to about 10% for the PEM installations (Böhm et al., 2019). In general, the compression costs are relatively low, and decreases even more if the scale of the electrolyser is consequent.

Moreover, the balance of plant includes all subsystems required for the operation of the facility. This encompasses processes such as heat recovery and rejection, waste collection and disposal, power supply and distribution, handling of process materials for transport, control, safety, and maintenance and repair. All the required material such as power transformers, wires, pumps, and compressors are included in the balance of plant. The main cost component of the balance of plant is the power supply system, which represents 20% of the total cost for a medium-scale electrolyser, as analysed here.

2.4.2 OPEX electrolyser

The cost of electricity and water are not accounted for in the operational expense term of the LCOH but are assigned to the *Cost of Electricity* and *Cost of Water* terms respectively. Therefore, the OPEX of the electrolyser only includes labour, maintenance and repair, insurance, taxes, and other expenses required to operate an electrolyser. The yearly electrolysis OPEX for a PEM electrolyser of 50 MW is considered to be 5% of the electrolyser investment costs for the further computations (Clean Hydrogen Partnership n.d.).

Default parameter: $\omega = 5\%$

3 Power Generation Plant

3.1 The wind and solar mix

A main challenge facing solar and wind energy is the reliability of electricity generation due to their intermittent nature. In this study, the production facility is even more vulnerable to intermittency since it is not connected to the grid and lacks the capacity to store surplus energy. According to a study led in California, combining solar panels with wind turbines in a hybrid network can enhance the capacity factor of the entire system. A solar-wind mix can smooth out energy production if the wind and solar irradiation have a complementary pattern at the selected location (Nouri et al., 2019).

Studies in Australia showed the complementarity and synergy between wind and solar energy. A first study about the prospects of renewable energy in Australia mentions the complementary pattern of solar and wind (Shafiullah et al., 2012). A second study assessed the synergy of solar and wind resources in Australia and concluded that there are clear indications of the complementary nature of solar and wind resources across different regions of the country. The study adds that it becomes evident that mitigating variability and intermittency is possible. Moreover, the study states that the temporal synergy between solar and wind resources reaches its peak when very close to the western and southern coasts (Prasad et al., 2017). Interestingly, 'Site 1' is located on the western coast, very close to the sea.

The power output calculated from the data retrieved from the NASA database seems to indicate complementarity between wind and solar energy in the chosen location in Australia. Specifically, the following pattern emerges. At the start of the day, solar output ramps up while wind output declines. Conversely, in the afternoon, solar output begins to decline, while wind output ramps up. This interplay is depicted in the graph provided in Appendix 4, illustrating the typical weekly profile at the selected locations.

The specific wind-solar mix is optimized as to minimize the electricity cost per kg of hydrogen based on local weather data, the size of the electrolyser, technical characteristics of the electrolyser, wind turbines and solar panels.

3.2 Solar PV parameters

This subsection delves into the parameters used to calculate the energy production of the solar farm.

3.2.1 PV module surface

Solar panels are assumed to have a surface of 2.5 square meters.

$$\text{Default parameter: } A = 2.5\ m^2$$

3.2.2 Conversion efficiency

The conversion efficiency of a solar module is a measure of how well a solar panel converts solar irradiance into electricity. The conversion efficiency of panels varies depending on the model. Based on a benchmark of 57 PV modules from various manufacturers, a median efficiency of 22% is established (TaiyangNews, 2024), see Appendix 5.

$$\text{Default parameter: } \eta = 0.22$$

3.2.3 Performance ratio

The performance ratio accounts for losses within the rest of the PV system, such as inverter losses, mismatch losses, shading, and cable losses. According to a report by the Australian Renewable Energy Agency, the average temperature-corrected performance ratio of 26 large-scale solar farms in Australia is 79.3% (ARENA, 2022).

$$\text{Default parameter: } PR = 0.793$$

3.2.4 Solar module installed capacity

According to the IRENA, modules of 0.5 kW are the norm nowadays, with some modules going beyond 0.6 kW already available (IRENA, 2022). In this study, an installed capacity of 0.5 kW is assumed.

$$\text{Default parameter: } C^S = 0.5\ kWp$$

3.2.5 Solar module installed cost (CAPEX)

The IRENA publishes total installed costs per kilowatt peak of solar PV in its yearly *Renewable Power Generation Cost Report* (IRENA, 2022). This study uses the global weighted average total installed costs of solar PV, which amounted to $ 876 per kilowatt peak in 2022.

$$\text{Default parameter: } IC^S = 876\ \frac{\$}{kWp}$$

3.2.6 Solar module operating cost (OPEX)

Next to CAPEX costs, the IRENA also publishes estimations of OPEX costs for PV plants for OECD countries since 2010. In this study, the OECD values for the OPEX costs are used across the different sites. OPEX amounted to $17.8 per kWp in 2022 (IRENA, 2022).

$$\text{Default parameter: } OC^S = 17.8 \frac{\$}{kWp}$$

3.3 Wind turbine parameters

This subsection delves into the parameters used to calculate the energy production of the wind farm.

3.3.1 Power coefficient

The power coefficient C_p for a wind turbine is a measure of how efficiently the wind turbine and the associated system convert the wind energy into electricity. The maximum power coefficient is constrained by the Betz limit, which is approximately 16/27, or 0.59, representing the theoretical maximum fraction of wind energy that any wind turbine can extract (Kalmikov, 2017). In practice, the amount of power a wind turbine can generate is closer to 50% of the available wind power (Shafiullah et al., 2012). A study on 10 different wind turbine models, ranging from 330 kW to 7,500 kW in rated power, observed similar coefficients of performance across sizes. All studied turbines reached performance coefficients near 0.5 for wind speeds within the range of 5 m/s to 10 m/s (Libii, 2013).

$$\text{Default parameter: } C_p = 0.5$$

3.3.2 Air density

The air density in coastal areas, as in any location, can vary depending on temperature, humidity, and altitude. However, at sea level, the standard air density is approximately 1.225 kg/m³ at 15 °C and 1013.25 hPa. This value can decrease with altitude and will also change with variations in air temperature and humidity (Ulazia et al., 2019; Avila et al., 2019).

$$\text{Default parameter: } \rho = 1.225 \frac{kg}{m^3}$$

3.3.3 Rotor diameter

R is the area swept by the rotor of the turbine in square meters (m²), which is equal to Pi times the square of the radius of the rotor ($\pi * r^2$). According to the IRENA, in 2022, the weighted average rotor diameter varied by country, ranging from 105 meters to 163 meters (IRENA, 2022). The median value for the 12 countries provided is used as the default value for rotor diameter (Appendix 6).

$$\text{Default parameter: } d = 141\ m$$

3.3.4 Power law exponent

The exponent α depends on factors such as surface roughness, wind speeds, and temperature. An exponent of 0.14 or (1/7) has been widely chosen as a representation of the prevailing conditions (Shafiullah et al., 2012).

$$\text{Default parameter: } \alpha = 0.14$$

3.3.5 Wind turbine operating range

The cut-in wind speed for the wind turbines, which is the wind speed at which they begin generating power, is set at 3 meters per second.

$$\text{Default parameter: } v_{min} = 3\ m/s$$

The cut-out wind speed for the wind turbines, which is the wind speed at which they stop generating power to avoid mechanical damage, is set at 25 meters per second.

$$\text{Default parameter: } v_{max} = 25\ m/s$$

3.3.6 Wind turbine installed capacity

According to the IRENA, in 2022, the weighted average installed capacity varied by country, ranging from 2.6 MW to 4.8 MW (IRENA, 2022). The median value for the 12 countries provided is used as the default value for the installed capacity (Appendix 6).

$$\text{Default parameter: } C^W = 4020\ kWp$$

3.3.7 Wind turbine installed costs (CAPEX)

The most up-to-date data about CAPEX costs for onshore wind are the regional total installed costs reported by the IRENA in its Renewable Power Generation Cost Report that is reviewed and published on a yearly basis. The IRENA reported a global weighted average cost of capital for onshore wind of 1,274 $/kWh in 2022. This cost will be used as capital expenditure for wind turbines. (IRENA, 2022).

$$\text{Default parameter: } IC^W = 1274\ \frac{\$}{kWp}$$

3.3.8 Wind turbines operating costs (OPEX)

The IRENA also publishes the OPEX costs for onshore wind in OECD countries. This number of $36 per kilowatt peak is used for the analysis. (IRENA, 2022).

Default parameter: $OC^{W} = 36\ \frac{\$}{kWp}$

4 Desalination Unit

This section delves into desalination and sets parameter values based on the literature. The first subsection focuses on the water quality required for the electrolysis process and the cooling process. The second subsection provides a brief overview of desalination before outlining the most suitable technology to supply water to the facility under study. The third subsection describes the process of purifying water to the quality level required by the electrolyser. Further, the fourth subsection addresses the water consumption of the entire production facility. It establishes the quantity of water required for the electrolyser and the capacity of the desalination plant needed to meet the demands of the hydrogen production plant. It also sets the water requirements for the cooling process and additional maintenance needs. The fifth subsection explores various factors influencing energy consumption in desalination. Finally, the sixth subsection establishes the cost per cubic meter of water.

4.1 Water quality

The facility analysed in this study requires two types of water with different quality levels. Specifically, the electrolyser demands higher purity water compared to the cooling system. The following two paragraphs will discuss each type of water in detail.

The efficiency of the electrolyser is sensitive to the quality of the feed water, as impurities can negatively affect performance, hydrogen quality, and the electrolyser's lifespan. Exclusively using water of suitable quality extends the device's lifespan and reduces overall maintenance and replacement costs. Furthermore, regularly removing impurity residues from the electrolyser is crucial for maintaining optimal operation over the years (Becker et al., 2023). The water used in the electrolysis process must be purified to meet the specifications of demineralized and deionized ASTM Type I water, also known as "ultrapure water", as defined by the American Society for Testing and Materials (ASTM). ASTM Type I Water has a low electrical conductivity, a resistivity typically higher than $\frac{1\mu S}{cm}$, and a maximum total organic carbon content of less than 5 µg/L, including minimal sodium and chloride levels. (Jonsson & Massgard, 2021, Becker et al., 2023; Almutairi & Binhazzaa, 2023)

Another water type utilized in the facility is referred to as "fresh water," which serves for cooling, power generation, and maintenance without needing to meet ASTM Type I standards. To obtain fresh water from the sea, seawater undergoes screening, clarification, and filtration before going through the desalination process once.

4.2 Desalination – Comparative Analysis

Desalination is a process that involves the removal of salt and various impurities from seawater, wastewater, or groundwater to generate fresh water. Over the last two decades, desalination has been widely employed to address water shortage issues and significant reductions in desalination costs have been achieved (Zheng et al., 2020).

Two commonly employed desalination methods are distillation, where water is evaporated and subsequently condensed to eliminate impurities, and reverse osmosis, which involves pushing water through a semi-permeable membrane to separate salts and other imperfections (Zheng et al., 2020). Sea Water Reverse Osmosis (SWRO) does not require heating to evaporate the water which makes it less energy intensive than distillation. SWRO reduces electricity requirement compared to thermal technologies such as multi-stage flash distillation (MSF) and multi-effect distillation (MED). When evaluating technologies commercialized at scale, the literature suggests that SWRO is currently the most efficient and cost-effective option for clean water production (Kim et al., 2019; Curto et al., 2021; Feria-Díaz et al.,2021).

The cost attractiveness of reverse osmosis (RO) is reflected in the global installed capacity: In 2020, RO accounted for 68.7% of installed capacity, MSF for 17.6%, MED for 6.9%, and 6.8% was attributed to other technologies that played a marginal role (Curto et al., 2021). SWRO is anticipated to dominate the global market, thanks to lower energy consumption, cost and environmental impact (Caldera & Breyer, 2017; Ghaffour et al., 2013; Gude, 2016; Jonsson & Massgard, 2021).

Based on the factors outlined above, SWRO is the desalination technology chosen to produce the fresh water and ultrapure water. A representation of the Reverse Osmosis desalination process is represented in Appendix 7.

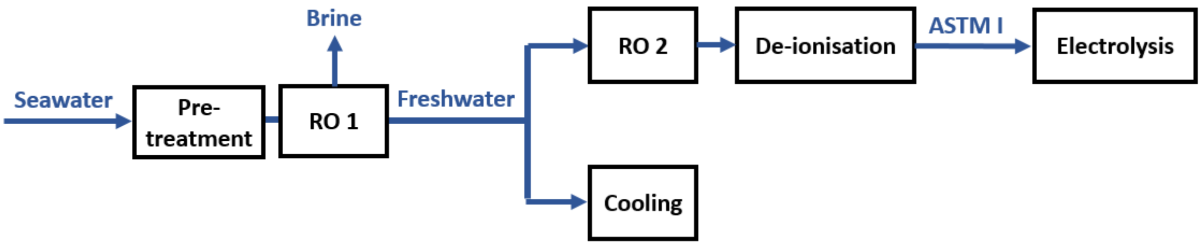
4.3 The desalination process

The desalination of water generates additional cost and operational complexities because it consists of a succession of treatments. This subsection briefly describes the process. Appendix 8 illustrates a typical SWRO desalination plant.

Seawater's high salinity and the presence of dissolved solids pose a threat to the membranes employed in SWRO systems, leading to increased costs. Therefore, the desalination processes generally start with a pre-treatment phase where screening removes large debris that could damage equipment further down the line. Chemicals are added to purify the water and reduce the concentration in organic materials, while filtration and clarification removes suspended solids.

After pre-treatment, the freshwater for cooling purposes undergoes a single pass-through RO membrane, whereas the water for the electrolyser must pass through reverse osmosis twice and undergo electro-deionization to meet the ASTM I standard (Feria-Díaz et al., 2021). As explained before, reverse osmosis uses pressure to force water through a semipermeable membrane, removing contaminants and impurities to produce clean water. The system includes high-pressure pumps along with an energy recovery device to recover hydraulic pressure from the concentrate stream (Kim et al., 2019). Electro-deionisation is done via an ion exchange resin, to achieve high purity water (Almutairi & Binhazzaa, 2023). A simplified representation of water flows is depicted in figure 6.

Figure 6: Simplified representation of water flows.



4.4 Water Consumption

To quantify the total water consumption, a comprehensive analysis of the facility's usage is conducted, consisting of three components: seawater (SW) utilized in the desalination process, ultrapure water (UW) employed in the electrolysis process, and freshwater (FW) utilized for cooling.

In accordance with ISO 14046:2014 standards, the following definition of water consumption is used: "Amount of water withdrawn from a water source that is not returned to its source of origin because it is incorporated into the products, lost through evaporation, or discharged as waste stream due to its degraded quality" (*ISO 14046:2014*). In this case, the facility does not increase the local fresh water stress since abundant seawater is the sole source of water.

4.4.1 Seawater

It is worth noting that among various water sources such as surface water, groundwater, brackish water, and recycled water, seawater is the source of water that requires the most intensive desalination process. As a consequence, a larger volume of seawater is required to produce the same output of freshwater. Only 40% of the seawater volume is effectively converted into freshwater. Some of that fresh water is directly used for cooling, while the rest is further processed to become ultrapure water for electrolysis. A part of the freshwater produced is also used to wash the membranes of SWRO to maintain their efficiency (Jonsson & Massgard, 2021; Becker et al., 2023). The remaining 60% of the initial seawater intake is left over as a hypersaline concentrate, commonly referred to as "brine", which necessitates proper disposal. If not done properly, disposal also carries detrimental environmental impacts (Jones et al., 2019).

4.4.2 Fresh Water

According to the IRENA, cooling makes up for more than 50% of the water needs of green hydrogen facilities. As explained in subsection 2.1 of this chapter, an advantage of PEM electrolysis is that it generates less heat than alkaline production, thereby reducing the need for cooling (IRENA, 2023).

The freshwater consumption is determined by the specific design of the cooling system. The three primary cooling options are: evaporative closed-loop cooling, once-through cooling, and air cooling. Several factors affect the choice of the cooling technology such as the type of electrolyser, the electrolyser's efficiency, the climatic conditions surrounding the facility, the age of the equipment and its operating profile. This study encompasses a PEM electrolyser operating under a variable profile in dry climates, alongside cooling equipment that is considered to be in its early life. In this context, an evaporating cooling water system is the most suitable option (Department of Climate Change, Energy, the Environment and Water & Australian Hydrogen Council, 2022). Appendix 9 provides a comparative table of the different cooling systems.

Water conservation in an evaporative system is higher than in a once-through cooling. A part of the water is not consumed or evaporated during the process and can be reused, resulting in a lower water usage. By reducing the need for constant replenishment of water, the evaporative closed-loop system leads to cost savings in water procurement and treatment. This makes it a financially attractive choice, particularly in areas with arid climates and restricted access to water resources. Evaporative systems also have a scalability advantage since they can accommodate larger electrolysers, making this solution suitable for scaling to larger sizes.

60 litres of freshwater are required per kilogram of green hydrogen for an evaporative system in warm and arid regions (Department of Climate Change, Energy, the Environment and Water & Australian Hydrogen Council, 2022). On average, around half of the freshwater utilized in the cooling loop is consumed through evaporation. In this study, it is considered that 33 litres of new freshwater have to be supplied per kg of hydrogen.

$$FW_{cons} = 33\ \frac{L}{kg_{H2}}$$

Latest research highlights that the energy source of the desalination unit, is a significant parameter affecting the water consumption. Power generated from fossil fuels or nuclear energy, consumes a large amount of water for cooling and the steam that drives turbines (Zhang et al., 2022). On the contrary, wind and solar energy do not require a consequent amount of water due to the absence of a consequent cooling process. Wind energy requires water only for washing the turbines and the blades, while photovoltaic solar uses water only to wash dust or dirt from the panels (Nouri et al., 2019). Therefore, this study does not consider the water consumption of the power generation plant.

4.4.3 Ultrapure Water

According to the literature, this study considers that 10 litres of ASTM Type I water is required to produce 1 kg of hydrogen (IRENA, 2022).

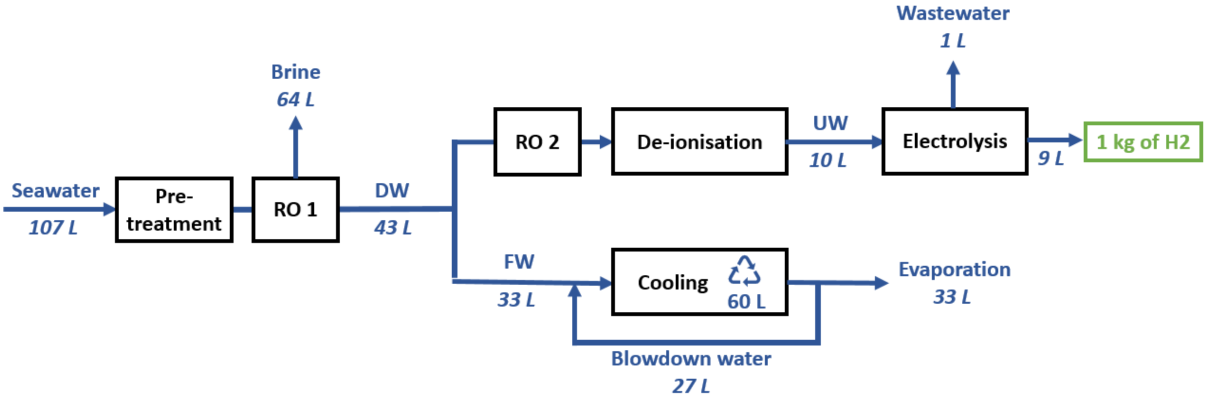
$$UW_{cons} = 10\frac{L}{kg_{H2}}$$

4.4.4 Total Water Consumption

The underlying schema summarizes the findings of this subsection. For each kilogram of green hydrogen produced by a 50 MW electrolyser, the total seawater intake is 107 litres. This supplies around 43 litres of desalinated water. The water flows are represented in figure 7.

$$DW_{Cons} = UW_{Cons} + FW_{Cons} = 43\ \frac{L}{kg_{H2}}$$

Figure 7: In depth representation of water flows



4.5 Cost of Water

The aim of the following computations is to determine the cost per cubic meter of fresh water coming from the desalination unit. A thorough literature review concerning the cost of water is conducted to establish an approximation that best suits this case study.

The levelized cost of water (LCOW), represents the cost in dollars per cubic meter of fresh water produced from the desalination unit over the lifetime of the plant. The LCOW is already actualised, so the cost of water (CW) is not subject to discounting in the LCOH formula.

The cost of the desalination process is influenced by the size of the desalination facility due to economies of scale. As explained in the previous subsection, a small desalination facility is considered. In a technology review for the cost assessment of water treatment systems, the authors provide a detailed analysis of the expenses of a SWRO plant. According to their study, the cost for a SWRO facility producing 3785 m3 per day is approximately 1.4 $\$/m^3$(Bhojwani et al. 2019). Another report, state that, considering both OPEX and CAPEX over a 20-year period, reverse osmosis achieves a price of $0.67 per cubic meter of desalinated water (Jonsson & Massgard, 2021). According to Caldera & Breyer (2017), the cost ranges from $1.25 per cubic meter in 2015 to $0.77 per cubic meter in 2030. Shalaby (2017) indicates that the average cost of producing one cubic meter of desalinated water for small plants is around $1.25 (Shalaby, 2017). In this analysis, the cost per cubic meter is assumed to be 1.25 $. Our assumption is justified as it aligns with the cost estimates of the literature for small scale desalination units.

$$\text{Default parameter: LCOW} = 1.25\ \frac{\$}{m^3}$$

4.6 Desalination energy consumption

Of the overall energy consumption of the desalination unit, 70% is allocated to the RO process, with the remaining 30% dedicated to water pre-treatment, pumping, distribution, maintenance, and brine disposal (Feria-Díaz et al., 2021).

The energy consumption is highly influenced by the size of the desalination facility. A plant that has larger capacity operates more efficiently and thus reduces the cost per unit of water processed (Zhang et al., 2022). In this research, a desalination unit of small size is considered as approximately 600 m^3 per day are sufficient to cover the water requirements of the electrolyser. The size of the desalination unit is in line with the volumes of high purity water consumed by the 50 MW electrolyser.

As outlined in a technical paper, the specific energy requirements of SWRO ranges between 3.5 and 6 $\frac{kWh}{m^3}$ considering the pre-treatment phase to meet the standards of cooling water (Department of Climate Change, Energy, the Environment and Water & Australian Hydrogen Council, 2022). For additional purification to meet the ASTM Type I requirements, an extra 0.4 – 0.7 kWh/m^3 is needed, which is relatively minor (Kim et al., 2019). In this research, an energy consumption of 5 kWh per cubic meter of freshwater and ultrapure water is employed, similar to the value used in Becker et al. 2023.

Since the electrolyser consumes 43 litres of desalinated water to produce 1 kg of H_2, desalinating water to produce one kg of H_2 consumes 0.215 kWh.

$$SEC^{DW} = DW_{Cons} * 5 \frac{kWh}{m^3} = 43 \frac{L}{kg_{H2}} * 0.005 \frac{kWh}{L} = 0.215 \frac{kWh}{kg_{H2}}$$

Chapter 5 Results and analysis

In chapter 5, the results of the model implementation across the three locations are discussed and analysed to understand the underlying differences shaping the LCOH at each location. Moreover, the cost proportion of the different components is discussed along with the WACC, the mix of renewables, and the amount of hydrogen produced. This aims at highlighting the key components influencing the LCOH.

1 Analysis of model implementation

The underlying table summarizes the findings from three optimisation scenarios conducted in excel. The table provides a breakdown of the production costs associated with the green hydrogen production.

Table 5: Model results

	Site 1	Site 2	Site 3	Unit
LCOH	4.56	4.81	5.92	$/kg
Electrolyser cost	1.13	1.19	1.47	$/kg
Water cost	0.05	0.05	0.05	$/kg
Electricity cost	3.37	3.56	4.39	$/kg
Lifetime hydrogen production	55,584,196	52,600,956	42,642,485	kg
LCOE Wind	25.92	27.31	33.46	$/MWh
LCOE Solar	51.86	47.68	71.47	$/MWh
Number of wind turbines	12	12	12	/
Number of solar modules	0	0	0	/

Before delving into the comparative analysis of the different sites, it is essential to benchmark these results with the costs described in the literature. According to the International Energy Agency (IEA, 2022), production costs range from $2 to $6 per kilogram of hydrogen. Thus, the model's results are consistent and fall within this expected range. It can be seen that the production costs at site 1, which are the lowest among the three sites, are still 52.00% higher than brown hydrogen and 133.85% higher than grey hydrogen.

1.1 Site comparison

The comparison across the different sites reveals differences in hydrogen production costs. These observed cost discrepancies are exclusively attributable to local solar and wind conditions since the same technical and cost assumptions for the components were applied to all three sites.

Site 1 stands out as the most cost-effective location with a LCOH of $4.56 per kg. This cost advantage is primarily driven by a lower electricity cost, at $3.37 per kg, and a lower electrolyser cost per kg, at $1.13. The lower electricity cost indicates that *site 1* has more favourable wind conditions since wind power represents 100% of the renewable energy mix and wind turbines are identical across sites. This is reflected in the fact that *site 1* has the lowest wind LCOE. These favourable wind conditions allow for lower electricity costs and a larger hydrogen production, which reduces electrolyser costs by spreading capital investments over a larger number of kilograms.

In contrast, *site 3* has the highest LCOH with $5.92 per kg. Less favourable wind conditions increase its LCOE to $33.46/MWh and limit production volume to 42.6 million kg per year. As the electrolyser operates fewer hours, it produces a smaller mass of hydrogen, thereby spreading the costs of the electrolyser over less units. This results into a higher electrolyser cost. When comparing site 1 and site 3, a reduction of approximately 13 000 kg in hydrogen production results in a 30% increase in electrolyser cost per kilogram, rising from $1.19/kg to $1.47/kg.

Regarding solar, it can be inferred that s*ite 2* has superior conditions for solar energy since it has the lowest solar LCOE, as solar panels are assumed to be the identical. Despite all sites using the same number of wind turbines and no solar panels, different LCOE and LCOH values highlight the important role of local renewable energy in determining the overall green hydrogen production costs.

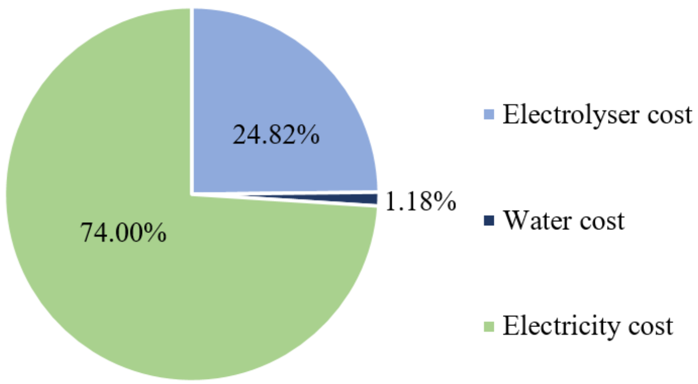
1.2 Costs distribution

The cost structure is almost identical across the locations with some minor differences. The three sites are showcasing approximately the following distribution: 74% electricity costs, 25% electrolyser costs and 1% water costs for the three sites. Figure 8 below shows the share of the main costs for *site 1*. *Site 2* and *site 3* are shown in Appendix 10 and Appendix 11.

This similarity of the cost structures across different locations can partially be attributed to the uniformity of key components such as the desalination unit, the wind turbines, the solar panels, and the electrolyser.

Electricity is by far the most substantial cost components. This result is in line with the previously cited report by Lazard, which revealed that for electrolysers exceeding 20 MW, electricity costs represent 40 – 70% of the levelized cost of hydrogen (Lazard, 2021). The surge beyond 70% in this case is attributable to the utilization of a 50 MW electrolyser, which falls into the higher category of systems larger than 20 MW. As explained in chapter 4, electrolyser investment costs decrease sharply as the module size increases, decreasing to 600 $/kWh for a PEM electrolyser of 50 MW.

Figure 8: total share of the main LCOH costs for site 1



1.3 Weighted average cost of capital

As discussed in chapter 4, there is no common WACC value or standard risk-return for green hydrogen projects as this is a nascent technology. Additionally, WACC values vary across projects, companies, and monetary cycles. As highlighted in a report of ESMAP, several risks impact the cost of capital for clean hydrogen projects, including engineering, procurement and construction (EPC) overruns, offtake defaults, technology non-performance, withdrawal of regulatory incentives, and exchange rate fluctuations (ESMAP, 2023). Uncertainties in so-called emerging countries are even higher. Large clean hydrogen projects in emerging markets encounter high financing costs due to actual and perceived risks, discouraging investors in this new industry (ESMAP, 2023). For all these reasons, conducting sensitivity analyses on the WACC is important to test the resilience and financial viability of green hydrogen projects under different financing scenarios.

The underlying table presents the sensitivity of the LCOH to variations in Wind LCOE and WACC, with WACC ranging from 6% to 20% and wind LCOE ranging from $16/MWh to $36/MWh.

Table 6: Sensitivity of the LCOH ($/kg) to Wind LCOE and WACC

		WACC %							
	4.56	6%	8%	10%	12%	14%	16%	18%	20%
Wind LCOE ($/MWh)	16	2.85	3.27	3.71	4.18	4.67	5.18	5.69	6.22
	18	3.06	3.53	4.02	4.54	5.08	5.63	6.20	6.78
	20	3.28	3.79	4.32	4.89	5.48	6.09	6.71	7.34
	22	3.50	4.05	4.63	5.25	5.89	6.54	7.22	7.90
	24	3.71	4.31	4.94	5.60	6.29	7.00	7.72	8.46
	26	3.93	4.57	5.24	5.95	6.69	7.45	8.23	9.02
	28	4.15	4.83	5.55	6.31	7.10	7.91	8.74	9.58
	30	4.37	5.09	5.85	6.66	7.50	8.37	9.25	10.14
	32	4.58	5.35	6.16	7.02	7.91	8.82	9.76	10.71
	34	4.80	5.61	6.47	7.37	8.31	9.28	10.26	11.27
	36	5.02	5.87	6.77	7.72	8.71	9.73	10.77	11.83

For a wind LCOE of 16 $/MWh, an increase in WACC from 6% to 12%, increases the LCOH by 47.01%. Additionally, an increase in the WACC from 6% to 20% would result in a LCOH increase of 180%. Those substantial increases result from higher financing costs and impact the overall expenses associated with the hydrogen production. This highlights the significant influence of the WACC on the attractiveness of green hydrogen projects.

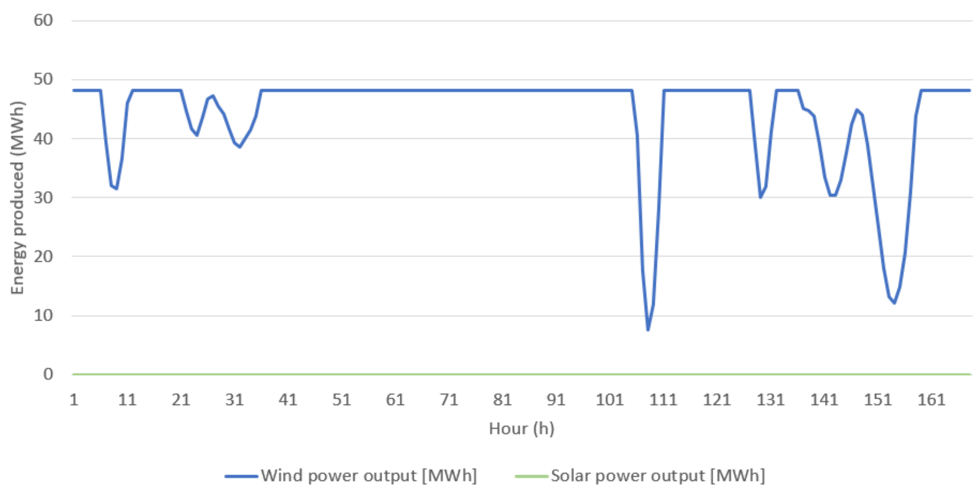
As stated by IRENA in section 3.3 of chapter 1, green hydrogen could become competitive with fossil-fuel based hydrogen in regions endowed with favourable renewable energy sources. When both wind energy costs and financing conditions are favourable, the economics of green hydrogen production start to become attractive. For instance, at a wind LCOE of $16/MWh and a WACC of 6%, the LCOH approaches the cost range of brown and blue hydrogen (2.85$/kg). This indicates that under optimal conditions, green hydrogen production costs can potentially compete with the production costs of other methods. However, this observation should be taken with a grain of salt. The model considers a large-scale electrolyser, which introduces economies of scale and consequently aids in reducing the overall cost of hydrogen production. Moreover, capital should be relatively low and renewable electricity very cheap. According to the IRENA, the cheapest wind power projects can achieve in 2022 is USD 0.024/kWh (IRENA, 2022). Nevertheless, it shows that the combination of low energy costs and low financing rates is essential to achieve competitive production and advancing the adoption of green hydrogen.

1.4 Mix of renewables

For all the sites, wind emerges as the dominant source of power. The prevalence of wind energy is due to its lower LCOE and reduced intermittency when compared to solar energy. Without battery storage, the facility is unable to effectively mitigate the stronger inherent variability of solar production, which fluctuates between day and night. The higher LCOE for solar compared to wind is a global pattern. According to IRENA (2022), the global weighted-average LCOE for wind ranges from $0.033 to $0.035 per kWh, while for solar, it is $0.049 per kWh.

Consequently, the three projects rely on wind energy, which offers a more stable and consistent generation patterns, at lower cost. In the three cases, the model opts for 12 wind turbines and no solar panels. This allows the power generation plant to produce an energy amount close to the 50 MW needed for the electrolyser. The figure below displays the hourly energy output generated by 12 wind turbines at *site 1* over a one-week period. The pattern of energy generation is similar across the three sites (*site 2* and *site 3* in Appendix 12 and Appendix 13.)

Figure 9: Energy production at site 1



To contextualise the study's findings, the renewable energy mix of site 1 is benchmarked against other solar-wind hybrid projects in Australia. An analysis of five renewable energy projects in Australia suggests that wind turbines receive a larger share of the installed capacity compared to solar panels. Specifically, wind and solar accounted respectively for 79.19% and 20.81% of the installed capacity as depicted in Appendix 14. Observations from this benchmark indicates that wind also appears to dominate the mix, though 20.81% is allocated to solar. This discrepancy may stem from the benchmarked project's ability to transfer electricity to the grid, its use of battery storage or its application in a use case that diverges from hydrogen production.

The model's outcomes align with the literature reported LCOE. According to IRENA (2022), the global weighted-average LCOE for wind energy is estimated to be between $33 and $35 per MWh, with some projects even achieving costs as low as $24 per MWh. For solar energy, the average LCOE stands at $49 per MWh (IRENA, 2022). The wind LCOE calculated by the model are between $25.92 to $33.45 per MWh. For solar energy the results are $47.68 per MWh in *site 2*, $51.86 per MWh in *site 1*, and 71.47 per MWh in *site 3*. The slight variance in solar energy costs in site 3 can be attributed to lower solar irradiance at site 3.

1.5 Hydrogen Production

A key technical parameter that directly impacts the amount of hydrogen produced is the specific energy consumption of the electrolyser ($SEC^{electrolyser}$). In this study, it is assumed that 55.5 kWh of electricity are needed to produce 1 kg of hydrogen, while the resultant hydrogen embodies an energy density of 33.3 kWh. Consequently, this indicates a 40% energy loss during the process. It underscores the potential to reduce production costs through technological enhancements in electrolyser efficiency.

Considering the intermittent nature of the energy sources and the operational parameters of the PEM electrolyser, the three sites produce approximately 50 000 tonnes of green hydrogen over their lifetime translating to an average yearly production around 4700 tonnes. By coupling back to the energy density of hydrogen of 33.3 kWh per kg, the facility produces around 157 GWh equivalent of hydrogen per year.

To put this energy production in perspectives it represents around 2% of the annual output of a nuclear reactor, which typically generates about 7,800 GWh per year (*Nuclear Power Reactors - World Nuclear Association*, n.d.). When compared to the energy density of 1 litres of traditional fuel for cars, one litre of gasoline contains around 9.7 kWh of energy. Therefore, the yearly production of the electrolyser is equivalent to 16 135 000 litres of gasoline. As the combustion of a litre of gasoline emits 2.3 kg of CO_2, the hydrogen production would reduce emissions by around 21 500 tonnes (Elert, n.d.).

The average total energy produced in the renewable power plant for the three different sites amounts to 285.8 GWh. On average, the equivalent of 157 GWh comes out of the facility in hydrogen. This implies that 45% of the total energy supplied is lost during the electrolysis and desalination processes.

1.6 Water

Regarding the water expenses, those are uniform across all sites due to the application of a standardized cost of $0.05 per kg. The water consumption of the electrolyser depends on the total volume of green hydrogen produced. To sustain the green hydrogen production observed in the three different sites, approximately 1,500 m^3 of seawater and 600 m^3 of desalinated seawater are required per day.

The desalination facility's annual energy consumption, averaged across the three sites, amounts to approximately 2.7 GWh. With the average wind LCOE at $28.9 per MWh, the average energy expenditure for the desalination unit is estimated to be $80,000 per year. The water cost represents on average 1.07% of the total production cost. Hence, from an economic standpoint, water cost is not a significant factor affecting the LCOH.

Chapter 6 Conclusion

The first part of this chapter includes main insights and implications that can be drawn from the research. The second part addresses the limitations of the current research, acknowledging that some assumptions may impact the generalisation of the results. It further provides suggestions for future research.

1 Key Findings

1.1 Theoretical

First of all, the research contextualizes the discussion surrounding the development of green hydrogen as a potential low carbon solution. Green hydrogen is often presented as a very promising solution for the energy transition. It is essential to emphasize that hydrogen is best suited for specific applications where direct electrification is impractical. This is due to the considerable energy losses incurred during the electrolysis process and the potential reconversion back to electricity. Therefore, the strategic deployment of hydrogen should focus on sectors where it provides the most efficiency such as ammonia production, heavy-duty transportation, and steel manufacturing. As emphasized, high production costs prevent green hydrogen to compete with its fossil-fuel counterparts. The analysis has pinpointed financing rates, electricity costs and the electrolyser as the predominant factors influencing overall expenses.

One key challenge identified is the high WACC rates, which mirror the financial risks and uncertainties linked with green hydrogen project development. This study demonstrates that WACC significantly influences hydrogen production costs, with high rates pushing up costs and impeding the adoption of green hydrogen. Addressing this challenge is crucial for the uptake of green hydrogen.

A second challenge identified concerns the LCOE. An initial statement from the IRENA argued that producing hydrogen in regions rich in renewable energy can potentially lower production costs and compete with blue hydrogen. The production costs computed for site 1, which are the lowest among the three sites, are still 82.40% higher than blue hydrogen. Additionally, the production costs computed at the three sites remain much higher than grey and brown hydrogen. Nevertheless, the research shows that green hydrogen can potentially become economically interesting in regions with abundant renewable resources. In fact, in scenarios where electricity is priced at \$16/MWh and the WACC approaches 6%, green hydrogen comes within the cost range of blue and brown hydrogen.

In this research, water is identified as a critical input for hydrogen production, with particular emphasis placed on analysing water supply and associated costs. This study finds that the energy consumption associated with seawater desalination is not significant in comparison to the energy demands of the electrolyser. Furthermore, the incremental cost of water desalination remains relatively low compared to the overall cost of producing 1 kg of hydrogen. This underscores the economic viability of using SWRO in coastal regions facing water stress.

1.2 Managerial

This thesis not only contributes to the literature on green hydrogen production but also serves as a practical tool for industry practitioners. This research provides practical insights that can guide future green hydrogen projects by introducing a flexible, location-specific cost model. Developers with specific costs for wind turbines, solar power, and electrolysers can utilize the model to calculate the production costs of green hydrogen at specific locations. This allows them to determine the economic attractiveness of hydrogen production in particular regions.

The findings of this study have exposed the notable variations in production costs across different sites. This underscores the model's ability to deliver precise and location-specific cost assessments, which is instrumental for industry stakeholders in making informed decisions.

2 Limitations & suggestions for further research

This section critically examines the boundaries and weaknesses of the research. It acknowledges the inherent limitations of the study, such as certain modelling assumptions, and external factors that may impact the generalisation of the findings. This transparent assessment of limitations is meant to provide context to interpret the results.

2.1 Battery and grid connection

A significant limitation identified in this study is the absence of energy storage, such as batteries, and the lack of integration with the electrical grid. This influences the allocation of the renewable energy mix, resulting in a model that predominantly favours wind energy. Consequently, the model fails to capture the potential complementarity of wind and solar power, which could mitigate resource intermittency. Incorporating a battery or connecting the facility to the grid would make the system setup more realistic and would potentially increase the output of the electrolyser. Future iterations of the model should include a battery or a grid connection to better reflect the realities of renewable energy deployment and its implications for green hydrogen production.

2.2 Electrolyser

Another limitation is that this research studies a 50 MW PEM electrolyser, which benefits from economies of scale that significantly reduce the costs of the electrolyser. It is important to recognize that these cost reductions are specific to the large-scale PEM technology employed in this study. Future research should consider diversifying the scope to include other technologies, such as alkaline electrolysers, and to explore other electrolyser sizes. This would provide a more comprehensive understanding of the cost dynamics across technologies and sizes, ensuring that the findings are applicable to a broader array of scenarios.

2.3 Scope of costs

In this research, a structured approach is used to systematically take the major expenses into considerations via assumptions and hypotheses. However, some costs are not included into the model. For instance, building costs are excluded from this analysis, which could affect the overall cost assessment. Building costs often represent a substantial investment in greenfield projects, and their omission may lead to an underestimation of the true economic cost associated with green hydrogen infrastructure development.

Additionally, another limitation of the study is the impact of stack degradation. Over time, the efficiency of the electrolyser stack diminishes, leading to reduced annual production of green hydrogen. This efficiency reduction is not considered in the optimisation, although the costs of stack replacement are. In light of these limitations, future research should aim to broaden the scope of the analysis beyond these two modelling assumptions.

Another limitation of this research is its exclusive focus on the production costs of green hydrogen. While this study provides a detailed analysis of the factors influencing production expenses, it does not extend to the subsequent costs associated with transport and distribution to end users. The logistics of moving hydrogen from production sites to places of consumption can add considerable costs, particularly when these sites are distant from demand hubs. The exclusion of transportation and distribution costs means that the final price of green hydrogen, as it would be available to consumers, is not fully represented in this study. As such, the research findings should be interpreted with the understanding that the actual cost for the final user will be higher than the production costs. This gap highlights the need for future research to integrate this logistical chain into the cost analysis. By examining the interplay between production site locations and demand hubs, future work can contribute to the development of a more cost-effective hydrogen adoption.

2.4 Environmental impact

This study does not question all the environmental consequences of the production facilities. Several critical environmental factors remain unexplored. These include aspects such as material sourcing, the utilization of precious metals, and the recyclability of components within the hydrogen production process. Furthermore, it's essential to address the challenges of brine generation, the by-product of seawater desalination. By encompassing these overlooked factors, future research can provide a more comprehensive understanding of the environmental implications associated with green hydrogen production.

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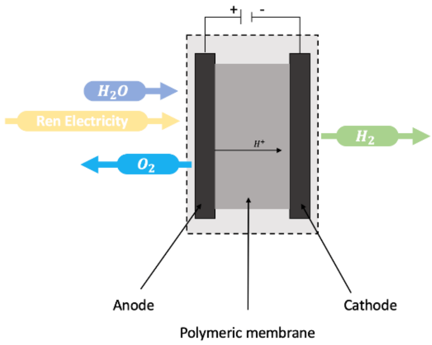
Appendix

Appendix 1: Representation of a PEM electrolyser



Source: Adapted from (Carmo et al., 2013) and (Sayed-Ahmed et al., 2024)

Appendix 2: In and out of scope cost components

The costs ranked in decreasing order of influence are based on a paper of *Agora Industry and Umlaut (2023)*. For the purpose of the research, 2 additional columns were added. The column "component" to understand where the parameters are considered: in the "Electrolyser", in the "Desalination unit" or in the "Power generation plant" (Power). "General" includes costs that are applicable to the electrolyser, desalination unit and power generation plant. "Others" concern costs not covered in this research. The column "Addressed" states whether the parameter is addresses in the study or nor.

Cost		Notes	Component	Addressed
Electrolyser CAPEX		Account for CAPEX scaling influence.	Electrolyser	Yes
Discount rate		Also known as Weighted Average Cost of Capital.	General	Yes
Electricity price		Should include all charges.	Power	Yes
Electrolyser efficiency		Specific energy consumption including auxiliary power [kWh/kg-H2].	Electrolyser	Yes
Electrolyser system lifetime		Major cost driver due to distribution of CAPEX.	Electrolyser	Yes
Stack lifetime & replacement		Costs for stack replacement to be included in the CAPEX.	Electrolyser	Yes
Stack degradation		Considered through average specific energy consumption.	Electrolyser	No
Engineering, Procurement, Construction		Contains usually detailed planning and control, purchasing, execution of construction, installation work and commissioning.	General	Yes*
Buildings		Reflect cost difference between greenfield and brownfield.	General	No

Balance of Plant		Balance of plant typically includes power supply, water conditioning, and process utilities like pumps, process-value-measuring devices, and heat exchangers.	Electrolyser	Yes
OPEX		Typically, in the range of 1.5-5% of CAPEX	Electrolyser	Yes
Compression		Consider compression costs for system output below reference pressure.	Electrolyser	Yes
Hydrogen quality		Identified as a minor cost driver. Nevertheless, it is recommended to calculate with a level 5 quality to ensure that there are no technical issues.	Electrolyser	Yes
Water supply		Costs are to be considered if a seawater desalination plant is required.	Desalination Unit	Yes
Electrical grid		Assumption of an existing grid.	Others	No
Contingency		Not considered in most studies	Others	No
Funding		Funding programmes strongly influenced by political conditions and vary over time.	Others	No
Properties		Vary significantly between countries as well as urban and rural areas.	Others	No
Hydrogen transport & storage		Multiplicity of possible applications	Others	No
By-product revenues		Omit revenues from by-products (waste-heat, oxygen).	Others	No

To be considered   Individual decision   Not to be considered

*According to the computations made by IRENA, the EPC costs are considered within the total installed cost.

Source: (Agora Industry et al., 2023)

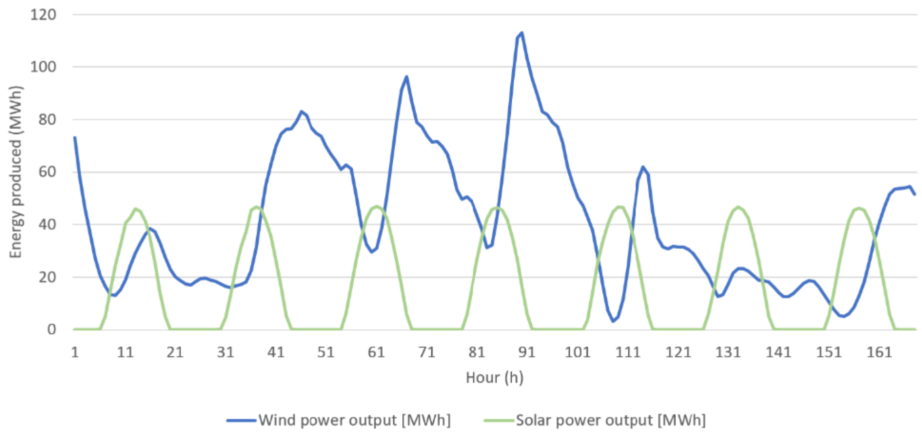
Appendix 3: Coordinates of the three sites.

Precise GPS coordinates of the three sites

Site	Latitude	Longitude	Country
Site 1	-26.856239867	113.755645808	Australia
Site 2	-26.7515°	15.1755°	Namibia
Site 3	43.2167°	5.3898°	France

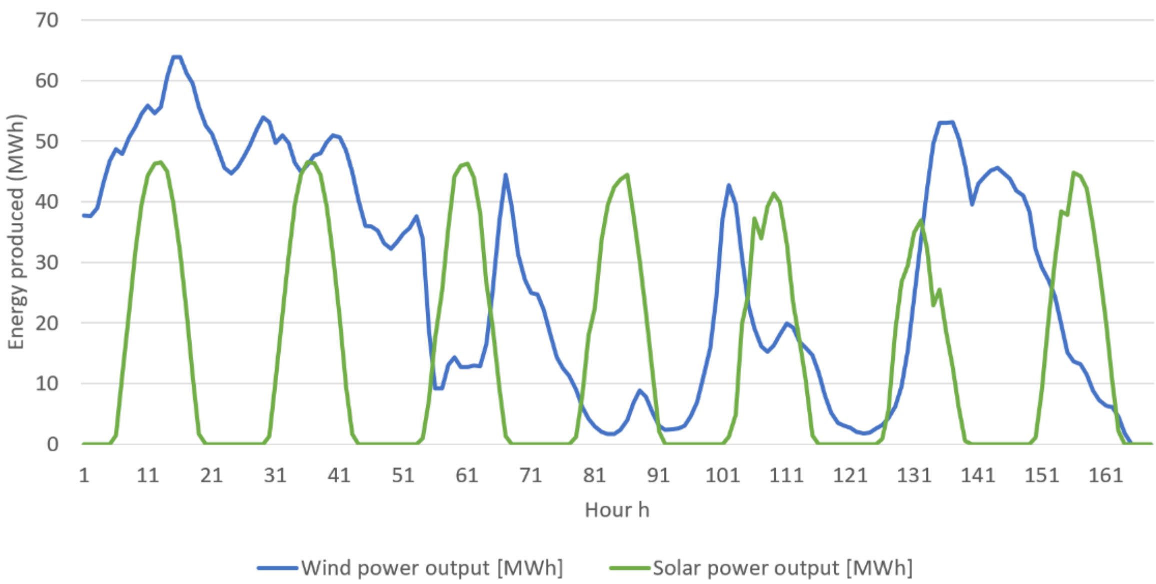
Appendix 4: Weekly profile of the selected sites.

Energy production profile at site 1*



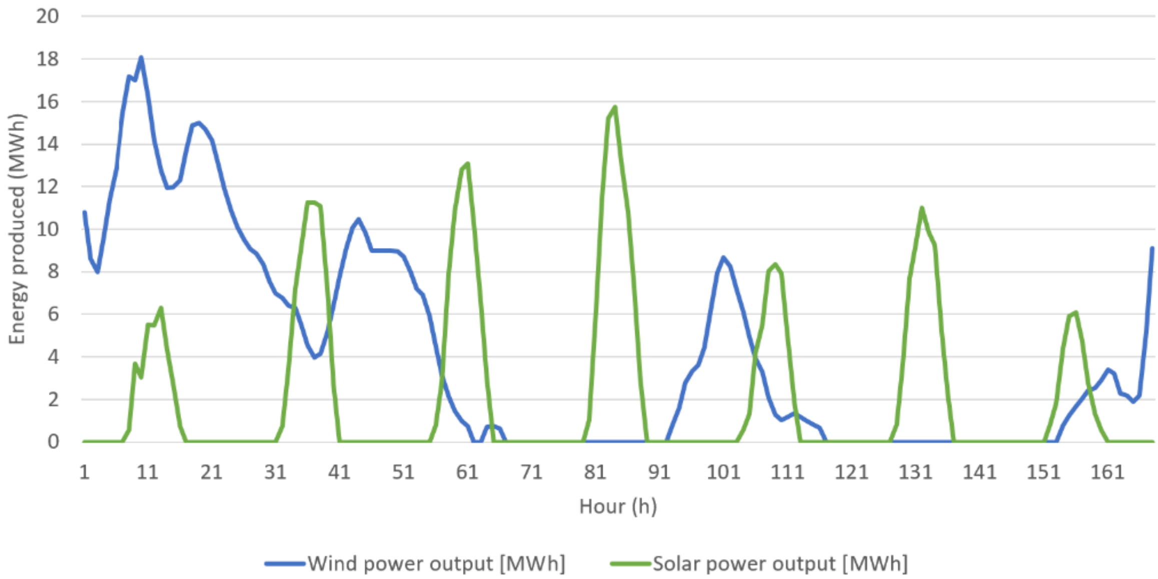
* The displayed energy output was determined using five wind turbines and 100,000 photovoltaic (PV) modules, employing default parameters, and not accounting for the maximum energy production associated with the installed capacity.

Energy production profile at site 2*



* The displayed energy output was determined using five wind turbines and 100,000 photovoltaic (PV) modules, employing default parameters and not accounting for the maximum energy production associated with the installed capacity.

Energy production profile at site 3*



* The displayed energy output was determined using five wind turbines and 100,000 photovoltaic (PV) modules, employing default parameters and not accounting for the maximum energy production associated with the installed capacity.

Appendix 5: Benchmark of PV modules.

Solar module producers' efficiency for different cell technologies in December 2023

Company	Technology	Efficiency (%)
Aiko Solar	ABC	24
Akcome	HJT	22.37
Akcome	PERC	21.68
Astronergy	PERC	21.5
Astronergy	Topcon	22.65
CSI	HJT	22.5
CSI	TOPCon	22.5
CSI	PERC	21.7
CECEP	TOPCon	22.1
CECEP	PERC	21.5
DAS Solar	PERC	21.7
DAS Solar	TOPCon	22.5
DMEGC	TOPCon	22.45
EGing	PERC	21.56
EGing	TOPCon	22.45
Qcells	PERC	21.5
Qcells	TOPCon	-
Qn-SOLAR	PERC	21.57
Qn-SOLAR	TOPCon	22.45
Runergy	PERC	21.5
Runergy	TOPCon	22.5
GCL-Si	PERC	21.6

GCL-Si	TOPCon	22.3
Huasun	HJT	23.02
JA Solar	PERC	21.6
JA Solar	TOPCon	22.5
Jinergy	HJT	21.85
Jinergy	PERC	21.57
JinkoSolar	PERC	21.68
JinkoSolar	TOPCon	22.65
Jolywood	TOPCon	22.53
LONGi	HPBC	23.2
LONGi	PERC	21.7
Maxeon	IBC	23
Meyer Burger	HJT	21.8
REC	HJT	22.3
Risen	HJT	22.5
Risen	PERC	21.7
Seraphim	PERC	21.57
SolarSpace	PERC	21.57
SolarSpace	TOPCon	22.45
SPIC	IBC	22.8
Suntech	PERC	21.7
Suntech	TOPCon	22.4
Talesun	PERC	21.6
Trina Solar	PERC	21.6
Trina Solar	TOPCon	22.5
Tongwei	HJT	23
Tongwei	PERC	21.7
Tongwei	TOPCon	22.5
URECO	HJT	22.44
URECO	PERC	21.57
URECO	TOPCon	22.45
Yingli	PERC	21.57
Yingli	TOPCon	22.36
Yingli	PERC	21.57
ZNSHINE	PERC	21.57
Mean		**22.06**
Median		**22.00**

Source: (TaiyangNews, 2024)

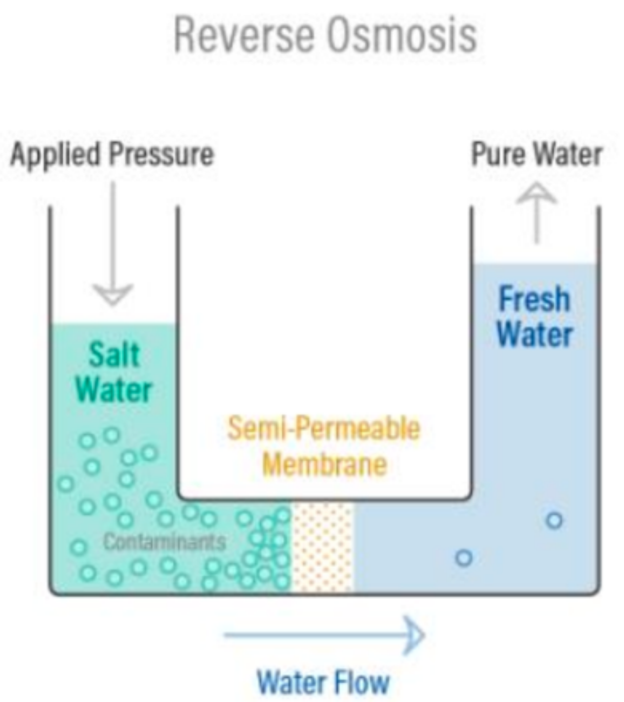
Appendix 6: Wind turbines Benchmark.

Wind turbine weighted-average rotor diameter and name plate capacity in 2022

Country	Year	Nameplate Capacity (MW)	Rotor Diameter (m)
Brazil	2022	4.19	144
Canada	2022	4.67	148
China	2022	4.27	163
France	2022	3.09	121
Germany	2022	4.63	139
India	2022	2.62	130
Japan	2022	3.30	105
Sweden	2022	4.61	145
Türkiye	2022	4.81	145
United Kingdom	2022	3.85	115
United States	2022	3.41	126
Vietnam	2022	3.27	153
Mean	**2022**	**3.89**	**136**
Median	**2022**	**4.02**	**141**

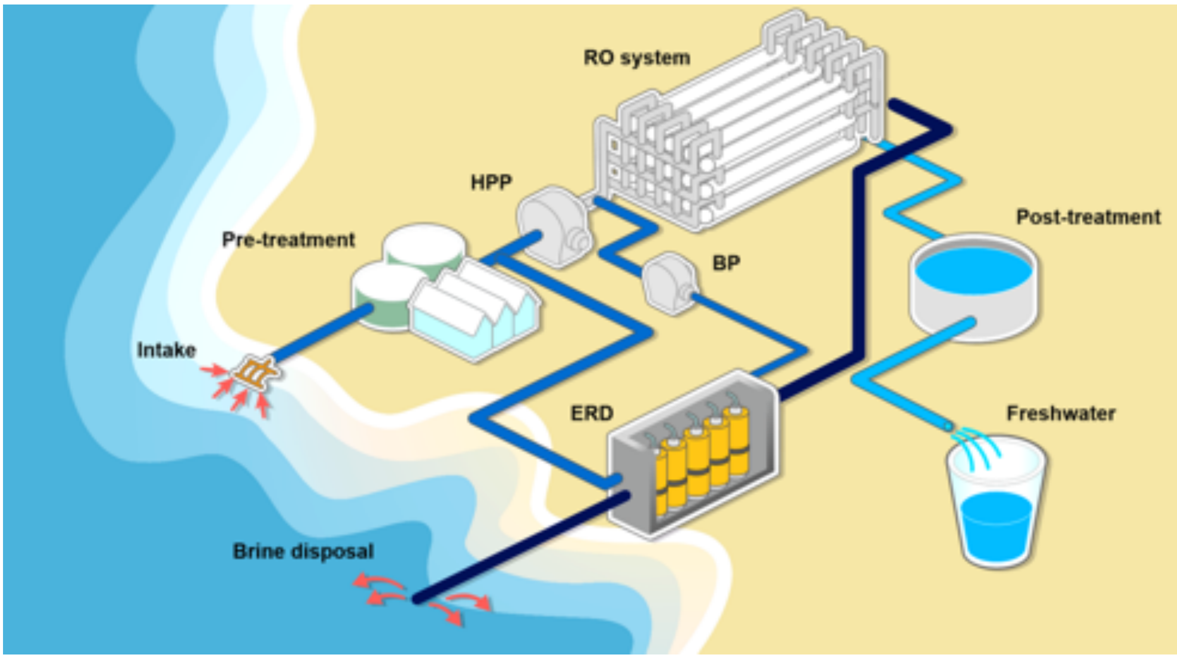
Source: (IRENA, 2022)

Appendix 7: Schematic representation of a Reverse Osmosis process.



Source: (Puretec, 2024)

Appendix 8: Schematic representation of SWRO plant



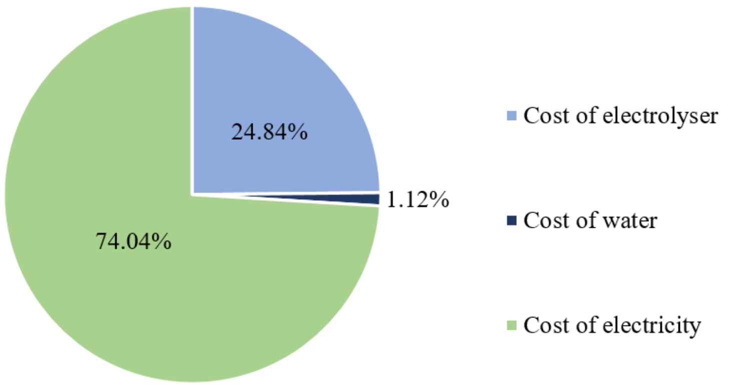
Source: (Kim et al., 2019)

Appendix 9: Comparative table of three different cooling systems.

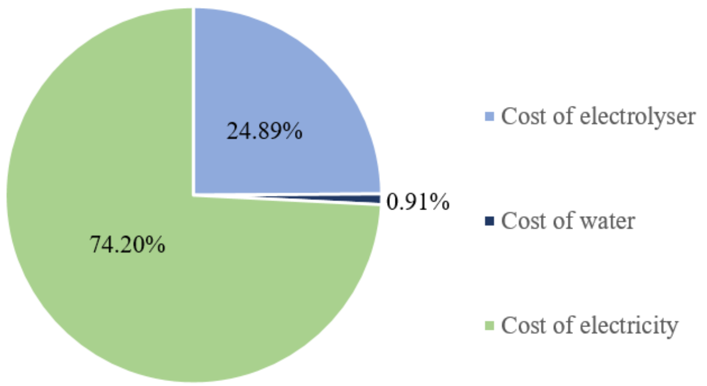
ONCE THROUGH COOLING		EVAPORATIVE COOLING		AIR COOLING	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**	**Advantages**	**Disadvantages**
Little or no water consumption No treatment of cooling water needed Low energy use	Large & continuously replenished total water requirement Siting must be adjacent to water body Potential environmental impact due to high temperature of return water High maintenance	Less total water required than once through Lower energy use Higher efficiency in removing heat	Higher water consumption due to evaporation, higher in dry zone Treatment of cooling water required High maintenance	Zero water required Lower maintenance No waste stream discharge	High capital cost High energy use Large footprint Less effective in dry zone, high temperature Fan noise

Source: Department of Climate Change, Energy, the Environment and Water & Australian Hydrogen Council. (2022).

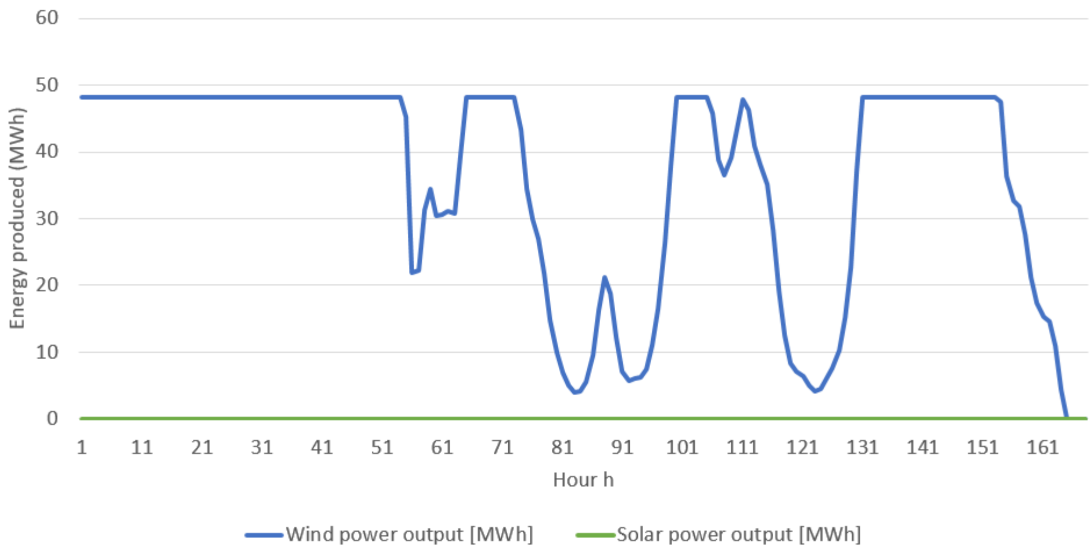
Appendix 10: Total share of the main LCOH costs for site 2.



Appendix 11: Total share of the main LCOH costs for site 3.



Appendix 12: The pattern of energy generation at site 2.



Appendix 13: The pattern of energy generation at site 3.

Appendix 14: Benchmark of mixed wind and solar power generation.

Solar-wind hybrid projects in Australia

#	Country	Name	Component	Value	Unit	Share
1	Australia	Iberdrola	wind	210	MW	66.25%
1	Australia	Iberdrola	PV	107	MW	33.75%
1	Australia	Iberdrola	total	317	MW	100.00%
2	Australia	PGWF	wind	2.5	MW	71.43%
2	Australia	PGWF	PV	1	MW	28.57%
2	Australia	PGWF	total	3.5	MW	100.00%
3	Australia	Kennedy Energy Park	wind	43.2	MW	74.23%
3	Australia	Kennedy Energy Park	PV	15	MW	25.77%
3	Australia	Kennedy Energy Park	total	58.2	MW	100.00%
4	Australia	White Rock Wind Farm	wind	175	MW	89.74%
4	Australia	White Rock Solar Farm	PV	20	MW	10.26%
4	Australia	White Rock	total	195	MW	100%
5	Australia	Gullen Range Wind Farm	wind	165.5	MW	94.30%
5	Australia	Gullen Solar Farm	PV	10	MW	5.70%
5	Australia	Gullen Range	total	175.5	MW	100.00%
			Wind average			**79.19%**
			PV average			**20.81%**

Source: (Iberdrola, 2022), (ARENA, 2023), (ARENA, 2020), (White Rock Wind Farm, n.d.), (*Gullen Range Wind Farm*, n.d.)

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