AALBORG UNIVERSITET

FEASIBILITY OF A PTH PROJECT IN ICELAND

SUSTAINABLE ENERGY PLANNING AND MANAGEMENT
4. SEMESTER
MASTER THESIS

Alba de la Viuda Rodriguez

4th semester. MASTER THESIS
Institute of Planning
Sustainable Energy Planning and Management
Rendsburggade 14, 9000 Aalborg

Title:

Feasibility of a PtH plant in Iceland

Project:

P10-project

Project period:

February 2024 - June 2024

Project author:

Alba de la Viuda Rodríguez

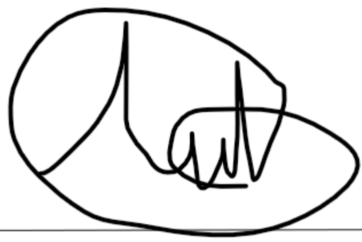
Supervisor:

Anders N. Andersen

Number of pages: 83
Bibliography: 15
Finished: 03/06/2024

Synopsis:

The aim of this project is to examine the feasibility of a Power-to-Hydrogen project in Iceland. The motivation behind this study is that Power-to-hydrogen potentially can relieve the challenge of fluctuating electricity production and produce fuel for other sectors with more difficult electrification. The feasibility is determined by the development of various scenarios in EnergyPRO to perform an Energy System Analysis and determine the yearly hydrogen production of each one of them. The economical feasibility will take as input the expected hydrogen productions from the EnergyPRO model and the investment necessary to calculate the NPV, IRR and payback time. Moreover, the environmental impacts of the best scenario will be studied and measures to reduce them will be presented. Furthermore, social acceptance will also be taken into account and measures to improve it will be presented as well.



Alba de la Viuda Rodríguez

By signing this document the author confirms is liable for the content of the project.

Preface

I would like to express my gratitude to Anders N. Andersen for his supervision of this project and for providing valuable feedback, as well as for his assistance with the energyPRO modelling.

Furthermore, I would like to express my gratitude to Blue Power Partners for their invaluable support during this project and their expertise.

Abbreviations and expressions

GHG: Greenhouse Gas
SDGs: Sustainable Development Goals
PtH: Power to Hydrogen
PtX: Power to X
EU: European Union
GDP: Gross Domestic Product
EV: Electric vehicles
H2: Hydrogen
NH3: Ammonia
CAPEX: Capital expenditures
OPEX: Operating expenses
AE: Alkaline Electrolysis
SOEC: Solid Oxide Electrolyzer
PEM: Proton Exchange Membrane
AEM: Anion Exchange Membrane
NPV: Net Present Value
IRR: Internal Rate of Return
IPCC: Intergovernmental Panel on Climate Change
EIA: Energy Information Administration
UN: United Nations
EEA: European Environmental Agency
IEA: International Energy Agency
EEA: European Environmental Agency

Table of Contents

Chapter 1 Introduction **1**

Chapter 2 Problem Analysis **2**
2.1 The Issue of Global Warming . . . 2
2.2 The need for green energy . . . 8
2.2.1 Power generation sector . . . 9
2.2.2 Transport sector . . . 11
2.2.3 Other sectors . . . 12
2.3 The need for PtX solutions . . . 13
2.4 The Barriers in PtX . . . 14
2.5 Challenges in PtX . . . 15

Chapter 3 Research Question and Research Design **17**
3.1 Research Question . . . 17
3.2 Research Design . . . 17

Chapter 4 Theoretical Framework **19**
4.1 General Systems Theory . . . 19
4.2 Choice Awareness . . . 20

Chapter 5 Methodology **22**
5.1 Energy system analysis in energyPRO . . . 22
5.2 Economic feasibility study . . . 23
5.3 Literature Review . . . 24
5.4 Leopold Matrix . . . 25

Chapter 6 H2 production and economic feasibility **27**
6.1 PtH technology . . . 27
6.1.1 Introduction . . . 27
6.1.2 Hydrogen production. Different technologies . . . 27
6.1.3 Electrolysis process description . . . 31
6.1.4 The electrolizer. Different technologies . . . 32
6.1.5 Renewable Hydrogen production system (RHPS) selection . . . 39
6.2 EnergyPRO model . . . 39
6.2.1 Models . . . 40
6.3 Economic parameters . . . 41
6.3.1 Market study of products . . . 41
6.3.2 Investment costs . . . 45
6.3.3 Governmental incentives . . . 46
6.4 Summary of parameters used on the EnergyPRO model . . . 47
6.5 Final results from EnergyPRO modelling . . . 47

6.5.1 Sensitivity Analysis . . . 48

Chapter 7 Environmental impact **56**

7.1 Impact assessment . . . 56

7.1.1 Impacts from the wind farm . . . 56

7.1.2 Impacts from the hydro-power station . . . 57

7.1.3 Impacts from the hydrogen facility . . . 57

7.1.4 Leopold Matrix . . . 58

7.2 Measures to decrease the environmental impact . . . 60

7.2.1 Measures to decrease the hydro-power station impact . . . 60

7.2.2 Measures to decrease the wind farm impact . . . 60

7.2.3 Measures to decrease the hydrogen plant impact . . . 61

7.3 Environmental monitoring . . . 61

Chapter 8 Social Acceptance of the local community **62**

8.1 Main complaints and concerns of the community . . . 62

8.2 Measures to improve social acceptance of the project . . . 63

Chapter 9 Discussion **65**

9.1 Changes in the model and their effect on the feasibility . . . 65

9.1.1 Establish a minimum capacity for the electrolyzer . . . 65

9.1.2 Changing the size of the facilities . . . 66

Chapter 10 Conclusion **68**

Bibliography **69**

Introduction 1

The consequences of global warming are deleterious not only for the environment but also for human society and the actual way of living. The causes for this phenomenon are mainly derived from human actions, especially from the emission of GHG which has been rapidly increasing since industrialization. Awareness of the problem has increased and there is a huge flow of thought and action to stop emissions and become carbon neutral.

To tackle this situation the main focus lies in renewable energies, however, as they suffer a lot of variations and direct electricity storage is not efficient other solutions are needed. Furthermore, there are sectors such as transport where direct electrification is not possible or inefficient and other solutions are needed to transition away from fossil fuels.

On this basis, the aim of this project is to study the feasibility of a Power to Hydrogen in Iceland. PtH uses electricity to convert water into hydrogen and other by-products. Hydrogen can be stored and has been shown to be a possible solution for transport to become independent from fossil fuels. Hydrogen can be used as fuel directly or it can be transformed into other e-fuels without emitting GHG. In addition, since it can be stored, it can be used to regulate the electricity grid with the surpluses that renewable energy creates and ensure energy security.

Therefore, studying the feasibility of PtH is socially relevant. This project will not only identify the best techno-economic solution but also consider its environmental and social impacts.

Problem Analysis 2

2.1 The Issue of Global Warming

Over the past decades, the scientific community has collected countless evidence proving that the temperature of our planet is increasing with constant records in the last 25 years. [McNall, 2011] [MacMillan og Turrentine, 2021]

During these years longer and hotter heat waves, more frequent and lengthy droughts, heavier rainfall, etc. have been noticed. There is no doubt, climate change is happening.[National Academies, 2016]

It is also known that some of the consequences of climate change are interacting simultaneously as overfeeders, accelerators or initiators of additional warming mechanisms with an exponential contribution to climate change. It can be mentioned for instance:

- Melting of the permafrost. The frozen and solid permafrost becomes a mud slurry with the consequently carbon dioxide and methane (a gas molecule with 28 times more greenhouse effect than CO_2 one on a 100-year timescale) release and destroying the land base to grow forest and local vegetation, typical carbon sinks and land formers. [European Commission, 2022] [EPA, 2021a]
- Ocean changes. Earth's ocean temperatures are getting warmer too, with an accelerated melting process of glaciers and ice poles, stronger hurricanes, variation of marine currents patterns and sea level rise with catastrophic consequences for coastal populations. [McNall, 2011] [Zandalinas et al., 2021] [Sea Level Rise, 2024]

  The rise in ocean water temperature interacts with and drives the following occurrences: the expansion of water when temperature increases causing the sea level rise and area expansion (larger oceans means larger sun heat absorption); evaporation of seawater (atmospheric H_2O vapour amplifies GHE); changes in the salinity disturb the current patterns (due to melting of poles ice and currents changes); the influx of surface ocean temperatures (change of rain patterns with erosion increase and desertic areas development). [National Geographic, 2024] [Buis, 2022] [EPA, 2021b]
- Polar glacial ice meltdown. It provokes: a reduction of albedo effect with associated additional increase of temperatures; blocks the formation of sea ice; disrupts the sinking of denser cold, salty water; and in consequence is a huge feeder of the above-described phenomena [Graversen et al., 2014]
- Land erosion due to deforestation and loss of flora. It is a circular system linked to rain pattern changes, loss of the forest area, water shortage, desertification, ... [Ioras et al., 2014]

- Wildfires due to excess of dry combustion materials in the forests in summer. They release massive amounts of GHG (water vapour, Methane-CH_4 and Carbon Dioxide-CO_2, contributing to desertification, loss of land, forests, soil moisture decrease,... [Kim og Sarkar, 2017]
- Loose of forest which is a natural CO_2 sink, water retention system and cloud creator. As previously mentioned it is evidence of different mechanisms acting. [EEA, 2023b]
- Population displacement. The abandonment of rural areas due to climate change is at the same time an additional source of the greenhouse effect due to the loss of forests, massive wildfires, desertification,... [Alverio et al., 2023] [Mantero et al., 2020]

All in all, it is quite certain that global warming has proven to be an issue with an accelerated worse scenario in the coming years for a growing percentage of the world population. [Zhang et al., 2022]

Besides the above-mentioned climate and weather changes linked to global warming, is also necessary to emphasize that the scientific community is assessing different impact scenarios for the population depending on the level of increase of Earth's surface temperature, which are as follows:

- Our planet warms by 1.5 degrees. This scenario could occur as early as 2026 if current trends continue. The main effects will be extreme weather events more often, poorer harvests and a heightened risk of food shortages.
- Our planet warms by 2 degrees. Also, a likely to happen scenario in the near future will have the following consequences: heat waves will become a plague while in other regions frequent floods will become an issue.
- Our planet warms by 3 degrees. This is the scenario we are likely to face if the warming trend is not interrupted now. The effects that have been foreseen for this scenario are mainly a motion of an uncontrollable climate spiral, the consequences of which are difficult to assess. Famine is likely for billions of people which will increase the risk of war.
- Our planet warms by 4 degrees. In this scenario, most ecosystems will collapse with severe heat waves in summer and many major cities will be flooded.
- Our planet warms by 5 degrees. If we reach 5 degrees of global warming, Earth will become a greenhouse by itself. Most of our planet will be rendered uninhabitable. The total number of people living on Earth could fall to 1 billion.

[IPCC, 2024]

Once established the destructive impact of temperature increases it is necessary to determine the point of no return when the damages inflicted by the temperature increase are irreversible and the different above-described interactive mechanisms feed themselves. This point is not that clear. [Randers og Goluke, 2020] [Aengenheyster et al., 2018]

According to several studies, 1.5ºC is the tipping point that should not be reached to avoid severe consequences even though it is not a certainty. The grade of resilience and adaptation of the described warming scenarios is unknown. However, as a general conclusion if the temperature rises over 1.5 degrees it will result in increasingly severe consequences for the climate, sea levels, coastal life and ecosystems. [World Economic Forum, 2023]

In accordance with this data, several countries have started to implement actions to avoid surpassing those levels of 1.5°/2.0°C increase. These efforts began to take shape with the Paris Agreement (COP21). In 2015 196 countries adopted a legally binding agreement "to maintain the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels". [UNFCCC, 2024]

The countries with legally binding agreements so far are Sweden, the UK, France, Denmark, New Zealand, and Hungary. Countries with proposed legislation include Canada, South Korea, Spain, Chile, Fiji and most of the EU Member States. There are many countries with in-policy documents including but not limited to: the United States, China, Japan, and Germany.

It is obvious that before taking corrective actions it is necessary to first study the root causes behind Global Warming in such a way that the corrective actions implemented will contribute to efficiently alleviating the problem. [McNall, 2011].

As for the causes for this temperature increase, there are several theories: human activities during the industrial age (mainly greenhouse gases -GHG- emissions as responsible); the natural cycles of earth temperatures; increased volcano activity [NASA, 2024]; solar radiation variations [NASA, 2019] or even sunspots changes or solar wind variation with spot sun coronal mass ejections into the space [Scientific American, 2009].

However, among those theories, only the first one (emissions from industrial activity) has consensus among the scientific community as the primary contributor to Earth's warming. The other theories have been discredited or simply not considered powerful enough to justify the registered temperature rise. [Masson-Delmotte et al., 2018]

Therefore, human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C. Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate.[Masson-Delmotte et al., 2018]

The Intergovernmental Panel on Climate Change (IPCC) quotes literally: "The current rates of increase of the concentration of the major greenhouse gases (carbon dioxide, methane and nitrous oxide) are unprecedented over at least the last 800,000 years and several lines of evidence clearly show that these increases are the results of human activities." [Masson-Delmotte et al., 2018]

In parallel it is necessary to analyse the impact of these GHG. Several models to predict their effects have been running during the last years and it is necessary to emphasize the complexity of these simulations due to the uncertainty in climate predictions resulting from structural differences in the global climate models as well as uncertainty due to variations in initial conditions or model parametrizations.[Semenov og Stratonovitch, 2010]

The running of these models confirms the general consensus about the direct relationship between the anthropogenic greenhouse gas increase such as:

- the dominant contributor to the observed increase in extreme precipitation intensity;
- the responsible of more than 50% of global mean surface temperature;
- their direct association with climate change

[EIA, 2022] [Yoro og Daramola, 2020]

This is exemplified in the following graph:

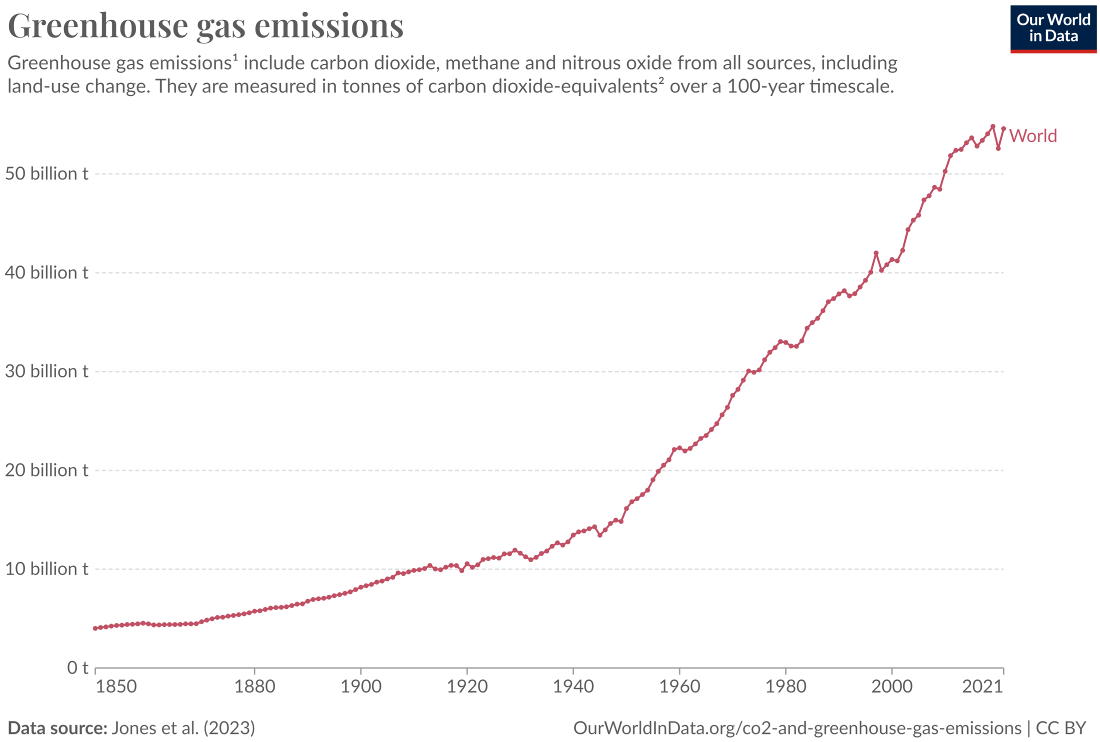


Figure 2.1. Total GHG emissions
[Ritchie et al., 2024b]

Moreover, the fact is that this undesirable phenomenon can be described easily through this theory based on the increase of emissions of Greenhouse Effect Gases (GHG):

- Earth's atmosphere composition contains certain GHG that have been paramount for the development of life on Earth thanks to being the reason for the temperatures maintaining a value that could sustain life on Earth for millennia.
- However, since the Industrial Revolution, the massive need for energy was satisfied by the burning of hydrocarbons (coal, oil and gas) with uncontrolled skyrocketing GHG emissions.
- The direct consequence of the greenhouse effect increase above its natural value is the constant rise of average temperatures and consequentially the proliferation of a variety of regional problems.
- In parallel to this man-made GHG increase, humanity has not been able to implement massive systems to mitigate this undesirable presence of GHG in the atmosphere via the development of carbon sinks of CO_2 for instance forests or CCUS.

[McNall, 2011]

In the next graph IPCC plots in orange the estimated anthropogenic warming and with bands of different colours the expected evolution of warming depending on the implementation speed of CO_2 reduction. In summary, there is a low probability of topping the warming to the targeted max of +1.5°C unless there is a fast decline of emissions from 2020 to reach net zero emissions by 2055.

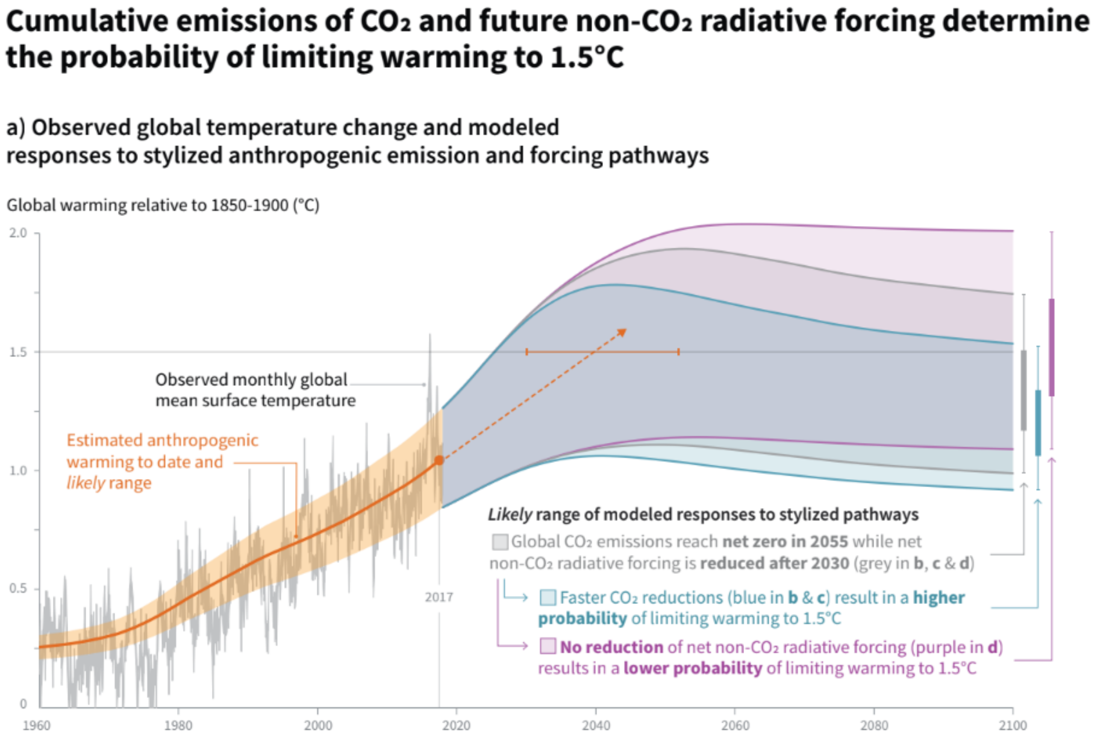


Figure 2.2. Observed global temperature change and modelled responses to stylized anthropogenic emission and forcing pathways
[IPCC, 2018]

It is important to emphasize that even though the global warming effects on people have been proven and the reason behind them is clear [McNall, 2011], there are some people, corporations and governments that refuse to acknowledge or act for a variety of reasons such as personal gain or to maintain the status quo. [Hall, 2019]

Consequently, even though there have been some actions implemented to reduce carbon emissions, they keep increasing at a tremendous rate. Since 2020 GHG emissions have grown by 40% and after a small plunge in emissions in 2020 due to the COVID-19 pandemic, they continue to grow. [EIA, 2022]

The efforts to implement green industries, develop net-zero strategies in the companies and legislate in countries are quite variable. A wide range of strategies are available to help reduce GHG emissions and meet emissions targets. Different opportunities can be explored to identify and implement GHG reduction:

- Energy Efficiency. Based on the need to choose energy-efficient solutions and best management practices to reduce the environmental impacts of power generation, increase a facility's operational efficiency, and decrease energy costs.

- Renewable Energy. Focused on the use of green power as a way to reduce the environmental impacts associated with conventional electricity generation. It is understood that green power is electricity produced from a subset of renewable resources, such as solar, wind, geothermal, biomass, and low-impact hydro.
- Supply Chain improvement. It works in process lines, using materials more efficiently, and reducing waste.
- Waste Reduction and Diversion Strategies. It is related to waste reduction and recycling in the workplace, including starting or expanding recycling collection programs, initiatives to reduce everyday trash, frameworks for food recovery programs, chase of high-performing water-efficient products.
- Reduce Methane Emissions. Oriented to livestock waste through anaerobic digesters or other technologies that this gas is also a natural by-product of. This gas can be also considered as a renewable and green energy source. Finally, oil and gas operations need to implement methane-reducing technologies and practices.
- Increase Fuel Efficiency in Transportation and Logistics. It is key that freight shippers, carriers, and logistics companies can improve fuel-efficiency systems and save money at the same time.

[EPA, 2024]

The European Union is one of the leading regions in the world pursuing drastic reduction of GHG and several goals and measures are being taken to diminish them CO_2 and try to stop the rise of global temperature. Under the Paris Agreement EU committed to be climate neutral in 2050, with net zero GHG emissions. [European Commission, 2024b]

EU is also aligned with the Sustainable Development Goals (SDGs) which were formulated by the United Nations General Assembly in 2015, in particular with SDG 7, Affordable and Clean Energy.[UN, 2024]

To achieve the above-mentioned goal ("to maintain the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels”), the EU has established a set of actions compiled in the agreement: “The European Green Deal” which settles the strategies to be carbon neutral by 2050. With these actions, Europe will be the first continent to achieve the target. The document contains initiatives that set the path for the green transition as well as important funding for the implementation of multiple actions. Among these initiatives, the main ones to be mentioned could be:

- The “European Climate Law”. It entered into force in 2021 and states a legal obligation for the EU members to fulfil the EU’s target of reducing net greenhouse gas emissions by at least 55% by 2030 (from the current 40%) and makes climate neutrality by 2050 legally binding.
- Legislation “Fit for 55”. It complements the previous Law with several interlinked revised laws and new proposed laws on climate and energy to align EU laws with the EU’s climate goals.

[European Council, 2024] [European Parliment, 2023]

2.2 The need for green energy

These mentioned laws that target the challenging common goal of climate neutrality by 2050 to avoid a common global goal or not reaching the tipping point of our climate [McNall, 2011] are focused on the drastic reduction of GHG emissions. Execution of this plan needs to look in detail into the different emission sectors and attack the largest emitters and those that can be adapted easily to new technologies.

As we can see in the next graph the generation of electricity and heat is one of the biggest emitters with one-third of total emissions throughput time globally followed closely by transport (>15%), manufacturing and construction (>13%) and agriculture (12%).[Ritchie et al., 2024a]

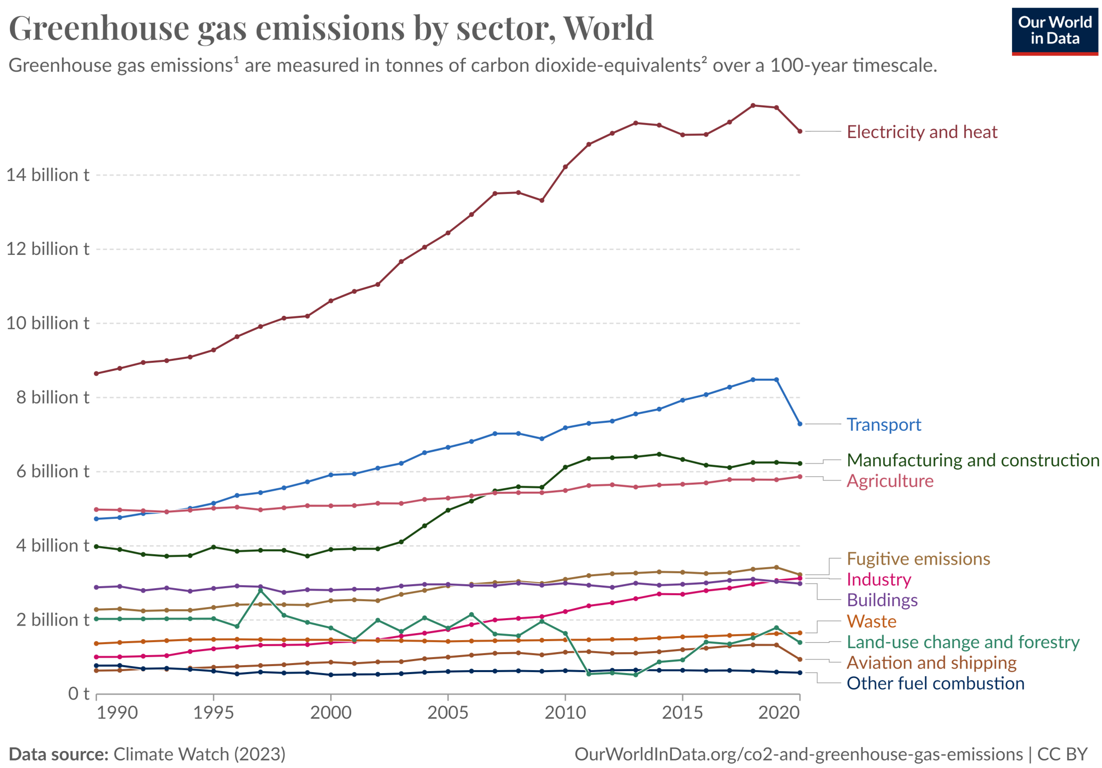


Figure 2.3. Global GHG emission by sector
[Ritchie et al., 2024a]

This is not an exception in Europe where despite the total contribution of GHG emissions representing less than 14% of the global world emissions, the power generation sector emits more than 30%, transport with 17% and building conditioning with 12% are the largest local emitters. Manufacturing (11%) and agriculture (10%) cannot be neglected. [Ritchie et al., 2024a]

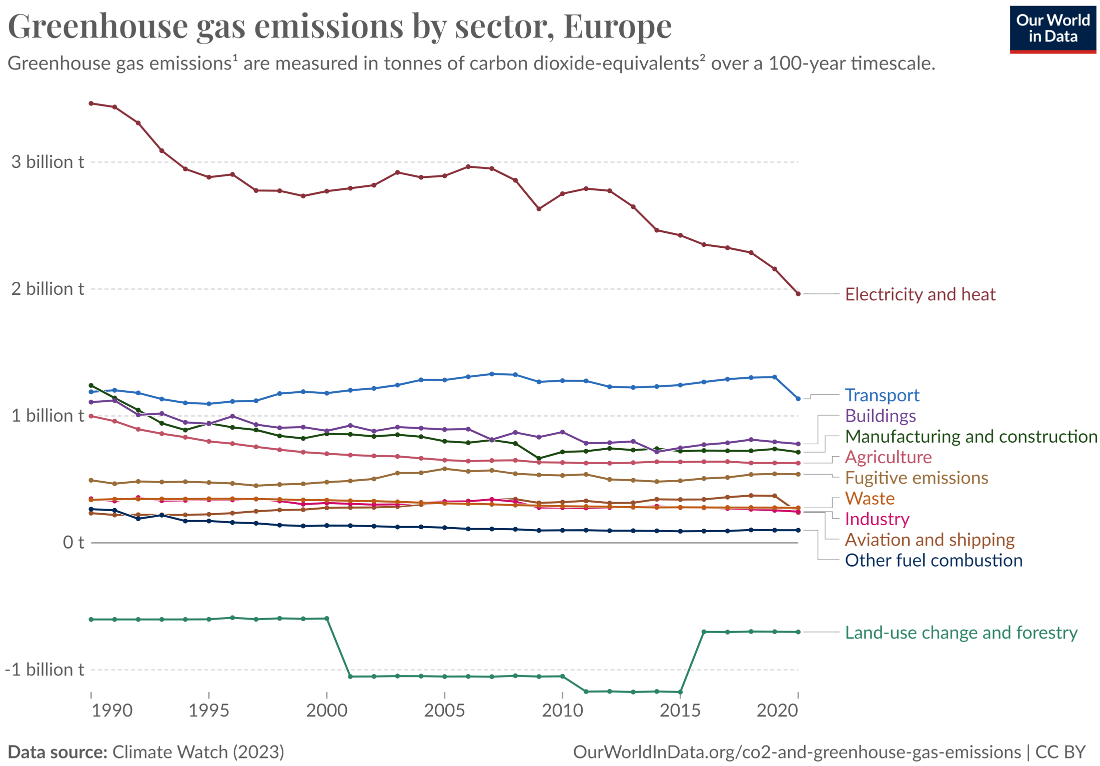


Figure 2.4. Europe's GHG emission by sector
[Ritchie et al., 2024a]

2.2.1 Power generation sector

There are different reasons for power generation to be targeted as one of the first sectors to be decarbonized, it is namely:

- one of the biggest emitters
- one of the sectors with more mature solutions to be decarbonized
- a transversal sector with other ones (more electricity could be used in other applications if electricity would be net-zero emitter)
- a highly dependant sector on hydrocarbon imports from countries politically unstable or volatile.

It is obvious that transitioning this sector from an oil and gas-based system into a renewable system is paramount.

[EMBER, 2023]

There has been a lot of work done in this regard in Europe, mainly in EU for some years now as it can be seen in the previous graphs with a slowdown of over 30% in the GHG emissions of this sector in the last 10 years [European Commission, 2023b] while the total production of electricity increased in the same period close to 5% [Dans, 2023]

Considering that globally in 2021 only 28.35% of the electricity was obtained from renewable sources, it can be seen that the European efforts on that front are working. [Ritchie og Rosado, 2024] [EEA, 2023a]

Even though green power generation is a valid solution to decarbonize this industry, it is necessary to detect potential weak points, to be addressed, analysed and solved to create a holistic and sustainable system. The main challenge is the integration of RES into electric grids. First, the utilities face network inadequacy, with a lack of physical capacity to accommodate supply and demand in locations where energy is produced.[Barth et al., 2024] Overlooking this circumstance that can be considered financial and not technical, we have secondly that as the share of renewables increases, the lack of real-time network management at low voltages could lead to network instability, which may affect highly on reliability and cause voltage instabilities, frequency inconsistency, and harmonic distortion of the power system. The reason behind this is the huge power variability of renewable resources: daily in the case of solar (null production at night), weatherly for windmills (variability linked to wind speed) and seasonally for hydro power (stationary rain variations and water disposal). This variability has been addressed thanks to complex adequation of the grid, promotion for change of consumer habits and use of gas power plants to balance the grid (which means an investment in a simple and partially unused backup unit). In summary, a lot of efforts have been made to alleviate the grid stress due to the progressive penetration of renewable energy in the last few years. [Iberdrola, 2024]

This trend will continue until 2050 due to the progressive increase of RES in the electricity generation mix. The integration of a significant number of variable renewables into power grids to ensure their stability requires an increase in the existing grid's flexibility:

- to allow electricity flow, not only from centralised power plants to users but also from small users/producers to the grid
- to establish intelligent grid and demand management mechanisms to speed response and reduce peak loads.
- to improve grid interconnection at the regional and international level
- to introduce energy storage capacity systems to store energy when production exceeds demand.

[IEA-ETSAP og IRENA, 2015]

This last point is critical to be implemented to make progressively unnecessary the use of fossil power generation plants as a backup for balancing the grid. Multiple systems have been studied and are in different development stages for Electrical Energy Storage (EES). Because electricity cannot be stored as is, electricity storage involves the conversion of electricity into other forms of energy using several technological options with different characteristics and performance: pumped hydro-PHS, compressed air-CAES, Hydrogen-based energy storage systems-HESS and PtX, Synthetic Natural Gas-SNG, electrochemical-batteries, superconducting magnets, flywheels, Thermal Energy Storage-TES,... [Kyriakopoulos og Arabatzis, 2016a]

Among electricity storage technologies, standard and pumped-storage hydro plants are currently the only commercial option for large-scale electricity storage. Nevertheless, this technology is limited and largely exploited worldwide since these plants require specific sites, with natural or artificial water reservoirs located at different geodetic elevations.

The other technology that is growing fast is linked to electrochemical batteries (lead-acid, lithium- and nickel-based, flowbatteries, etc). In spite of this technology can be easily implemented to decarbonize other sectors it is not clear whether it can be applied in massive storage and grid balance due to numerous challenges: limited lifetime and long-term efficiency; security concerns (inextinguishable fires), high energy density but poor power density; social concerns (massive utilization of scarce raw materials);... [Faunce et al., 2018]

The systems based on H_2 have been identified as the most promising techniques to absorb the surplus of RES and achieve balance grids. [Yue et al., 2021]

2.2.2 Transport sector

Special actions should be implemented for other sectors which are not so easily decarbonized, for instance, the transport sector.

The transport sector is the least-diversified energy-end-use sector, dominated completely by oil. In 2019, petroleum fuels accounted for 91% of U.S. transportation,[EIA, 2023] and 95% in the EU as of 2018.[EEA, 2018]

In 2022 the global consumption of oil for transport grew in comparison to previous years and represented 45% of global oil demand (43% in 2019). Road transport is actually the largest segment of global oil demand, making up 41 million barrels per day (21mbd for cars and 16mbd for trucks). [IEA, 2023]

Aviation consumes above 6 mbd and maritime transportation close to 3 mbd.[Jing et al., 2022]

Traditionally the transport sector has always been fuelled by thermal combustion vehicles (TCV) fed with liquid fuels made from oil because their high energy density allows them to transport and store a great deal of energy for their weight and volume.

The difficulty of transitioning into renewable energy lies, from a general point of view, on several reasons such as direct electrification is not easy in a vehicle; the utilization of batteries is questionable due to the massive utilization of scarce raw materials, recuperation issues and safety; limited autonomy; massive investments in new infrastructure;... If the different subsectors of vehicles are deeply considered, it can be seen that:

- For smaller vehicles travelling short distances and carrying lighter loads electrification is a viable option.
- The heavier forms of transportation by road would require much heavier batteries and electric motors that would rarely produce enough power to move massive tonnage and reach reasonable ranges. Furthermore, this heavy transport is among the fastest growing, meaning that solutions for these more complex vehicles should be considered too.

  [Spiller et al., 2023] [Gross, 2020]
- The scenario in maritime transport is even worse as electrification is unfeasible due to the long distances required to be achieved without stops and heavier loads moved than inland transportation.

  [Psaraftis og Kontovas, 2021] [Lind et al., 2022]

This issue becomes essential to be tackled as the expected contribution of sea transportation will reach 15% of global GHG emissions in 2050, bringing to light the deep need for solutions this sector needs to meet the climate goals. [SLOCAT, 2021]

Hydrogen, ammonia, and fuel cells (especially proton exchange membrane fuel cells), are potential alternative gas fuels to power the vessels. Ammonia can be used directly as a combustible fuel or as an excellent H_2 carrier. The fuel mixture of NH_3/H_2 can be burned together in internal combustion engines and the dissociated H_2 from NH_3 can power fuel cells or be an alternative fuel to heavy fuel oils burned in marine diesel engines. [EMSA, 2024]

- Finally, the intrinsic philosophy of aeronautics with the utilization of superlight materials, high-speed travel and extended flying ranges makes unfeasible the electrification of this subsector. In this scenario, only the utilization of high energy density sustainable fuels will work: synthetic fuels; biofuels produced from agricultural or forestry residues, algae, bio-waste, used cooking oil or certain animal fats; recycled jet fuels produced from waste gases and waste plastic; green H_2 or H_2 carriers;... [Airbus, 2024]

It is important to note that hybridization or other low-emission fuels (natural gas or propane) cannot be considered a solution when the target is a final net zero by 2050. Only the utilization of new low/zero carbon technologies could be valid.

2.2.3 Other sectors

Once the main drivers of carbon emissions (power generation and transport) have been analysed, the other emitter sectors (house/buildings conditioning, industry, agriculture,...) cannot be forgotten and convey that the solutions applicable to power generation and transport are perfectly applicable to those cases. Thus,

- Agriculture decarbonization of energy combustion, machinery and greenhouses can be addressed in a similar way to the transport sector due to the massive utilization of combustion engines in this sector.[EEA, 2023]
- Industry sector emitters are associated mainly with ammonia, cement, ethylene and steel processes. Its conversion to zero emissions is linked to energy-efficiency improvements, the use of electricity for heat generation instead of fossil fuels, the use of hydrogen and biomass as feedstock or fuel, and carbon capture technologies when other solutions are not viable.[de Pee et al., 2018]
- Heating, cooling, cooking... in houses/buildings should opt for thermal retrofitting, insulating and progressive substitution of oil and natural gas use, switching them to low-carbon alternatives, such as green electricity and green hydrogen. [Nijs et al., 2021]

It is important to emphasize that electricity will not be the single solution because especially during cold waves, when electric heat pumps are less efficient, electricity demand will peak, likely constraining the distribution grids. H_2-power devices such as fuel cells, boilers, and integrated hybrid heat pumps would help alleviate grid expansion and constraints, lowering costs and increasing the pace of decarbonisation of the sector.[Hydrogen Europe, 2021]

2.3 The need for PtX solutions

It has been stated that power generation and transport are the two main sectors emitters of GHG. It has been seen that renewable electricity can be a viable solution to eliminate fossil fuels for power generation as far as we can adequate the grids to the progressive incorporation of less flexible and non-GHG emission sources and this will require a reliable and affordable storage system. It has been seen that reaching the complete net-zero goal cannot be achieved unless GHG emissions in sectors that cannot be easily electrified as the transport sector (mainly heavy traffic by road and vessels both in long distances) are avoided. Finally how other emitter sectors (agriculture, industry and house conditioning) can be decarbonized was presented, with the help of hybrid solutions in which one vital component is the H_2 and PtX associated products.

In summary, H_2, H_2 carriers and associated PtX technologies are proposed as a transversal valid solution useful in all sectors in different ways. [Incer-Valverde et al., 2022]

Power to X is a new technology that uses electricity and a series of materials to produce components with a high energy density. The "X" means there are several options within this technology like hydrogen, chemicals (ammonia), synthetic natural gas (methane), and liquid fuels ... and all of them are based on the same principle. [Incer-Valverde et al., 2022]

Of all the options that PtX offers, hydrogen is the base of all of them. The production of hydrogen is predominately based on the electrolysis of water (H_2O) and takes place in electrolyzers. The electric current splits the water molecules into hydrogen (H2) in the cathode and oxygen (O2) in the anode. This green hydrogen can be used directly or in the production of other green products with higher energy density in chemical form to facilitate its storage and transportation. [Incer-Valverde et al., 2022]

The main advantages of this technology can be summarized as follows:

- It becomes crucial when we target a zero-emissions goal by massive utilization of renewable power generation. The unused surplus electricity that would unbalance the grid can be used to produce these components and store them to be used as fuels when needed. This use of RES makes the hydrogen turn into a green product (zero-emissions).
- The Hydrogen derivatives arise as good substitutes for fossil fuels with limited changes in the global distribution chain because they can be stored as gas or liquid in a similar way than nowadays fossil fuels are.
- High utilization flexibility as far as it can be used in different manners: production of electricity, run engines, heat generation, etc.
- It is a solution for systems that need a high energy density fuel. This property and the obtention through renewable energy makes it the only valid solution to power aeronautics and long-distance transportation (both land and maritime) with a 100% net-zero emissions system.
- The hydrogen-derived synthetic fuels do not contain deleterious chemicals with certain carcinogenic and disease effects which are present in gasoline or diesel.
- Zero harmful or toxic emissions during production and utilization, basically all the byproducts are water and oxygen.

- There is already a H_2 market in place (for instance in oil refining). It means green hydrogen can be used immediately.
- It suffers less storage degradation or losses during transportation than other energies, such as electricity or fossil fuels.
- It opens opportunities for limiting foreign energy dependence.
- It is easily scalable

[Chaubey et al., 2013]

A wide consensus has been reached that producing hydrogen from renewable energy sources (solar, wind, etc.) shows great promise for the world's sustainable development. [Chaubey et al., 2013]

Under this consensus, the EU strategy on hydrogen (COM/2020/301) was adopted in 2020 and suggested policy action points in 5 areas: investment support; support production and demand; creating a hydrogen market and infrastructure; research and cooperation and international cooperation. The full list of 20 key actions was implemented by the first quarter of 2022. Hydrogen is also an important part of the EU strategy for energy system integration. [European Commission, 2013]

Being hydrogen one of the raw materials and the base for other energy carriers it is paramount to develop a strong green hydrogen production system.

2.4 The Barriers in PtX

Despite, the Power to X and in general, all the hydrogen-associated technologies have a great potential to contribute to the energy transition and subsequent decarbonization of multiple sectors, they face several barriers that could slow down their development and deployment, such as:

- **Economical barriers.** The production cost of the products elaborated from renewable energy (falling from the current 2 €/l to 1,2 €/l by 2050) is still very high and uncompetitive against the traditional fossil fuels (cost around 0,5 €/l). Protective taxation of e-fuels could be the only solution. The initial investments for these new production plants and storage systems are also high and require incentives and strong financial support.[The Royal Society, 2019]
- **Regulatory barriers.** There is a lack of legislation to recognize and promote the products elaborated from renewable electricity. In a similar way there is not a clear harmonization of quality and safety standards that could help boost the development of Power to X technologies. It would also help a better coordination and integration of the different sectors that could benefit from this technology such as power generation, industrial, chemical and transportation. Finally, inadequate policies, incentives, and strategies from governments can also contribute to deterring the development of these kinds of barriers. [Skov og Schneider, 2022]
- **Technological barriers.** The PtX technology cannot be considered new because key technologies in the hydrogen network are mature or with working prototypes for technologies such as liquid hydrogen composite cryo-tanks and proton exchange membrane fuel cells. Nevertheless, more R+D is required to improve its efficiency and

reliability, reduce costs and achieve greater scalability. [Tashie-Lewis og Nnabuife, 2021] A larger distribution infrastructure to transport the different energetic vectors should be demanded, as the existing infrastructure is not fully compatible with this product so far. [Tashie-Lewis og Nnabuife, 2021] There are significant losses ($>$20%) of H_2 associated with its transport. In spite of these losses being fewer than other technologies it seems that for this technology to be effective, it must be produced locally to minimize energy loss.[Gaille, 2018] This technology does not perform well when the temperature is close to the water boiling point, which could lead to the technology being less effective in certain warm environments such as vehicles, factories, etc

- **Social barriers.** Awareness and acceptance of the society about the environmental and economic benefits of the PtX technologies are key in facilitating its deployment and utilization. For instance, hydrogen is not available with easy access today. This limited availability could produce a negative attitude and growing weariness in the people.[Martin, 2023]

  Another example can be that there is a certain concern of potential environmental harm. Hydrogen is an abundant gas and it is balanced with other gases in our atmosphere to create a specific result. When we produce hydrogen energy, we release more of this gas into our atmosphere. Too much hydrogen is known to interfere with the ozone that is present in our atmosphere with a potential deleterious impact on health. [Lakshmanan og Bhati, 2024]

  Other items that can influence people's attitudes are: cultural practices, experience with technologies, cost, safety, infrastructure availability, affordability, local community engagement, regional skill capability development, preservation of biodiversity and distributive benefits to the community influence the acceptance of GH. [Emodi et al., 2021]

Accordingly, a holistic approach is needed to enable an adequate legislative framework and the development of policies and strategies that consider technical, economic and social factors to overcome these barriers and achieve a scalable H_2 energy transition. This would result in reliable roadmaps and strategies for PtX and electrofuel utilization with benefits for society in parallel to achieving the common decarbonization goal. [Bade et al., 2024]

2.5 Challenges in PtX

After revision of different technological solutions, it seems that H_2 and associated products are critical to sustain the green transition to a zero emissions goal by 2050 and multiple barriers that could risk the successful deployment of these technologies have been identified.

It is also necessary to settle the targets and write the strategies to be followed in the next years to overcome those blocking points and reach the targets.

According to the International Energy Agency (IEA) [IEA, 2021] the global installed storage capacity is forecasted to reach over 270 GW by 2026. The main driver is the increasing need for system flexibility and storage around the world to fully utilise and integrate larger shares of variable renewable energy into power systems.

The storage for short-term solutions will be based predominantly on pumped hydro technology. The reason behind it being that it is the only commercially viable solution for massive energy storage. However, this system requires high differences in altitude reservoirs and water abundance at the same time and location, thus the expansion possibilities of this technology are very restricted due to geographical factors.

According to the IEA the evolution of H_2 production will grow rapidly in the next years. In 2050 Hydrogen and hydrogen-based fuels will be deployed in heavy industry and long-distance transport, and their share in total final consumption will reach around 10%. [IEA, 2022b] According to this source, if all projects currently in the pipeline were realised, by 2030 the production of low-emission hydrogen could reach 16-24 Mt per year, with 9-14 Mt based on electrolysis and 7-10 Mt on fossil fuels with CCUS. In the case of electrolysis, the realisation of all the projects in the pipeline could lead to an installed electrolyser capacity of 134-240 GW by 2030. Meeting governments' climate pledges would require 34 Mt of low-emission hydrogen production per year by 2030; a path compatible with reaching net zero emissions by 2050 globally would require around 100 Mt by 2030. [IEA, 2022a]

The same IEA estimates that the achievement of net zero emissions by 2050 implies having operative 3670 GW of electrolyzers.[IEA, 2022b]

On a more local focus, the European Union's strategy for a climate-neutral Europe has confirmed [European Commission, 2013] that hydrogen offers a solution to decarbonise industrial processes and economic sectors where reducing carbon emissions is both urgent and hard to achieve. That is based on that hydrogen can be used as a feedstock, a fuel or an energy carrier and storage, and has many possible applications across industry, transport, power and buildings sectors. In summary, it can bridge major sectors of an energy system, such as transport, electricity and others. All this makes hydrogen essential to support the EU's commitment to reach carbon neutrality by 2050 and for the global effort to implement the Paris Agreement while working towards zero pollution.[Kyriakopoulos og Arabatzis, 2016b]

In EU's strategic vision for a climate-neutral EU published in November 2018,[European Commission, 2024a] the share of hydrogen in Europe's energy mix is projected to grow from the current less than 2% 4 to 13-14% by 2050 and could reach 23% in certain scenarios.[European Commission, 2013] [European Commission, 2024c]

The priority for the EU is to develop renewable hydrogen and it aims to produce 10 million tonnes and import 10 million tonnes by 2030 in two phases:

First phase, 6 GW (1 million tons) of renewable hydrogen electrolysers by 2024 Second phase, 40 GW (10 million tons) of renewable hydrogen electrolysers by 2030. The third phase considers the hydrogen technologies mature enough to be deployed at a large scale to satisfy the 2050 needs.

[European Commission, 2024c]

3 Research Question and Research Design

3.1 Research Question

On these grounds, it can be stated that there is a need to develop further PtH projects globally despite the different changes that need to be surpassed, in order to meet the climate goals and prevent the globe from reaching the tipping point and endangering our society.

To accomplish this the viability of a PtH project from a wide perspective will be studied taking into account technical, economic, environmental and social factors with the aim to reach a conclusion on whether the project is viable or not and where the most important challenges lie. A study case of a project in Iceland will be the focus of this study taking into account not only the hydrogen facility but also the generating assets used to produce the electricity necessary to produce said hydrogen, in this case, a wind farm and a hydropower station.

Therefore, the following research question has been formulated:

Is a PtH facility connected to wind and hydro resources feasible in Iceland?

Hence, to answer the research question, the following subquestions have been formulated:

1. SQl: Is PtH in Iceland technically feasible, what would be the production?
2. SQ2: Is PtH in Iceland economically feasible, with and without incentives?
3. SQ3: Is PtH in Iceland environmentally feasible and sustainable?
4. SQ4: Is PtH in Iceland sociable acceptable?

3.2 Research Design

In this section, the research design for this project will be presented. The aim of the research design is to describe how the research is conducted to answer the research question.

Figure 3.1 shows the research design this project is going to follow.

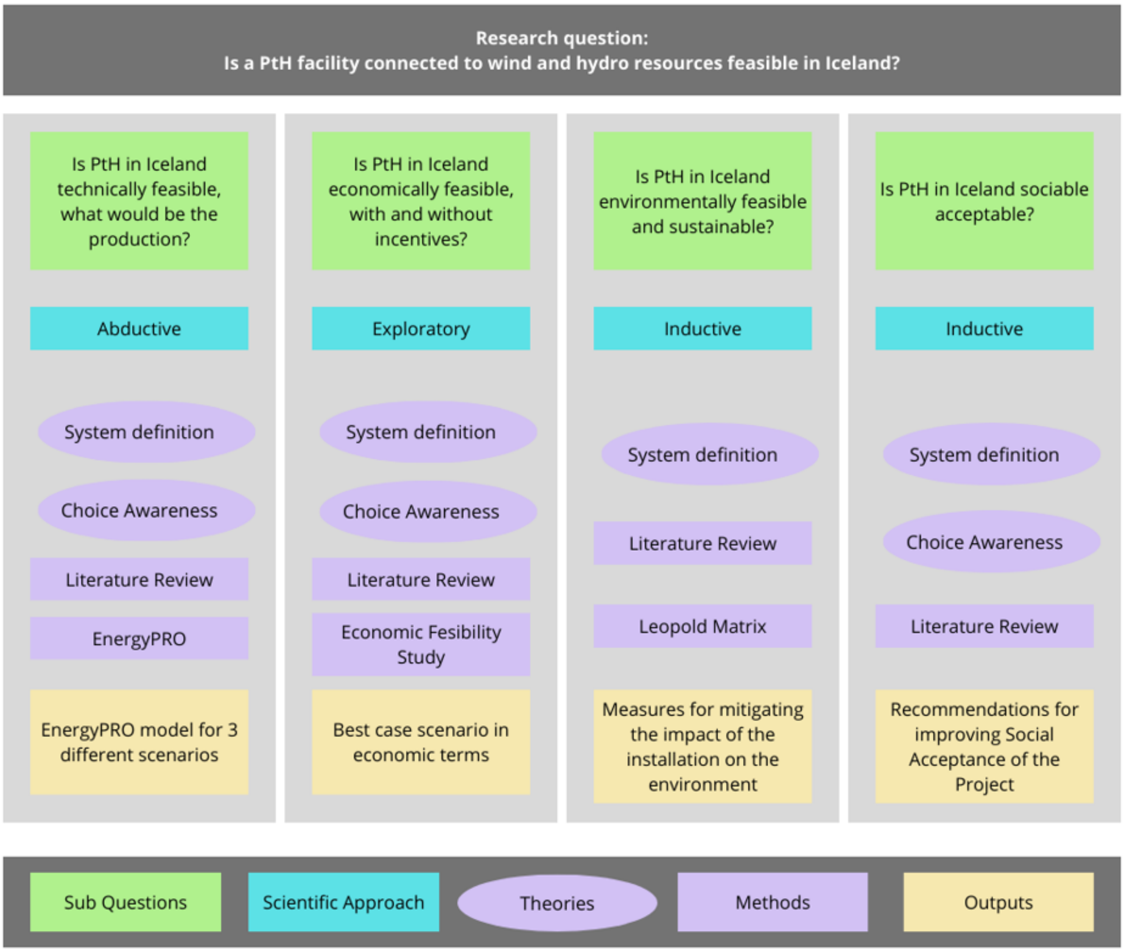


Figure 3.1. Research design

Theoretical Framework 4

The aim of this chapter is to account for the theoretical framework on which the project relies. The theories that have been used in the following analysis are as follows: General Systems Theory and Choice Awareness.

4.1 General Systems Theory

According to [Montuori, 2011], explaining complex phenomena scientifically can not be done by means of Reductioninsm, which is based on using simpler phenomena to explain more complex situations in doing so cutting them into pieces and explaining different parts individually. This approach does not take into account the environment surrounding the initial complex phenomena, how the studied system interacts with it nor the relation between the different parts it has been cut into to explain it. Thus, the system cannot be studied on its whole. [Montuori, 2011]

The General Systems Theory allows the study of not only the system itself but also the interconnections it has with its environment, allowing the understanding of the complexity of the system and its role with regard to other systems in its surroundings. To understand this fully "system" is defined as "a group of interacting, interdependent elements that form a complex whole". Therefore, it is also important to note that systems may appear inside others or with a certain degree of overlapping between each other. Furthermore, this theory also highlights the importance of acknowledging that systems are not static beings and usually are ever-changing, growing and adapting to stimuli from other internal systems, the external environment or other connected systems. According to this theory, there are open and closed systems, that even though are made of smaller components react differently to other forces. Closed systems do not interact with external forces and open systems need interactions with the environment to thrive. Open systems do not always maintain an equilibrium state, as closed systems do, due to their reactions to stimuli from the environment. However, according to the general system theory this disequilibrium state can be seen as a possibility to construct rather than destroy in open systems. [Montuori, 2011]

Consequently, the system this project aims to study will be open and the connections to the environment will be also be taken into account. In the following graph the system that is going to be studied is presented:

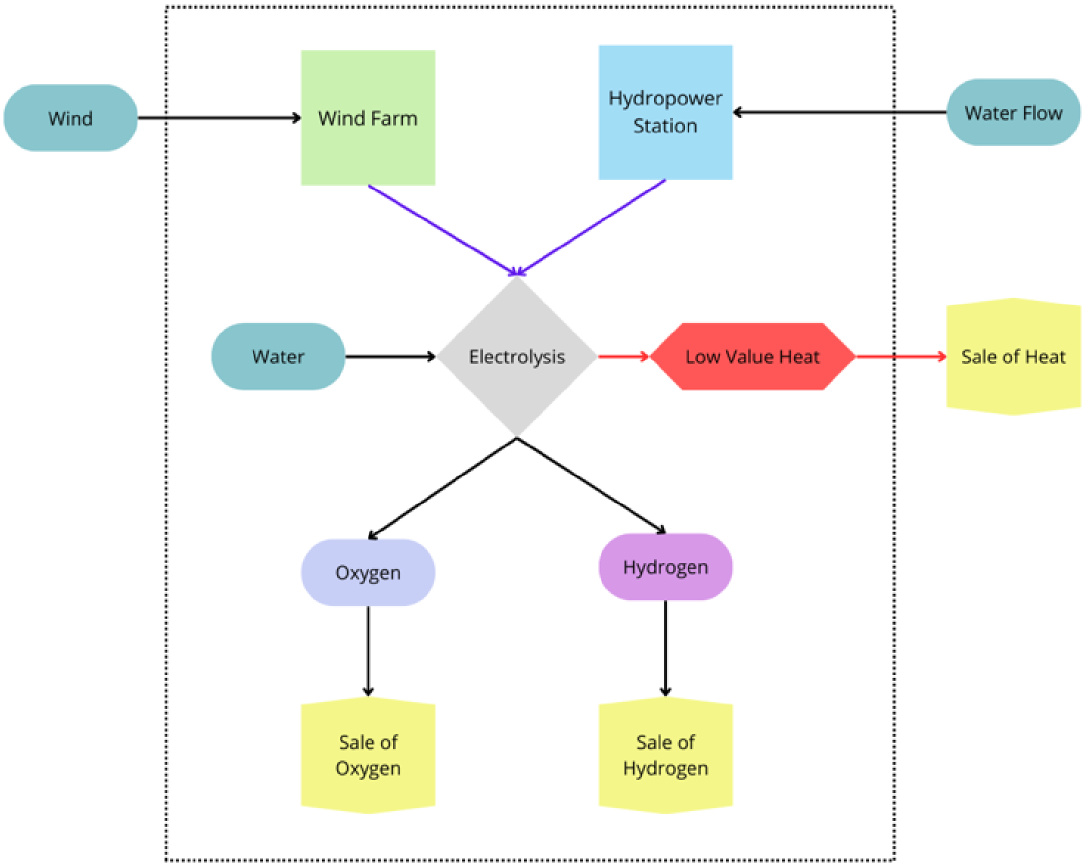


Figure 4.1. System definition

Inside the dotted rectangle, it can be seen the system this project is considering, which includes the wind farm, the hydro-power station and the electrolyzer and the outputs of said installation oxygen and hydrogen and their sale to off-takers. Even though, other main outside stimuli are also represented, like wind and water flow, others like political forces, legislation, and market trends are not represented. Other output from the electrolysis process, heat, is not taken into consideration in the model nor is its sale to third parties.

4.2 Choice Awareness

When implementing new energy systems and transitioning from a fossil fuel-based energy system to a sustainable one based on renewables, there are some situations in which society isn't aware of the possibilities. There are organizations with different objectives, many of them fighting to maintain the status quo to maintain or further their current interests. The reach of these organizations is deep and their actions sometimes lead to a "no choice" situation. This specific situation appears when society isn't aware of other possibilities apart from the options presented by the corporations. However, the Choice Awareness Theory states that society does have a choice. There are organizations wanting to maintain the status quo and try to suppress certain options from the decision-making process or influence it to further their agenda, nevertheless, there are several strategies that can be used to counteract these effects.

The theory is focused on the societal perspective of decision making from which an important element is that even though certain individuals are aware of facts, information and other options if the society as a whole is not aware there is no real choice. Moreover, societal perception can be manipulated without regard to individual knowledge. There are several situations in which there is no real choice such as: only presenting one option that has to be accepted or rejected. This can be done by convincing them that an option is not technically feasible, eliminating an option altogether or misinforming the public in some other regard to turn them against the other possibilities.

When trying a radical technology change such as the green energy transition there are a multitude of paths to follow all of them based on renewable energy, however, fossil-fuel companies through lobbying have managed to remain as a well-seen option by the public and governments by selling the idea of Carbon capture even though there is extensive research proving it is neither necessary nor ideal. This exemplifies how perception and choice can be manipulated by organizations with vast resources at their disposal.

Choice and the options presented with should be seen as a fight between different perceptions of reality. The focus on some technologies or solutions is influenced by groups and interests. In addition, alternatives that are not presented in a discussion are just as meaningful in terms of influence as those that are presented.

The impression of certain alternatives is due to a defence response from certain collectives that see their interests threatened. It can be done by actively suppression an alternative from the discussion and choice process, spreading misinformation regarding the threat alternative and also burying information that does not concur with the desired narrative.

To tackle this issue raising choice awareness is paramount, presenting all the possibilities and informing the public are the first steps to ensuring true choice when it comes to decision-making processes. Consequently, a greater choice awareness from society can force institutional changes and phase out lobby influences from the decision-making processes not only in energy system decisions but also in other important choices.

For this project, this theory gains importance when presenting the different alternatives, so that there is no bias and even though there are alternatives that are not studied further at least are recognized as a possibility.

Methodology 5

This chapter describes the methods used to answer the research question and subquestions of this report and explains their characteristics and the application given to them in this project. The methods used in this report are Energy System analysis in energyPRO, Economic feasibility study, Literature Review and the Leopold Matrix.

5.1 Energy system analysis in energyPRO

To assess the feasibility of the Hydrogen plant and optimize the operation of the facility an Energy System Analysis will be conducted.

To perform the Energy System Analysis there are several methods such as modelling with Excel or programming it in other software. However, there are some specialized programs to do so like EnergyPRO and EnergyPLAN. EnergyPRO specialises in the "economic assessment of investment alternatives in the energy sector factoring in both a detailed simulation of the alternatives' technical behaviour in the energy system and the business economic implications"[Østergaard et al., 2022]. As the aim of this project is to optimize the operation of the plant and not a more general system analysis, the specialized software EnergyPRO is the better option to asses the production on an hourly basis of the different presented alternatives.

The Energy System Analysis carried out in this project models the production of the Wind farm considering the wind speed and the hydro-power production taking into account the water intake from the river and the height differential. Furthermore, as the project is presented as an off-grid situation the hydrogen production is calculated considering the type of electrolyzer and the hourly production of the aforementioned sources of electricity. Moreover, one of the alternatives considers Pump-back Hydro-power adding another source of consumption and enabling other storage options. To do so several technical parameters are considered such as the efficiencies of the different installations, the height of the wind turbines, the height differential for the hydro-power station and other technical considerations.

In addition, the economic aspect of the feasibility study is also considered. As an input to the model, the following parameters will be supplied: selling price for hydrogen and oxygen outputs, DEVEX[1] and CAPEX for the installations and price for water usage. Moreover, the OPEX ratios will be used as an input and the model will calculate the total OPEX

[1]When developing a project all the expenditure before construction can be considered as DEVEX instead of CAPEX. This includes design, permits, project management, stakeholder management, etc. and the necessary manpower to carry it out

depending on the usage of the facilities. All these considerations influence the optimization of the facility and the calculations are done accordingly to minimize costs and maximize benefits.

5.2 Economic feasibility study

The Economic feasibility study takes into account to forecasted costs and benefits of a project to determine if the project is going to be profitable and if the investment makes sense, as explained thereafter:

- Cost breakdown. Determining the costs of the project whether they come from the development, construction, operation or investment is paramount to studying the feasibility. Whether the costs are fixed or variable is important, however, all of them should be minimized to increase feasibility. In this project, the main costs are due to the construction of the facilities and the purchase of machinery. Nevertheless, the Operation and maintenance and Development costs of the project cannot be dismissed and neither can other costs as water purchase.
- Revenue projection. The other main pillar is the revenues the project is forecasted to produce. Maximizing the revenues is the aim of optimization too. The revenue from this project is due to the sale of the final product and the main by-products of the electrolysis which are hydrogen and oxygen. To project the revenues created the production is modelled and optimized and with a set hydrogen and oxygen price annual revenues are calculated.

[Roberts, 2024]

However, to make sense of these parameters a simple subtraction is not enough and the results produced by it could be deceiving. To take into account several more complex behaviours several parameters are studied in what is referred to as indicator analysis which are the following: [Prosperi, 2021]

- Net Present Value (NPV): It represents the difference between the present value of cash inflows and the present value of cash outflows over a period of time. To calculate NPV, one must estimate future cash flows, determine the appropriate discount rate, and subtract the initial investment. The discount rate typically reflects the opportunity cost of capital or the expected returns of alternative investments with similar risk profiles. This analyses all the cash flows associated with each project at a single date and takes into account the depreciation of money over time. This means that all cash flows are discounted (at a discount rate that takes into account inflation and the desired benefits of the project) so that they represent the true value of future money. All the discounted cash flows are added and the investment costs are deducted. If the result is positive, it is a promising project as the projected earnings exceed the anticipated costs; if it is zero, it will pay the costs but not make a profit; and if it is negative, it is not worth the investment.

$$NPV = \Sigma \frac{Cashflow}{(1+DiscountRate)^t} - Investment$$

[Prosperi, 2021]

- Internal Rate of Return (IRR): It represents the discount rate that makes the NPV of all cash flows from a particular investment equal to zero, allowing for the comparison of investments with different scales and durations. To calculate it the following formula is used:

  $$NPV = \Sigma \frac{Cashflow}{(1+IRR)^t} - Investment = 0$$

  To interpret the results is easy, one of these three scenarios can occur:

  – IRR greater than the discount rate, indicating the profitability of the project
  – IRR equal to the discount rate, indicating no profit
  – IRR smaller than the discount rate, indicating that the project is not profitable.

  [Prosperi, 2021]
- Discounted Payback: This method discounts the projected cash flows to the present value using a specific discount rate, usually the company's cost of capital, and then determines how many years it takes to cover the initial investment with these discounted cash flows. It's particularly useful for comparing projects with similar cash flows but different timings. Investments with shorter discounted payback periods are generally preferred as they allow investors to recoup their initial outlay more quickly, reducing the risk exposure. It is calculated by adding all the discounted cash-flows to the negative initial disbursement until it reaches zero, on which point the discounted payback has been reached. [CFI, 2015]

To calculate the previously mentioned Discounted Rate the inflation and the capital cost need to be taken into account as follows:

$$NominalDiscountRate = i + g + i * g$$

where i is the money or capital cost[2] and g is the inflation. [Accountinginside, 2024]

5.3 Literature Review

The literature review methodology is paramount in the research of all topics and is used widely in the academic field. It is aimed mainly to identify, evaluate, and interpret all available research relevant to the studied area. This methodology section outlines the approach undertaken to conduct the literature review in the following chapters. [Moahmmed, 2021]

To start with the following steps are followed to carry out the literature review:

- Formulating the study question. The goal of the study should be defined thoroughly and at the same time, the issues of the study should be presented as well
- Searching for existing literature. When doing so there must be full coverage, including all articles in the area of study. Moreover, articles in related fields also should be considered.

[2]Capital cost is the rate of return a company needs to earn to justify the cost of a capital project and includes the cost of both equity and debt. [Hayes, 2023]

- Inclusion examination. Filtering which articles are going to be used in the analysis by date, source, content, ...
- Quality evaluation. Asses if the study design and methodology are valid for the desired study.
- Data processing. From the final selected articles, the relevant information for the study is extracted.
- Summarizing. Collecting all the data extracted in the previous step arranging or comparing it to reach a conclusion

[Moahmmed, 2021]

With the aim of answering the research question introduced in the preceding chapter, an extensive exploration of the existing literature was undertaken. This comprehensive review involved examining each topic individually and also exploring potential interconnections between them. By doing so, we aimed to gain a holistic understanding of the subject matter. The process of literature evaluation was multifaceted. The available literature was meticulously filtered based on its content. Furthermore, only literature that directly addressed the research question was considered for inclusion. Any outdated material, derived from unreliable sources, or lacking a robust methodology was excluded from the analysis. Once the relevant literature was identified, data was collected from various sources, extracting key insights, to serve as the foundation for the subsequent analysis. To enhance readability and accessibility, the collected data was synthesized and integrated into the narrative. With the aim to provide readers with a clear overview of the existing knowledge landscape while maintaining a cohesive flow.

5.4 Leopold Matrix

An Environmental Impact Assessment is a study that considers all the impacts and effects on the environment of the deployment or development of a new project whether they are negative or positive. To perform an EIA there are several steps to be followed.

- Objective Statement: Clearly define the major objective that the project aims to achieve.
- Technological Possibilities: Analyze the available technological options and methods for achieving the project's objective.
- Proposed Actions with Environmental Impact: Describe one or more proposed actions, including alternatives, that may have environmental consequences.
- Baseline Environment: Detail the characteristics and conditions of the environment before any actions are initiated.
- Engineering Proposals and Cost-Benefit Analysis: Present engineering proposals for the actions, along with an analysis of their monetary benefits and costs.
- Environmental Impact Assessment: Evaluate the potential environmental impacts resulting from the proposed actions.
- Impact on Environment: Assess how the proposed actions will affect the existing environment.
- Summary and Recommendations: Summarize the findings and provide recommendations based on the analysis.

[Leopold et al., 1971]

To determine the reach of the impacts two aspects of them need to be considered. The magnitude of the impact, the scale of the impact on the environment, and the importance, the significance of the impact on the environmental conditions. Magnitude is usually based on hard facts and thus quantitative, however, importance relies more on expert judgement thus being open to interpretation and qualitative. Both values range from 1 to 3 where 1 is the lowest impact and 3 is the highest. [Leopold et al., 1971]

The Leopold Matrix is a good tool for analysing this data, as it enables the grouping of all impacts in a single table, allowing for the assessment of their relative magnitude and importance. On the horizontal the actions which cause the impact are listed and grouped depending on several factors, and on the vertical axis the baseline environmental conditions that could be affected by the actions are listed. The complete matrix counts with 100 actions listed and 88 affected conditions, the total possibilities are countless however there are many not likely as there are lots that don't interact. [Leopold et al., 1971]

To better use the matrix first the actions that are going to be taking place should be highlighted and later, the magnitude should be determined as well as the expected importance of said impact in the different environmental conditions. To show both values in the same value each individual box is divided diagonally, in the upper left-hand magnitude is shown and in the lower left-hand side importance is shown. Once all of the actions and conditions affected by the project are identified a reduced version of the matrix is produced taking out any that is not used. [Leopold et al., 1971]

Once the greatest impacts with the uppermost importance have been highlighted by the matrix, taking advantage of facts and the opinion from experts, measures to diminish these impacts should be provided as well as the study of other alternatives to reach the desired goal presented in the objective statement. These will ensure that the negative impact on the environment is minimized as the greatest threats are dealt with first and foremost. [Leopold et al., 1971]

H2 production and economic feasibility 6

Modelling, plant operation, profits, investment cost and incentives

6.1 PtH technology

6.1.1 Introduction

As previously reviewed the energy supply requires a certain balance between security, equity (accessibility and affordability), and environmental sustainability. This has been named as “The Energy Trilemma”. The quest to reduce carbon emissions in order to slow down and eventually stop global warming and climate change is rapidly developing all kinds of renewable energies with technical challenges that place H2 at the centre of grid balancing, storage and transport ecosystem. In this context, the typical renewables (solar and wind) have been able to drastically reduce their costs and develop associated technologies based on H2 to bring them closer to the consumers and absorb the excess of production during the green production peak and valley consumption hours.[IRENA, 2023]

Another factor to take into account is the energy security which is nowadays gaining importance due to unstable geopolitical stage with energy supply tensions with a special impact in Europe. The control and tensions over energy sources that started in the 70s [Beasley, 2023] and peaked during the early 80s (not so critical during the 90s) [IEA, 2017] are being used nowadays as a way to achieve political ends. Worldwide, energy produced locally is being prioritized over energy imports and this trend is favoring renewables and nuclear energy in all regions. This means that governments are willing to pay a premium for locally sourced energy. [Department for Energy Security and Net Zero, 2023], [Department of Energy, 2022], [European Commision, 2023]

All these development gets the H2 also to the centre stage as a key local enabler to secure the energy supply [IRENA, 2022]

Accordingly, H2 is an enabler that will intervene transversally in solving The Energy Trilemma. Therefore, it is crucial to understand the technologies surrounding H2 that could be used.

6.1.2 Hydrogen production. Different technologies

Hydrogen can be generated using several different ways, such as thermochemically, electrochemically, photochemically, photocatalytically, photoelectrochemically, biologically,. . .

[Balat, 2008]

The following figure illustrates the different technologies, classified according to the conversion process:

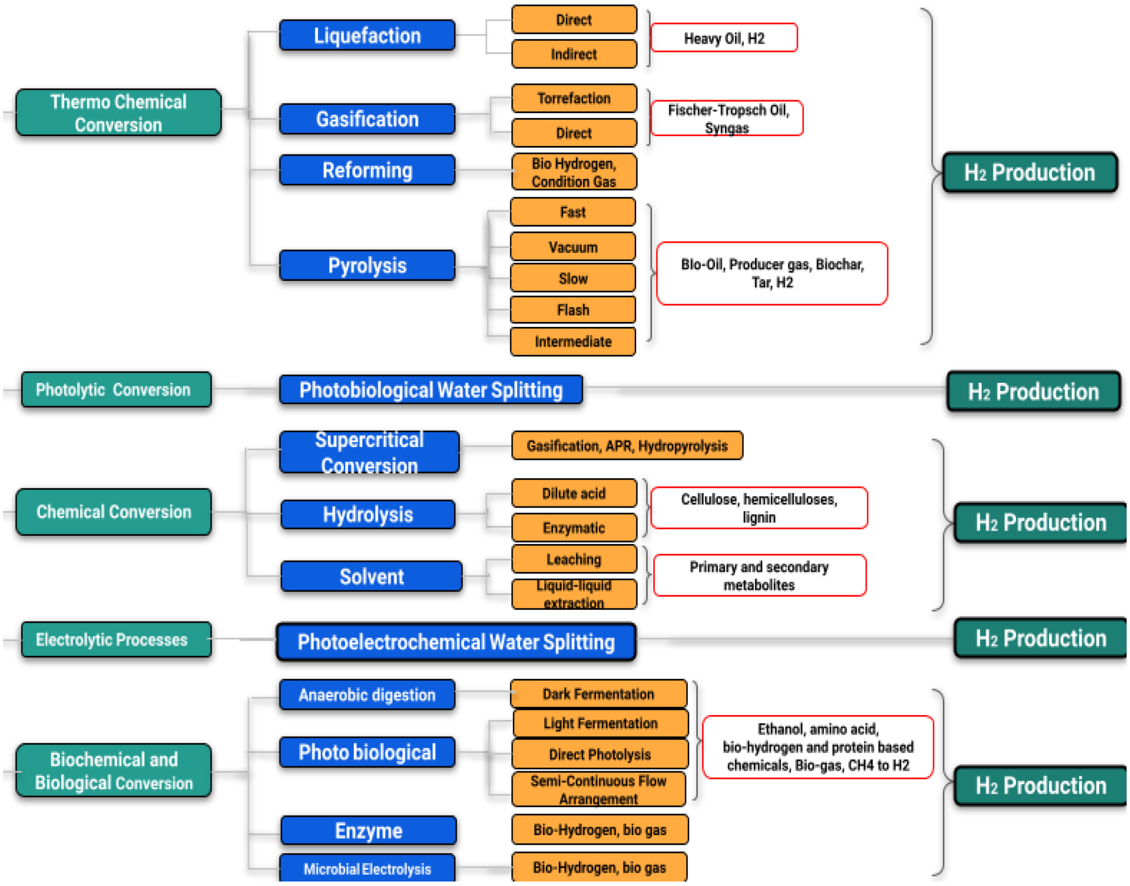


Figure 6.1. Different technologies of hydrogen production
[Ahad et al., 2023]

Although this work does not focus on all means of H2 production but only on green H2 generation, a short description of all the methods can contribute to a better understanding of the current H2 production scenario and the associated costs which are vital to determine the economic feasibility of this project potentially implemented in Iceland. It is important to say that more than 99% of the H2 production cannot nowadays be considered as "green" due to its fossil origin (from natural gas, coal or by-products in the petrochemical industry) and CO2 is produced as a residue. It is also known that these currently used methods are cheaper than the green ones (this will be largely elaborated in other chapters of this work). Different colours have been associated with each H2 production technology to easily classify them depending on their impact on the environment, pollution caused and CO2/GHG emissions. [Ahad et al., 2023] [CIC Energigune, 2022]

The following methods can be found in literature as ways for H2 production:

- **Natural gas reforming** (also called steam methane reforming or SMR). It is the most used method nowadays for hydrogen production (more than 62% of total) [IEA, 2023]. It is a thermochemical system based on methane reforming with water steam at high temperature (approx. 900ºC) and pressure: $CH_4 + H_2O \rightarrow CO + 3 H_2$ - 191,7 kJ/mol. This process can be optimized with additional water addition to the process ($CO + H_2O \rightarrow CO_2 + H_2$ - 40,4 kJ/mol). The obtained CO_2 is released into the atmosphere categorizing this hydrogen as "grey" since 9–12 tonnes of CO_2 are produced for every tonne of hydrogen. The hydrogen would be considered "blue" if the CO_2 would be sequestrated and stored underground. [CIC Energigune, 2022]

- **Coal gasification**. This process starts with the gasification of coal into CO, H_2, CH_4, ash, tar, H_2S, NH_3, HCl and HCN and later separation, purification and reprocessing of different constituents to increase the H_2 output [Midilli et al., 2021]. More than 21% of global H_2 production uses this technology that cannot be considered in any case "Net zero" due to the generation of CO_2 and other residues. In fact, it is considered the most contaminant process for H_2 production being classified as brown/black hydrogen.[IEA, 2023]
- **By-product generation**. This hydrogen is produced at refineries and in the petrochemical industry during naphtha reforming [1] and is often used for other refinery and conversion processes (e.g. hydrocracking and desulphurisation [2]). It represents nowadays the 16% of the global production. This hydrogen is considered grey as far as CO_2 production in the processes. As in previous cases, the sequestration and storage of the CO_2 would convert this H_2 into "blue". [IEA, 2023]
- **Pyrolysis**. It is still in an experimental phase and the process is based on the thermal decomposition of methane ($CH_4 \rightarrow C + 2 H_2 + 74{,}8$ kJ/mol) using nickel as a catalyst to be able to reduce the operation temperature from above 700°C to around 500°C. In normal industrial practice, the operative temperature range should be 800°C-1000°C and the pressure over 30 bar. [Kolb, 2020] The result is H_2 and solid carbon that can be utilized for tyre manufacturing or just buried. Despite CO_2 is not produced, it wouldn't be accurate to call it a 'zero emissions' method, because the extraction and transport of natural gas still results in fugitive emissions. [Weiland, 2009] A certain greenwashing of this process is acceptable if the methane comes from biofermentation (gas formation through the anaerobic digestion of energy crops, residues, and wastes) [Weiland, 2009] or from biomass gasification (conversion of an organic material into a gaseous product, called syngas, and a solid product, called char) [Musmarra, 2016]. Even in these cases, the leaks of methane during the whole chain does not allow the green label and a new category has been created: turquoise hydrogen, when it is obtained from hydrocarbons pyrolysis.[Kolb, 2020] It is important to emphasize that in all the processes which require high temperatures, the process can achieve a better carbon neutral status if the heat is generated with renewable sourced electricity. And that if the natural gas comes from biogenic sources, the process can even be more carbon-negative.[Kolb, 2020]
- **Thermochemical Processes**. All these processes target to produce hydrogen and oxygen with water and heat as the main consumable raw materials without the use of electricity. The H_2 is released from the molecular structure of the water ($H_2O \rightarrow \frac{1}{2} O_2 + H_2$) through different direct or hybrid cycles based on different

[1] Naphtha, any of various volatile, highly flammable liquid hydrocarbon mixtures used chiefly as solvents and as raw materials for conversion to gasoline

[2] Desulphurisation is a chemical process for the removal of sulfur from a material

chemical agents (S-I, Ce-Cl, Fe-Cl, Mg-I, V-Cl, Cu-SO4, S, Cu-Cl) which are reused. These processes are not yet considered industrial but experimental and can have the categorization of "green" as far as water and heat are obtained and treated without CO2 emissions.[Ozcan et al., 2023]

- **Biomass gasification**. Biomass gasification is a mature technology that uses a controlled process involving heat, steam, and oxygen to convert biomass to hydrogen and other products, without combustion. [Chen, 2011] A simplified reaction would be: (C6H12O6 + O2 + H2O → CO + CO2 + H2 + other species (char and tar)) The carbon monoxide then reacts with additional water to form carbon dioxide and improve the H2 outcome efficiency. (CO + H2O → CO2 + H2 (+ small amount of heat)) Despite CO2 being formed during the process this gas has been absorbed by the plants as part of their natural cycle. Thus, the final H2 obtained can be considered a low-net greenhouse gas emissions process. [U.S. Department of Energy, 2024a]
- **Biomass-derived liquid reforming**. This process consists of reforming biomass-derived liquids (ethanol, biofuels,..) with a high-temperature steam in the presence of a catalyst. The reaction looks in the case of the ethanol like: (C2H5OH+H2O → 2CO+4H2). Later a water-gas shift reaction is introduced: (CO+H2O→CO2+H2) [Emerson et al., 2014] As in the previous case the origin of the liquids (biomass) and the potential use of renewable energy for heat and processes make this system for H2 production a very low-emission one. Moreover, this process has the advantage of easy and cheap transportation of raw materials (liquids) with few or zero leaks. [Xiao et al., 2023]
- **Solar thermochemical hydrogen (STCH)**. It is based on the use of concentrated solar radiation as the energy source to generate high-temperature steam for driving an endothermic chemical transformation where certain metal oxides are working in continuous oxidation and reduction cycles (above 1400C) that obtain as the final result O2 and H2. The real inputs would be water and solar radiation, as the metal oxides don't need replacement and only act as a catalyst of the reaction. It is a promising technology because it can be more efficient than other technologies that use sun radiation (for instance the conventional photovoltaic cells). [Davenport og Saur, 2022]
- **Photoelectrochemical (PEC)**. Another promising technology in the experimental phase is the photoelectrochemical (PEC) water splitting, simply called photolytic process. The hydrogen is produced from water using sunlight and specialized semiconductors are immersed in the water-based electrolyte. The sunlight directly energizes the water-splitting process in such a way that water molecules are dissociated into hydrogen and oxygen. This technology is in the research stage but offers long-term potential due to the reduced or nil greenhouse gas emissions. [U.S. Department of Energy, 2024b]
- **Photobiological**. Some microorganisms such as green microalgae or cyanobacteria can produce hydrogen through biological reactions, using sunlight to split water into oxygen and hydrogen ions. These technology pathways are also in the research and development stage, but in the long term have the potential for sustainable, low-carbon hydrogen production. [Ghirardi et al., 2008]

- **Microbial biomass conversion**. It is based on the fermentation produced by some microbes that break organic matter molecules with the production of the hydrogen itself. The byproducts can be combined by enzymes to produce additional hydrogen. An additional small electric current can be introduced to enhance the H2 production of the system. This technology is not only useful for H2 production but also adds value to organic residues which are expensive to treat and neutralize otherwise. [Mudhoo et al., 2018]
- **Electrolytic Processes**. Electrolyzers use electricity to split water into hydrogen and oxygen. This technology is well-developed and available commercially, and systems that can efficiently use intermittent renewable power are being developed. This technology seems to be one of the best tools to achieve massive amounts of hydrogen at reasonable costs. In this point, it is necessary to mention that there are also different processes using this technology that can be summarized into two groups: low-temperature electrolysis (LTE) and high-temperature electrolysis (HTE). The selection of the most suitable electrolyzer technology is predominantly based on economic drivers, namely the levelized cost of hydrogen. However, there are other specific advantages and disadvantages that must be considered to arrive at the best final solution for each project. A deeper study is required accordingly to facilitate the right investment decision.[IEA, 2023]

6.1.3 Electrolysis process description

As previously mentioned, the hydrogen is produced in the electrolyzer via the electrochemical conversion of water into hydrogen and oxygen through the application of electrical energy, as in this basic formulation:

$$\text{H2O} + \text{Electricity (237,2kJ/mol)} + \text{Heat (48,6 kJ/mol)} \rightarrow \text{H2} + \frac{1}{2}\,\text{O2}$$

That simplified reaction is in fact the summary of two half-reactions, namely, the hydrogen evolution reaction (HER) (2H2O $\rightarrow$ 2H + 2OH-) and the oxygen evolution reaction (OER) (2OH- $\rightarrow$ H2O + $\frac{1}{2}$ O2) that take place in the cathode and the anode respectively. They are separated by an ion-exchange membrane. [Dubouis og Grimaud, 2019] The required electricity of 237,2 kJ/mol to drive the reaction is equivalent to a thermodynamic potential of 1.23V, but in reality, a much higher voltage will be used to overcome several barriers [Niblett et al., 2024], such as: electrical resistance of the circuit, activation energies (of the electrochemical reactions, obstacles related to gas bubbles, resistance to ionic transfer and electrochemical reactions), and mass transportation, especially due to the slow OER [Yu et al., 2021].To make the process more affordable, the overpotentials for both half-reactions should be lowered. This can be achieved by using electrocatalysts which can reduce the energy input and activation energy. The result is an endothermic reaction. The total energy needed for water electrolysis increases slightly with temperature, while the required electrical energy decreases. A high-temperature electrolysis (HTE) might, therefore, be preferable when high-temperature heat is available as waste heat from other processes or if it can be green and cheaply generated when the target is hydrogen 100% zero CO2 emissions. In case this heat generation is not possible the preferred solution should be based on a low-temperature electrolysis process (LTE).[Tüysüz, 2024]

6.1.4 The electrolizer. Different technologies

There are four already mature electrolyzer technologies for H2 production, namely: alkaline (AE), proton exchange membrane (PEM), anion exchange membrane (AEM), and solid-oxide (SOE) with different optimal operation environments. According to [Oldenburg, 2022] the most used technologies will be AE and PEM as shown in the following graphs. Nevertheless, the AEM and SOE can also be efficient in certain niche circumstances.

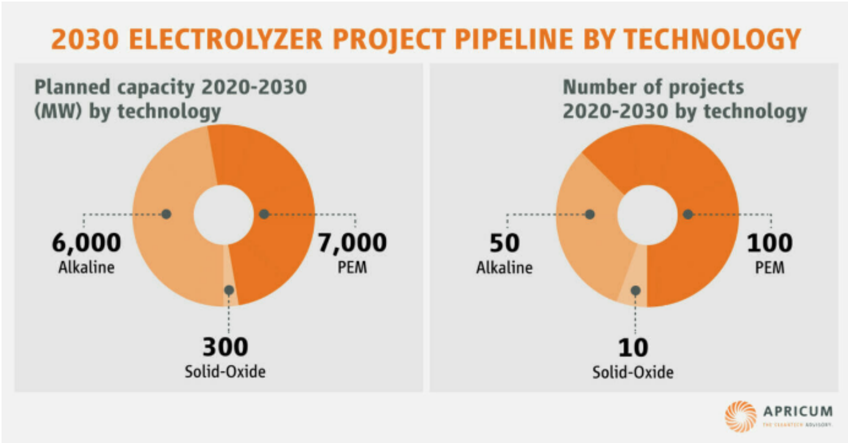


Figure 6.2. 2030 electrolyzer project pipeline by technology [Oldenburg, 2022]

The two main electrolysis technologies work at low temperatures: the AE (80–90 °C) with a liquid electrolyte, and the PEM (40–80 °C) with a solid electrolyte. The other promising electrolysis technology, the Solid Oxide Electrolysis Cells (SOEC), works at high temperatures (700–900 °C) and is based on solid oxide electrolyte. This high temperature technology is currently under development and the durability and material issues are the main concerns. [Ferrero et al., 2013b]

AE (Alkaline Electrolysis)

Alkaline water electrolysis uses concentrated lye [3] as an electrolyte and requires a gas-impermeable separator to prevent the product gases from mixing. The electrodes consist of non-noble metals like nickel with an electrocatalytic coating. In figure 6.3, a schematic flow diagram of an alkaline water electrolyzer is shown. The electrolyte is pumped through the electrolysis cell where the gas evolution takes place. Adjacent gas separators split both phases, and the liquid phase flows back to the electrolysis stack. Heat exchangers ensure that the optimal temperature is maintained, and the product gases can be purified afterwards. [Brauns og Turek, 2020]

The most-used electrolyte for alkaline water electrolysis is an aqueous solution of potassium hydroxide (KOH) with 20 to 30 wt.% KOH, as the specific conductivity is optimal at the typical temperature range from 50 to 80 ◦C [Shen et al., 2018]. Other alternatives are available, as for instance a cheaper NaOH with lower conductivity [D et al., 2019], or ionic liquids with lower degradation of electrodes however some display a certain degree of toxicity [Santos et al., 2013].

[3] Lye is an alkali metal hydroxide more specifically NaOH

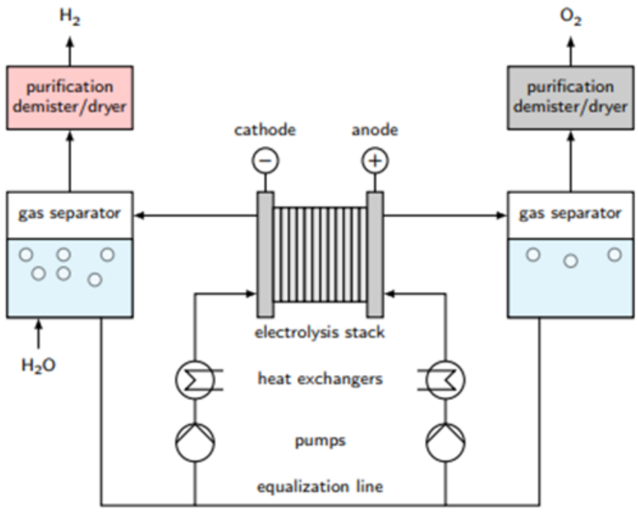


Figure 6.3. Schematic diagram of an alkaline electrolyzer [Brauns og Turek, 2020]

The main components of the electrolyzer core, the stack, are the electrodes which are separated by a thin porous foil, often referred to as a diaphragm or separator. This diaphragm prevents electrical shorts between the electrodes while allowing for small distances between them. State-of-the-art diaphragms include materials like Zirfon, a composite of zirconia [Lee et al., 2020], and Polysulfone [Xu et al., 2013] and the electrodes are made of Nickel-based metals [Dubouis et al., 2024]. [Brauns og Turek, 2020]

It is important to explain at this point that the repetitive start/stop affects the electrode behaviour causing the electrode degradation to be accelerated [Ursúa et al., 2013]. Nickel electrodes are known to degrade significantly after 5000 to 10,000 start/stop cycles [Ursúa et al., 2016].

The fluctuating nature of renewable energy limits operations due to time leads to a high number of startup and shutdown cycles and, therefore, can lower the expected system lifetime or electrolyzer manufacturer warranty agreements. This is due to the diaphragm being permeable to gases dissolved in the electrolyte. Limiting the lower operational load to 20% of the nominal load and requiring lengthy gas purging cycles during cold starts can be an effective solution for this issue, however, it results in long start-up times. The low gas barrier of the separator further limits the hydrogen output pressure of the electrolyzer. [Haoran et al., 2024]

In that situation, while solar and wind energy are often favoured due to their wide availability, other renewable energies, such as hydropower, biomass, and geothermal energy, are frequently utilized for the base load and minimize the number of starts and shutdowns. The potential connection of the electrolyzer to the grid to secure that minimum load base is also an alternative but H2 green consideration is only able if the grid guarantees a green electricity supply close to 100% (EU considers that Hydrogen produced in a grid-connected operation mode is only considered green if >90% of the electricity share of the grid is renewable). [European Commission, 2023a]

In summary, alkaline electrolyzers are to be preferred mostly for their record-low investment cost of 242 to 388 €/kW installed [Krishnan et al., 2023], low operational costs derived from their use of a potassium hydroxide solution during operation and the abundance of porous diaphragm-separator and catalyst materials (e.g., nickel). The ideal project environment for this system is a large-scale industrial installation requiring a fixed load base and resulting in steady H2 output at a low-pressure level.[Brauns og Turek, 2020]

PEM (Proton Exchange Membrane)

Proton exchange electrolyzers use a polymer electrolyte [4] and produce hydrogen from pure deionized injected water without any electrolytic additive. The central component of a PEM electrolyzer is the membrane, also known as the polymer exchange membrane which acts as both the gases (H2 and O2) separator and the electrolyte. [Chen et al., 2022] It plays a critical role in transporting protons during the electrolysis process because it ensures that only protons (H+) can pass through while blocking the migration of other compounds as described in this schematic diagram:

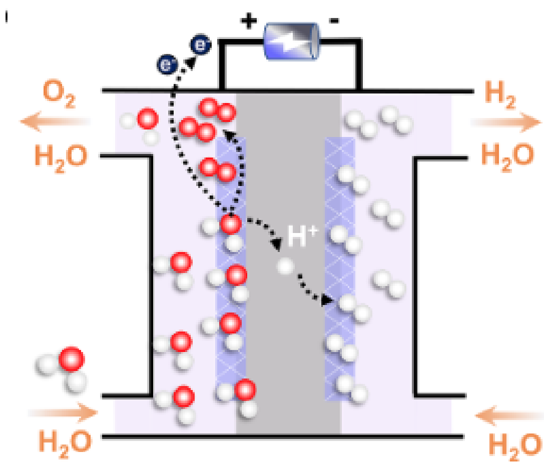


Figure 6.4. PEM operating principle
[Chen et al., 2022]

The acidic environment of PEM entails the need for costly materials such as platinum-, ruthenium and iridium-based catalysts, a perfluorinated ion exchange membrane, and titanium-based electrodes.[Chen et al., 2022]

There are a variety of advantages of PEM electrolysis, such as:

- high current density, [Falcão og Pinto, 2020]
- great energy efficiency (as high as 80%-90%), [Falcão og Pinto, 2020]
- low gas permeability, [Ahmed et al., 2022]
- high purity hydrogen [Aricò et al., 2012]
- compact design, [Scheepers et al., 2021]
- wide operating temperatures (20–80°C), [Scheepers et al., 2021]

[4] Polymer electrolyte is a compound capable of ion conduction made out of polymers (material formed by macromolecules linked together with a repeating structure), which can be synthetic or natural

- operation pressures of up to 200 bar. This high-pressure operation allows the hydrogen to be delivered and used at high pressure and minimizes the extra cost of pressurization. [Mo et al., 2016]
- use of pure water instead of an alkaline electrolyte is the reduced stress it places on critical equipment (e.g., pumps, valves, tubing) resulting in longer service intervals, easy handling and maintenance and in summary operational cost savings, [El-Shafie, 2023]
- but maybe the main advantage of a PEM electrolyzer is that it is well suited for off-grid installations powered by highly variable renewable energy sources (e.g., wind turbines). The fast start-up and wide operational load window enable an increased utilization compared to an alkaline system. [El-Shafie, 2023]

However, the exorbitant cost of the precious metal catalysts and also titanium electrodes makes PEM electrolysis a relatively higher investment than alkaline electrolyzers. [Krishnan et al., 2023]

To sum up, PEM water electrolysis can be considered a viable technology for high-purity hydrogen production at high pressure aligned with the high volatility of renewable energies.

AEM (Anion Exchange Membrane)

Anion exchange membrane (AEM) water electrolysis is the least developed of the electrolysis technologies discussed, although it has large potential to contribute significantly to the overall picture because of its low-cost materials utilization. [Miller et al., 2020]

It works in pure water or a slightly alkaline medium and the core of this process is a membrane that conducts hydroxide ions (OH-), separates the products and provides electrical insulation between the electrodes. [Kumar og Lim, 2022]

The basics of the process can be described in this simplified scheme:

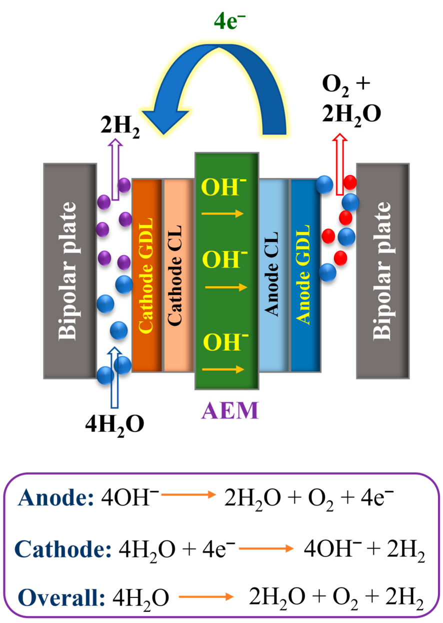


Figure 6.5. AEM electrolysis scheme and associated reactions [Vinodh et al., 2023]

When an electric current is applied, water molecules at the anode undergo oxidation producing O2 and H+ then at the cathode, reduction occurs where H+ is transformed into hydrogen. The membrane ensures that oxygen and hydrogen don't mix while allowing certain ions (OH-) to pass to complete the reaction.

One of the major advantages is that AEM water electrolysis uses cheap non-noble metal catalysts by using a low-cost transition metal catalyst based on Ni, Fe, Co,... [Yang et al., 2021].

One of the main problems of this process is the lack of cost-effective and long-lasting membranes suitable for use in an alkaline medium [Bernuy-Lopez, 2023a]. This technical challenge of the low durability of the membrane refers to the short device lifetime or longevity. Despite a PEM electrolyser stack working from 20,000 hr to 80,000 hr an AEM electrolyzer can work around >2000 hr, >12,000 hr,... It is clear that further R+D is required to be able to enter the commercializing stage of this technology. [Chand og Paladino, 2023]

All in all, in spite of the fact AEM development is still in the R+D phase, this technology is promising because it combines the key advantages of alkaline and PEM: a low-cost catalyst material and the operational flexibility resulting from gas-impermeable polymer membranes. A technical solution for the low durability of these ion exchange membranes will be key for the further development of this process. [Du et al., 2023]

SOEC (Solid Oxide Electrolyzer)

This process is a high-temperature electrolysis (HTEL) or steam electrolysis, as gaseous water is converted into hydrogen and oxygen at temperatures between 700 and 900 ◦C. The key components of a SOEC are a dense ionic conducting electrolyte and two porous electrodes as shown in this schematic graph and associated formulae. [Selysos, 2023]

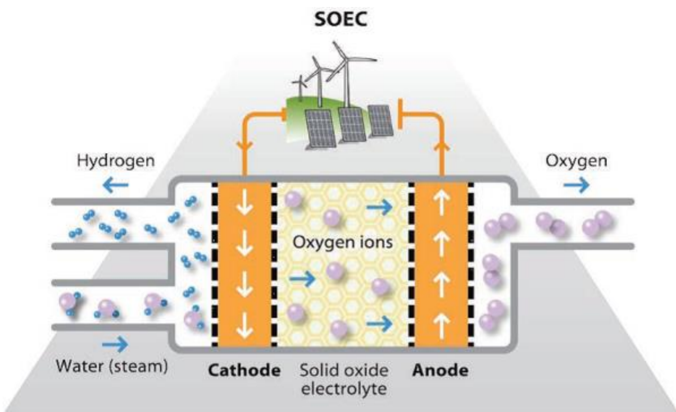


Figure 6.6. SOEC diagram
[Selysos, 2023]

$$\text{Anode: } 2\,O^{2-} \rightarrow O_2 + 4\,e^-$$

$$\text{Cathode: } H_2O + 2\,e^- \rightarrow H_2 + O^{2-}$$

$$\text{Net Reaction: } 2\,H_2O \rightarrow 2\,H_2 + O_2$$

Figure 6.7. SOEC formulas

Theoretically, SOEC stack efficiencies near 100% are possible due to positive thermodynamic effects on power consumption at higher temperatures. In normal operation efficiencies above 80% enable the use of abundant and relatively low-cost catalyst materials. [Nicita et al., 2020]

This unbeatable efficiency in comparison with other electrolysis processes is possible due to the high operational temperature that is only economical if a suitable waste heat source from the chemical, metallurgical, or thermal power generation industry is accessible. [Zhao et al., 2021]

Moreover, the high operating temperature requires a heat-resistant ceramic separator (solid-oxide) allowing the movement of ions at temperatures typically between 500-900°C and creating huge thermal stress in all the materials exposed to the heat. [Ni et al., 2008]

The solid oxide electrolyte requires in consequence to be made of compounds with zirconium, yttrium, scandia, ceria, lanthanum,... which results in an increase in manufacturing costs. [Bocanegra-Bernal og de la Torre, 2002]

The cathode is basically nickel with some degradation problems that require the incorporation of additional rare elements still under the research stage, such as lanthanum, strontium, scandium,... These exotic materials introduce a ramp-up in materials costs. [Chen et al., 2015]

The anode does not escape from this escalation of costs as lanthanum strontium manganate is typically formulated for this purpose and in some occasions even more exotic materials such as Gd-doped CeO2 or neodymium nickelate. [Chauveau et al., 2010]

The above considerations about exotic materials accessibility limit this process to niche opportunities associated with easy access to heat by means of other industrial processes. [Ferrero et al., 2013a]

Electrolyzer's materials criticality

One of the key considerations when developing these technologies is the intensive and rising use of critical or strategic materials. In figure 6.8 the critical materials in water electrolyzers based on supply constraints, demand rise, country risk, mining company concentration, etc are identified and summarized.

Except for titanium which is produced in stable countries and large quantities (low risk), the indicators for each assessed material are scored with a moderate to high supply risk in platinum (PEM) or mostly high risk in iridium (PEM), scandium (HTEL/SOEC), and yttrium (HTEL/SOEC). The high risk is based on the concentration of mining operations in very few countries, aggravated by critical political conditions in some of those countries, which bears the risk of sudden destabilization of the supply chains. These materials identified as critical are used in PEM and high-temperature electrolysis, whereas materials in alkaline electrolysis are not exposed to significant supply risks. [Kiemel et al., 2021]

Indicator	Platinum	Iridium	Titanium	Scandium	Yttrium
Country Concentration (HHI)	5.582 [high]	— [high]	1.334 [low]	7.896 [high]	7.896 [high]
WGI	0.09 [moderate]	—	0.68 [low]	−0.56 [high]	−0.56 [high]
HHI-WGI (scaled)	2.5 [high]	3.4 [high]	0.4 [low]	3.0 [high]	9.2 [high]
Companionality [%]	16.1 [moderate]	100 [high]	0 [low]	100 [high]	29 [moderate]
Company concentration (HHI)	1.883 [high]	— [high]	1.064 [moderate]	—	—
Demand growth	[high]	[moderate]	[moderate]	[high]	[moderate]
EoL-RIR [%]	11 [moderate]	14 [moderate]	19 [moderate]	0 [low]	(31) [neglected]
EoL-RR [%]	>50 [high]	>25-50 [moderate]	>50 [high]	<1 [low]	<1 [low]
Production [kg/a]	191 000 (2016)	7100 (2016)	170 000 000 (2016)	10 000 (2013)	9 200 000 (2013)
Demand conservative 2030 [kg]	~1050	~2100	~1 310 000	~8000	~4000
Demand conservative 2050 [kg]	~1300	~2650	~1 640 000	~25 500	~13 000
Demand progressive 2030 [kg]	~180	~360	~207 000	~1500	~1000
Demand progressive 2050 [kg]	~150	~200	~130 000	~2900	~1500

Figure 6.8. Material Criticality (Supply Risk) for Pt, Ir, Sc and Y [Kiemel et al., 2021]

Advantages and disadvantages

Taking into account all the information from different electrolyzer technologies and the availability of their raw material the following graph summarizes all of them, assigning several aspects of their design and functionality a category from "Excellent" to "Very bad"

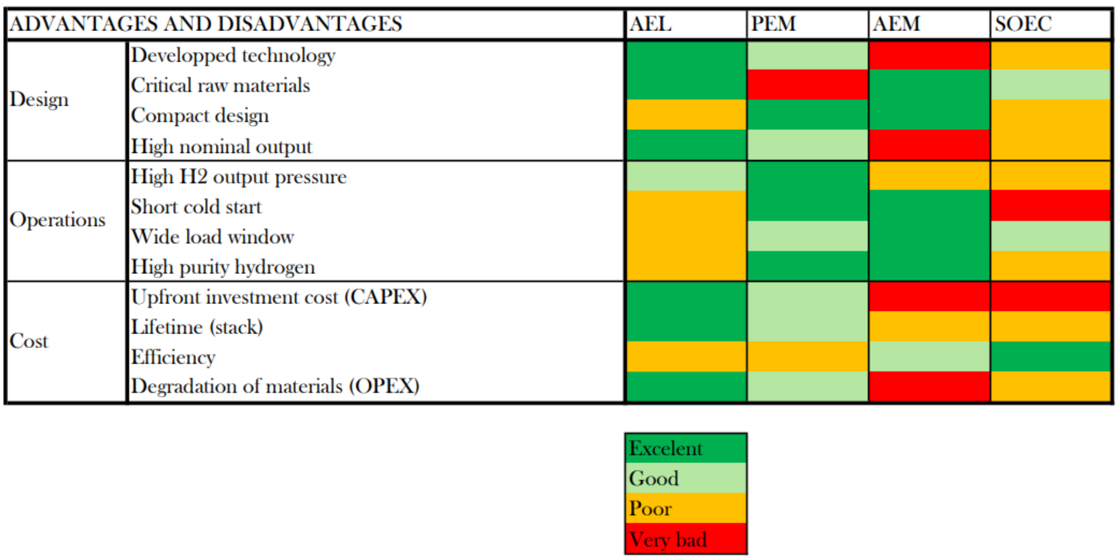


Figure 6.9. Comparison of electrolyzer technologies

6.1.5 Renewable Hydrogen production system (RHPS) selection

The Alkaline Electrolizer has been selected as the optimal option, given its suitability for the intended applications of this project. Different advantages that fit with this particular project can be mentioned:

- This technology has been proven effective for decades because it can produce high-purity hydrogen and it is renowned for its mechanical robustness and higher energy efficiency compared to other types of electrolyzers. The selection of simple lye electrolyte, electrodes and diaphragm redound in the simplicity of the concept and diminish the risk associated with the project.
- AE offers a reliable method for hydrogen production in case of a fixed load base with minimum CAPEX for large facilities under that configuration. The potential disadvantage of this system which is the difficulty of handling the variability of the renewable energy is negligible in this case because the proposed combination of hydraulic and wind generation with the possibility to retrofit the upper water reservoir when there is an excess of wind power generation guarantees always by far the minimum load required (20%) in this kind of electrolyzers and avoid the detrimental electrodes degradation and lack of overattentiveness in the long cold starts associated to repetitive start/stop operations.
- Another crucial advantage of this system is that it does not require the use of precious metals in its construction (low operation temperature) and operation (long duration of cheap electrodes). The degradation of the materials is low as well and the durability of the equipment is huge at the same time. This implies not only low CAPEX and OPEX but also low environmental trace due to very little consumption of easily accessible and recyclable materials.
- Furthermore, they operate at higher current densities and are less sensitive to impurities in the water supply, which can be a significant advantage in various settings.

The result is a low-risk solution, with low CAPEX and OPEX for this large facility, rendering a cost-effective solution for industrial-scale operations. It is also very important to consider the low environmental impact thanks to the overall low utilization of easily accessible and recyclable materials.

6.2 EnergyPRO model

The energyPRO software is used to perform detailed technical and economic analysis of energy plants. Its flexibility allows to model any desired facility taking into account a huge variety of parameters while optimizing the operation to maximize benefits. The main applications are:

- Model and simulate complex energy systems
- Perform investment analyses/feasibility studies
- Compare different scenarios

[Østergaard et al., 2022]

Several situations are going to be modelled using this program to simulate the production of an Alkaline electrolyzer connected to different sources of renewable electricity.

6.2.1 Models

To perform the feasibility study three models are proposed: Only Wind Farm Production, Wind Farm with Hydro-power Production and Wind Farm with Pump-back Hydro-power Production. These alternatives are considered in an off-grid configuration without the possibility of buying or selling energy to the grid.

Furthermore, as explained before the inputs for the electrolizer for all the alternatives are electricity and water while the outputs are hydrogen, oxygen and excess heat. The excess heat will not be sold and thus is not taken into consideration any further.

Only Wind Farm Production

In this alternative, the electricity to feed the electrolyzer comes only from the Wind Farm. This means there is no storage at all and the production has considerable peaks due to wind fluctuations. This configuration is not ideal because it would pose some operational disadvantages to the alkaline electrolyzers when running with fluctuating renewable energy sources (start/stop operations will result in increased degradation of electrodes and long cold starts thus poor efficiency). Nevertheless, it has been considered either way to allow comparison with the other alternatives.

This scenario's flow chart is as follows:

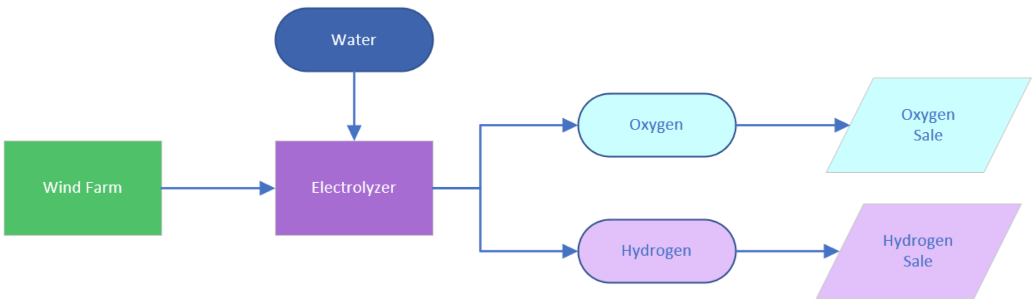


Figure 6.10. Only Wind Scenario flow chart

Wind Farm and Hydro-power Station Production

In this alternative, the electricity to feed the electrolyzer comes both from the Wind Farm and the Hydro-power facility. Consequently, there is no possibility to store the electricity once produced but water can be stored in the upper reservoir and used to produce electricity in the hydro-power facility when it is optimal to maximize benefits. This alternative allows a certain degree of energy storage in the form of water potential energy due to height differential and contributes to diminishing the operational disadvantages linked to an alkaline electrolyzer running with a fluctuating renewable energy source.

The stored high-gravity potential water helps to have a minimum operational load of the electrolyzer continuously and reduces frequent stops and starts thus their negative effect on the operation of the facility.

This scenario's flow chart is as follows:

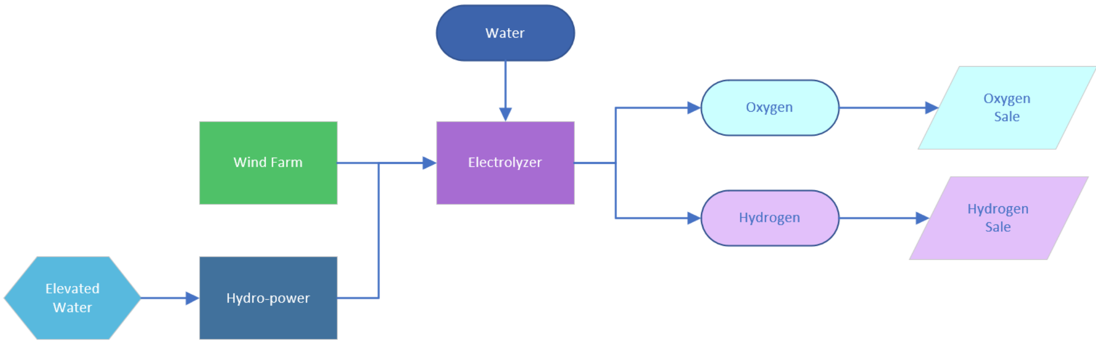


Figure 6.11. Wind and Hydro-power Scenario flow chart

Wind Farm and Pump-back Hydro-power station Production

In this alternative, the electricity to feed the electrolyzer comes both from the Wind Farm and the Pump-back Hydro-power facility. This alternative as the previous one allows a certain degree of energy storage in the form of water potential energy due to height differential in the upper reservoir. However, it also allows water storage in the lower reservoir that can be pumped back up to the upper reservoir if there is an overflow of electricity and the upper reservoir is not full. This allows tapping into the excess electricity not being used by the electrolyzer. This configuration is theoretically the best one to guarantee an efficient and smooth operation of the alkaline electrolyzer. Nevertheless, it implies also a greater CAPEX thus further economic analysis is required to establish the best alternative.

This scenario's flow chart is as follows:

6.3 Economic parameters

To perform the optimization of the aforementioned alternatives there are several economic parameters that also need to be taken into consideration besides the technical ones mentioned in table 6.3. To perform the feasibility study there are two main groups of parameters needed: pricing of raw materials and off-take products and other expenses like OPEX and CAPEX.

6.3.1 Market study of products

To establish the sale price of the products and the acquisition price of the inputs a market study is performed to determine if there are off-takers that could be interested and the expected price the products are going to have in the future. The current price is not taken into account as the project is not going to be finalised and running in the near future,

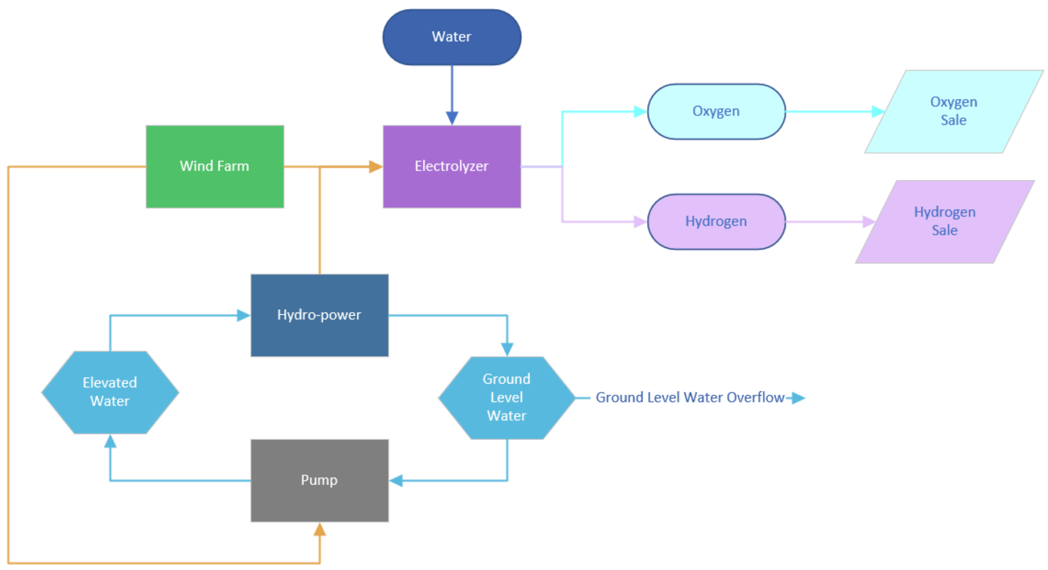


Figure 6.12. Wind and Pump-Back Hydro-power Scenario flow chart

rendering any calculation with current data unreal, thus a further study of the market development is needed to forecast the green hydrogen price in the future.

Hydrogen market price

To start with the main by-product of the processes and the aim of it, green hydrogen. It is important to make such differentiation as depending on the process followed to produce hydrogen its market price varies. There are several uses for hydrogen that can be differentiated into two large groups:

- Traditional. Including refining and feedstock to produce ammonia, methanol and other chemicals. Moreover, there are other uses of lesser significance as their consumption is really low in comparison.
- New applications. Transport, production of e-fuels, high-temperature heating and electricity storage and production. Other applications have more efficient low-emission alternatives.

[IEA, 2023]

Refining used more than 41Mt in 2022 from which less than 1% came from low-emission hydrogen. Whilst industry (mainly chemical production) purposes uses hydrogen from fossil fuels entirely, adding up to 53Mt in 2022 and growing. Transport's use of hydrogen is also growing and a bigger growth is expected in the following years, both directly (using hydrogen as fuel) and indirectly (to produce e-fuels for shipping and planes mainly), by 2030 it is expected 16Mt of hydrogen needed to meet the transport's sector demand. Besides in cars and transport vehicles, hydrogen also could be used in material handling equipment, mining trucks, and port operations vehicles. Furthermore, other forms of non-road transport such as trains and maritime transport are also starting to see the appeal of this fuel. There are several countries deploying hydrogen trains, however, there are others that have favoured electric ones due to lower operation costs. Shipping is also betting for hydrogen ships, as well as ammonia. As for aviation synthetic fuels based on hydrogen are the preferred solution but some companies are testing and developing direct use of hydrogen as a fuel. Moreover, the manufacturing sector's use of hydrogen has been ramping up in the last few years. Nevertheless, the use in buildings remains negligible and is not expected to grow as there are more efficient solutions in the market. Electricity generation from hydrogen is almost zero and ammonia produced from green hydrogen is expected to be preferred. [IEA, 2023]

Globally there is huge support for green hydrogen development with billions of euros in subsidies and other grants. Besides these, encouraging demand is paramount for the further development of the technology with several projects starting to be set in place to do so, such as carbon credit to incentivize green hydrogen usage across sectors or new demand generation which is proving to be more complex. [IEA, 2023]

Given this, the market price is due to evolve and the current green hydrogen price should not be taken into consideration as the reality in the following years will not remain the same. The cost for green hydrogen production will decrease with time from 4.6 €/kg (using AWE technology) in 2023 to 2.2 €/kg (Alkaline) in 2030. [Bernuy-Lopez, 2023b] While production costs for green hydrogen decrease it is expected that the price for non-green hydrogen will increase as more taxes on GHG emissions are implemented. The market prices will depend on the country and for Iceland the cost of importing green hydrogen in 2050 will be around 2.5 €/kg (while other countries could reach up to 4€/kg. [Carlson et al., 2023]

Oxygen market price

As another source of income, this project also considers selling the secondary by-product of the electrolysis, oxygen.

Oxygen has many uses that vary from heavy industry to medical uses. The steel industry is the major oxygen consumer, as it needs oxygen to increase the combustion temperature to replace other combustion materials. Furthermore, it is also used in the manufacturing of other metals as well as for other uses inside the sector. The chemical industry is also a major consumer that uses oxygen in refinery processes and coal gasification and to produce a wide variety of chemicals. Other industries that also use oxygen in their processes are the glass and ceramics manufacturing sectors, to allow for better heating patterns, control and higher efficiency. Moreover, the paper manufacturing industry uses it in a new bleaching process which is less harmful to water than the previous one. The healthcare industry uses oxygen in many treatments and since COVID-19 their demand has increased considerably. Other uses for oxygen are water treatment plants, underwater works, aquaculture and seaweed farming. [UIG, 2003] Besides these applications, others like mineral extraction, supporting ecosystems and enriching environments for insects should be mentioned.[Gustavsson et al., 2023]

While the cost of oxygen production has been decreasing over the years [Gustavsson et al., 2023], it is still high, the demand continues to grow as already established sectors need more and as well as new applications are discovered. [Mordor Intelligence, 2022]

Oxygen price varies depending on its purity, as several of the aforementioned applications don't need oxygen with high purity the prices are lower, for example for medical applications oxygen needs to be purer and the prices are much higher. The average prices range from 0,08 €/kg to 0,1 €/kg. [Gustavsson et al., 2023]

Water intake price and availability

As explained before the main raw material input for the electrolysis process is water. The cost of the water purchase will be included in the operation cost of the electrolyzer which will be described in the following chapter.

Due to the localization of the plant, the water can be diverted from the river directly for the electrolyzer consumption. In any of the alternatives presented this is an option as even if the water is being turbinated at the hydro-station it can be used after that process to feed the electrolyzer without having to duplicate the river's water flow. The estimated water intake for a 40 MW facility is around 45,000 m^3 per year, which taking into account the river's water flow is of minimal impact, as the river water flow exceeds by far that quantity. The following table presents the rated flow curve of the river being used as a reference for the project, Jokulsa I Fljotsdal.

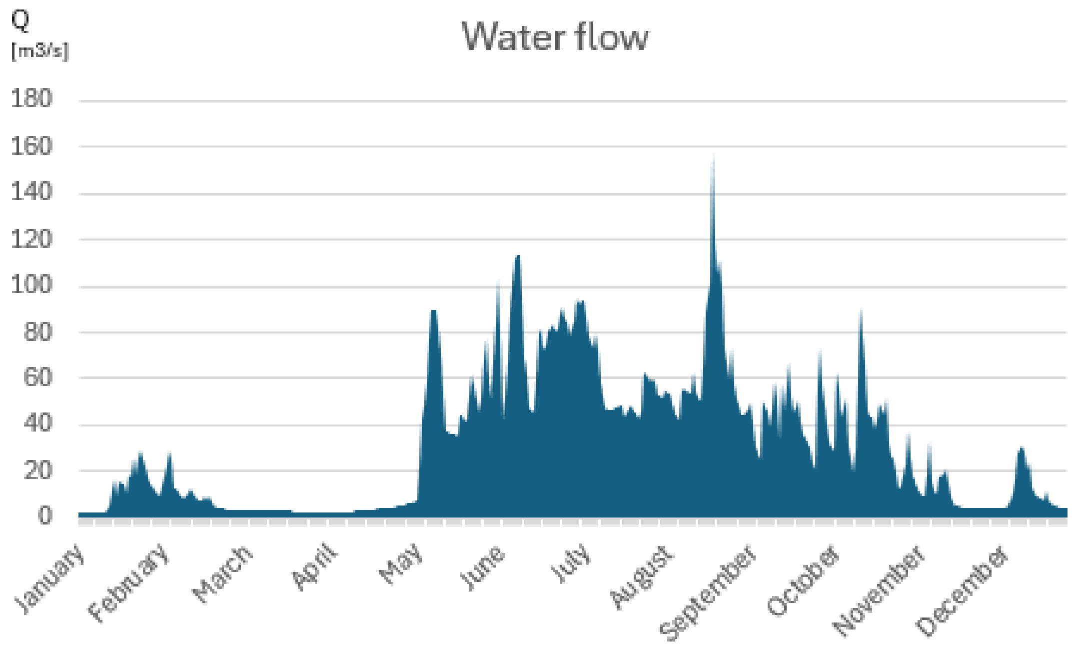


Figure 6.13. Water Flow from Jokulsa I Fljotsdal river. *Source: Icelandic Met Office*

From this data, the Flow Duration Curve (FDC) can be calculated. It represents the river flows sorted from highest to lowest during the year and it is used to determine how many days the minimum flow is not reached whether for the hydro-power facility or from an environmental point of view.

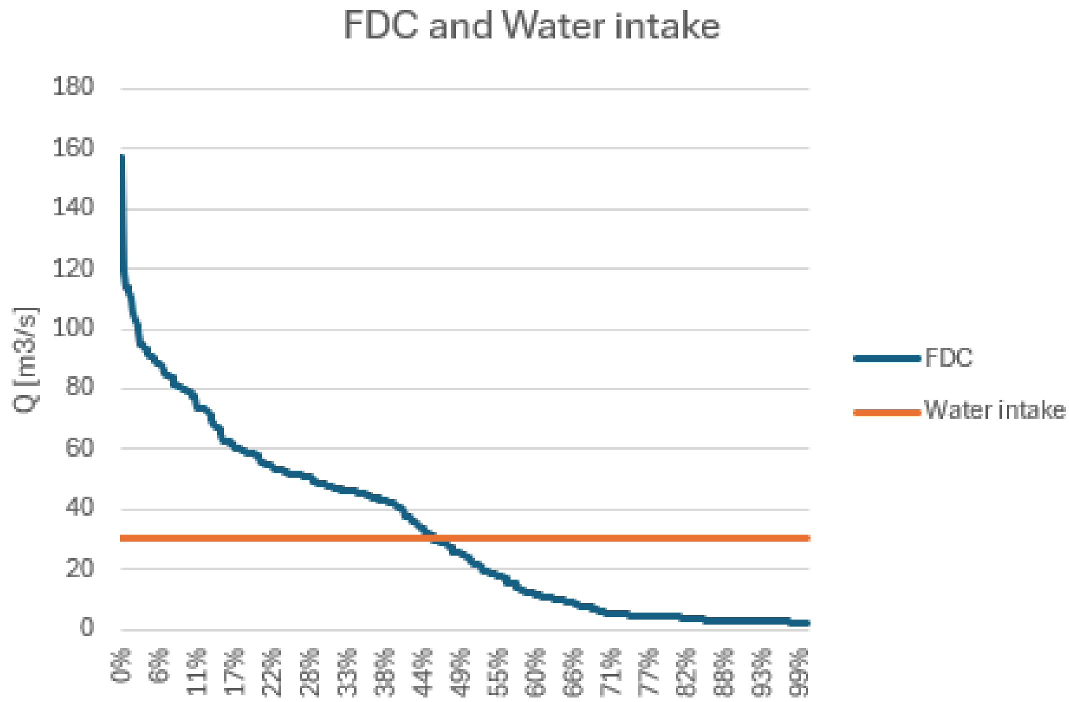


Figure 6.14. FDC compared to water intake

As it can be seen in the comparison between the FDC and the expected Water intake from the hydro-power facility, the Hydro-power facility could be working at full capacity 49% of the year and at least half capacity at around another 10%.

6.3.2 Investment costs

Usually when estimating the cost of a project the main factors considered are Capital Expenditure (CAPEX) and Operation and Maintenance Costs (OPEX). However, Development Expenditure (DEVEX) also should be taken into account when estimating the cost of a project, for this project DEVEX has been considered as part of the CAPEX.

CAPEX

The investment in the facilities necessary for this project is high, according to [IRENA, 2023] and other sources, the following investments have been considered.

Facility	CAPEX [million €]	Source
Wind Farm (50MW)	75,6	[IRENA, 2023]
Hydro-Power facility (40MW)	65,2	[IRENA, 2023]
Electrolyzer (40MW)	52	[IRENA, 2020]
H2 Pipeline	35	[Khan et al., 2021]

Table 6.1. CAPEX estimations

OPEX

Taking into consideration the aforementioned report and other sources that appear in 6.2 graph, the following OPEX are considered for the modelling of the project. Besides, the water intake price for the electrolyzer is 0,0012€/kg

Facility	OPEX [million €/year]	Source
Wind Farm (50MW)	1,4	[IRENA, 2023]
Hydro-Power facility (40MW)	1,3	[IRENA, 2023]
Electrolyzer (40MW)	1,04	[Brynolf et al., 2018]
H2 Pipeline	0,385	[Khan et al., 2021]

Table 6.2. OPEX estimations

6.3.3 Governmental incentives

As it has been stated throughout the report green hydrogen is a technology with a lot of momentum both politically and socially, thus as will be now explained there are several possibilities for the facility to be incentivized by a series of organizations.

As mentioned in the second chapter the European Union and other governments have road maps to develop green hydrogen to the extent needed to fulfil the climate goals. Iceland even though is not part of the EU follows its steps and takes some of the efforts even further. [Ministry of the Environment, Energy and Climate, 2024]

There are several ways to incentivize production when the technology is not mature or as cost-efficient as other options. The Icelandic government is currently studying these three:

- **Contracts for differences**. Where the government supplements the private producer or the private off-takers so the market sale price is lower and closer to the other options.
- **Cash-flow guarantee**. As a way of assurance, the government will reimburse money to producers if, at the end of the year, their economic benefit is negative
- **CAPEX subsidy**. Cash payment to the owners of the project for the construction of the facilities either upfront or in different payments if the conditions agreed upon are fulfilled.

[Ministry of the Environment, Energy and Climate, 2024]

The European Commission subsidies are focused on the first type to supplement the selling price. The ones that have already been granted range from €0.37 and €0.48/kg for 10 years of production[European Commission, 2024d]. Nevertheless, some other countries also consider CAPEX subsidies as the better option to facilitate the green transition and advocate for green hydrogen production. [Ministry of the Environment, Energy and Climate, 2024]

Nevertheless, Iceland hasn't set for either of them and is still studying the best way to approach the issue and the quantities for each subsidy.[Ministry of the Environment, Energy and Climate, 2024]

6.4 Summary of parameters used on the EnergyPRO model

For all the alternatives the main technical parameters remain the same and are as follows:

Electrolyzer type	Alkaline
Electrolyzer capacity	40 MW
Wind farm capacity	50 MW
Hydro-power height differential	500 m
Hydro-power capacity	40MW
Hydro-power pump capacity	20MW

Table 6.3. Technical parameters used in EnergyPRO

For all the alternatives the baseline economic parameters taken into consideration to calculate the yearly cash flow are as follows:

	PRICE [€/kg]
Hydrogen sale	2,5
Oxygen sale	0,09
Water intake	0,0012

Table 6.4. Product prices used in EnergyPRO

6.5 Final results from EnergyPRO modelling

Using the above-mentioned Energy Analysis in EnergyPRO for the 3 alternatives presented the following economic parameters with the baseline specifications are calculated.

As explained in the methodology section all three of these parameters are calculated taking into account the discount rate to portray the depreciation of money during time. The Discount rate used for all the alternative economic calculations is 5,06% which takes into account a 2% of inflation and a 3% capital cost. The period of time considered to perform these calculations and determine economic feasibility is 30 years which is the usual life of these facilities. The CAPEX of all the facilities is the one specified in the tables from the previous chapter. To take into account the extra cost of the pump and other equipment needed for the Pump-back hydro station an extra 10% is added to the standard hydro-power plant CAPEX and OPEX. For all these scenarios the hydrogen price is fixed at 2,5 €/kg. Moreover, besides the OPEX mentioned for the Electrolyzer in the previous chapter these calculations also consider changing the electrolyzer stacks every 8 years.

	NPV [million €]	IRR [%]	Discounted Payback [years]
WIND + HYDRO-POWER	23,5	6,78	21
ONLY WIND	-91	-3,4	+100
WIND + PUMP-BACK HYDRO-POWER	23,9	7,27	15

Table 6.5. Base results

In general, it can be observed that both the first and third alternatives are viable as their NPV is positive and their IRR is higher than the Discount rate. However, the second alternative is far from being viable as the NPV is negative and the IRR is not only lower than the Discount rate but negative altogether. In terms of Discounted Payback, the third, pump-back hydro, option is the lowest which means that is the option that reaches the break-even point faster and starts winning money. In the first option, wind with hydro, discounted payback is lower than the 30 years used to make these calculations but higher than the third and close to the limit. The second scenario's, only wind, discounted back is over 100 years which means that the investment is not recovered in that period of time making it highly unfeasible. Even though the Cash Flow from the third alternative is higher than the first one, their NPV is similar as the investment for the hydro facility is higher in the 3rd alternative due to the added equipment for the pump.

From this, we can say that both the first and third scenarios are viable, from which the third one appears to be slightly better due to its slightly higher NPV and IRR and lower Discounted payback time.

6.5.1 Sensitivity Analysis

Even though the results previously calculated seem to provide a clear overview of the best solution, a sensitivity analysis should be performed to determine how and in what magnitude each of the alternatives are affected by the factors taken into account in the first set of results.

Hydrogen price in the baseline model is assumed 2,5 €/kg but it is unclear if that value will be as forecasted or will vary, whether increasing or decreasing. Besides the variation in forecasted prices, this would also into consideration the possible subsidies for hydrogen offtake. To determine the model's dependence on the hydrogen price two other rounds of results are presented with a plus-minus 20% of the price and the following graph shows the two new options in comparison with the baseline one.

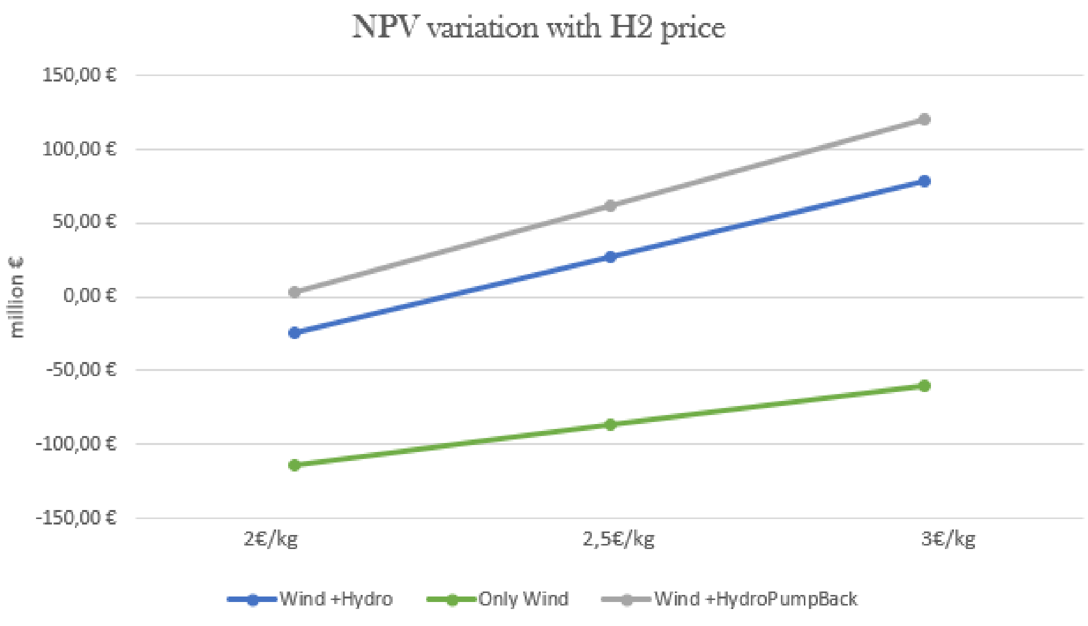


Figure 6.15. NPV variation with H2 price

As it can be seen the NPV of all the scenarios increases as the hydrogen prices do. However, the change does not follow the same rate in all the scenarios, being more noticeable in the Wind and Hydro-Pump Back Scenarios. Only the pump-back scenario remains positive with all three hydrogen prices. Meanwhile, the Only Wind scenario is unfeasible without regard to the hydrogen price chosen.

Figure 6.16. IRR variation with H2 price

The IRR also increases as the price rises, but again it can be seen that the highest IRR comes from the pump-back scenario.

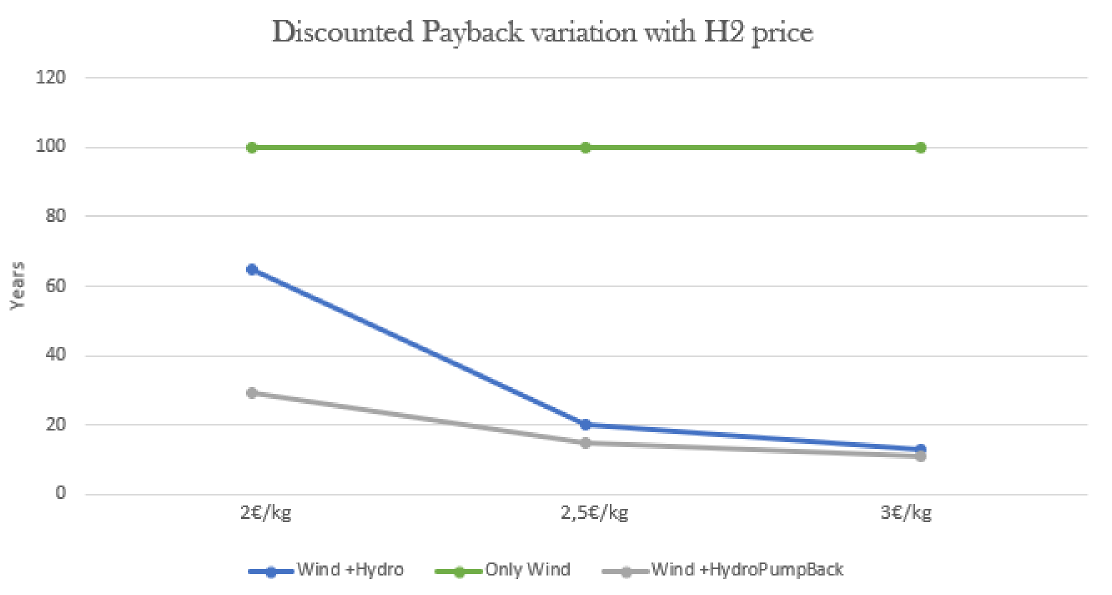


Figure 6.17. Discounted Payback variation with H2 price

As for the payback period, the Only Wind scenario's period is over 100 years for all of the proposed hydrogen prices. As for the other two scenarios it can be seen that the payback period decreases as the hydrogen price increases, getting closer as the price increases.

Besides hydrogen price, CAPEX and OPEX are also two of the main factors for these results and their quantity can not be assured either as the technologies evolve constantly as do the prices of their implementation. This mainly affects the electrolyzer as is the less mature technology and has suffered more changes in the past years. Furthermore, if the government implements subsidies on the investment of these projects the CAPEX to be considered would be reduced. Thus, two other situations with a plus-minus 20% of the CAPEX and OPEX of the electrolyzer are also presented. In addition, the CAPEX and OPEX of the wind and hydro facilities are also modified but slightly as they are more mature thus the variations that can be expected from these technologies are minimal, a plus-minus 5% of the CAPEX and OPEX of these technologies facilities are also considered.

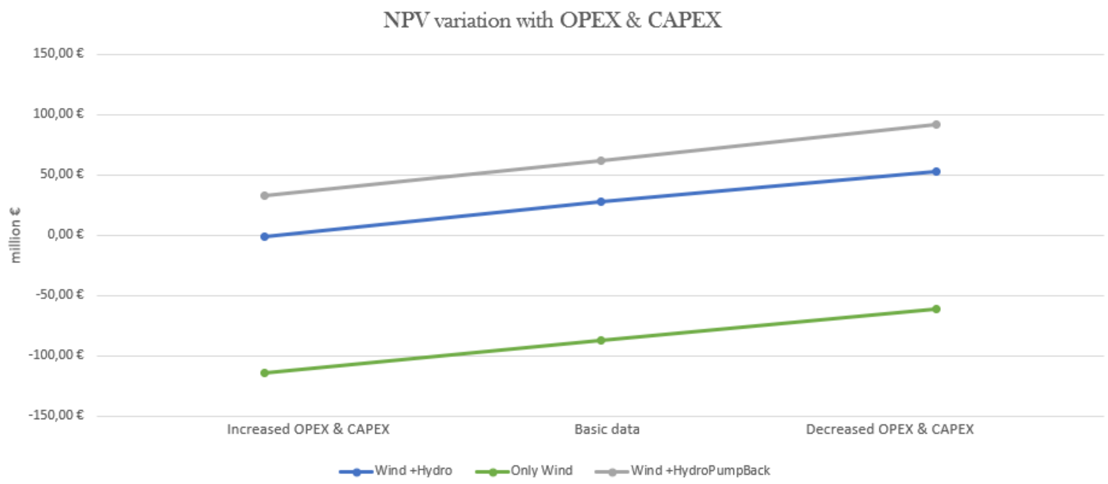


Figure 6.18. NPV variation with OPEX and CAPEX

As it can be seen as the OPEX and CAPEX decrease the NPV grows making the scenarios more beneficial. Again the Wind with HydroPumpBack Scenario is the one that remains positive without regard for the changes in OPEX and CAPEX. Moreover, the Wind Only scenario does not become beneficial even with a reduced CAPEX and OPEX.

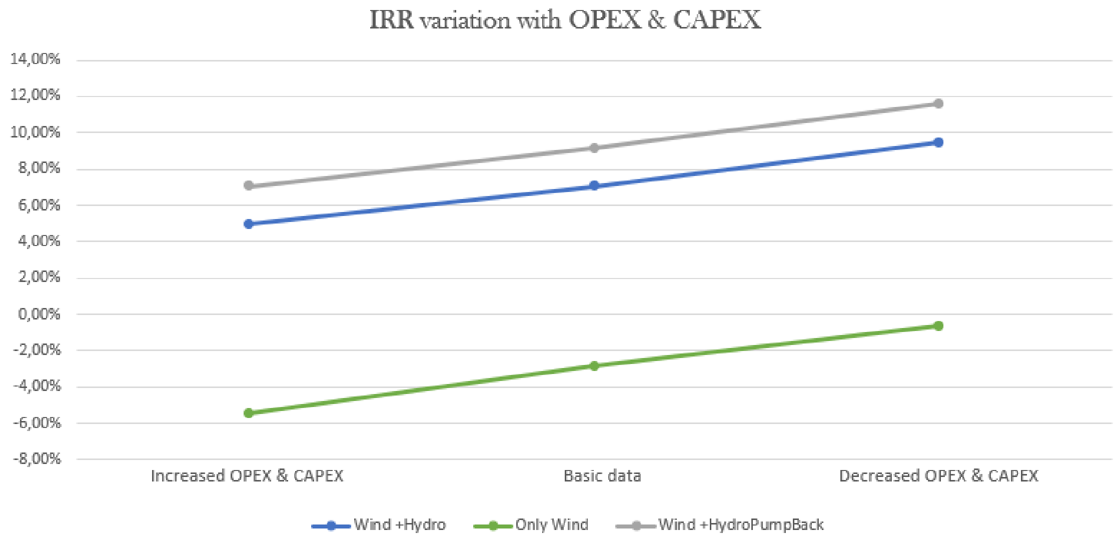


Figure 6.19. IRR variation with OPEX and CAPEX

As it can be seen the IRR behaves as the NPV and the scenarios feasibility increase at the same rate more or less.

Again the Only Wind scenario's period is over 100 years for all of the parameters. As for the other two scenarios it can be seen that the payback period decreases as the OPEX and CAPEX decreases too. The difference between these two scenarios is small with all the parameters changes.

Furthermore, inflation is not static and changes over time, thus its potential effect on the feasibility of the scenarios will be asses. The results of the baseline examples will be assessed with different inflation values, plus-minus 20% of the base parameter and a 10% of inflation as an extreme circumstance.

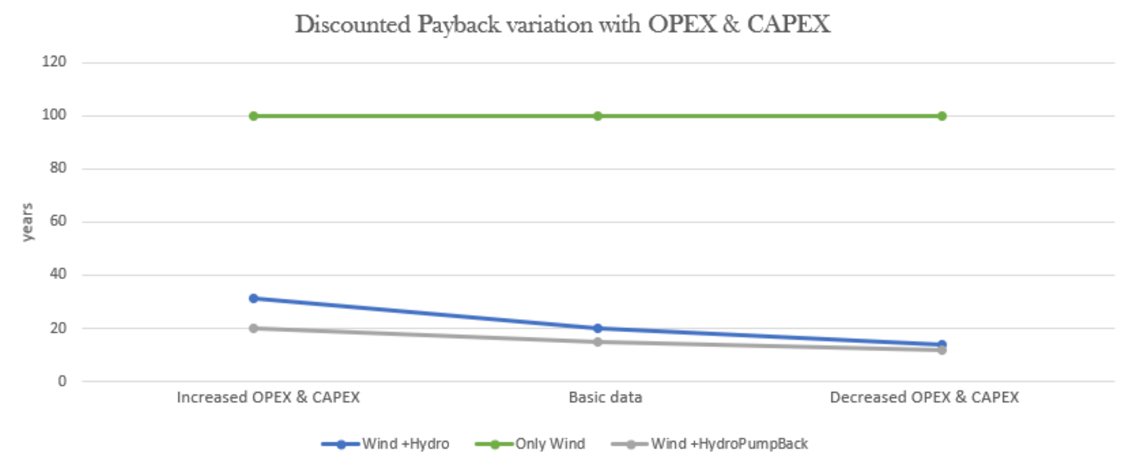


Figure 6.20. Discounted Payback variation with OPEX and CAPEX

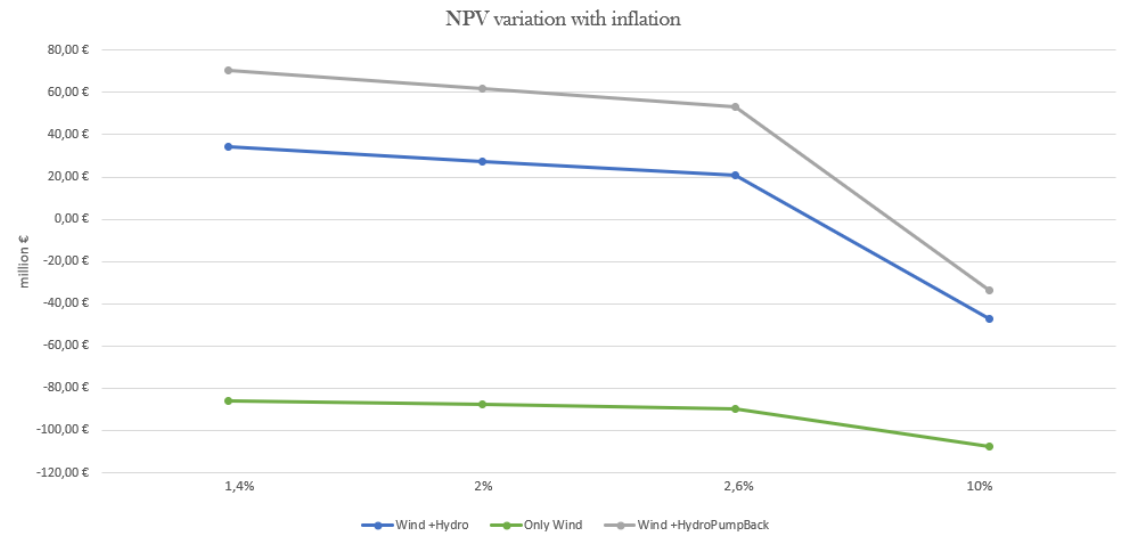


Figure 6.21. NPV variation with inflation

As it can be seen as the inflation increases the NPV decreases, in the extreme case scenario of having an inflation of 10%, which is very unlikely, neither of the scenarios is viable.

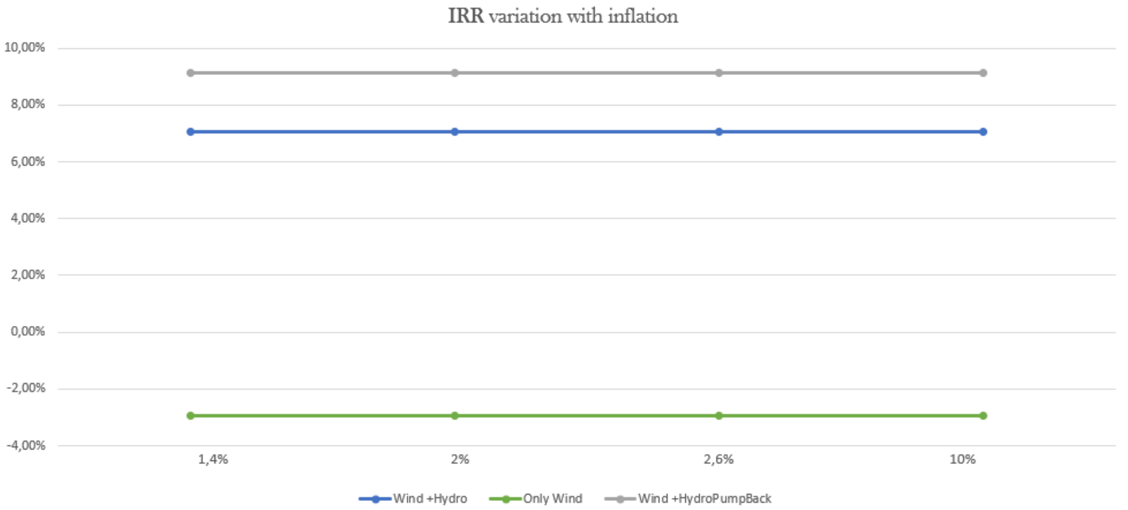


Figure 6.22. IRR variation with inflation

The IRR does not vary with inflation as the Cash Flow of the scenarios doesn't change and neither does the investment.

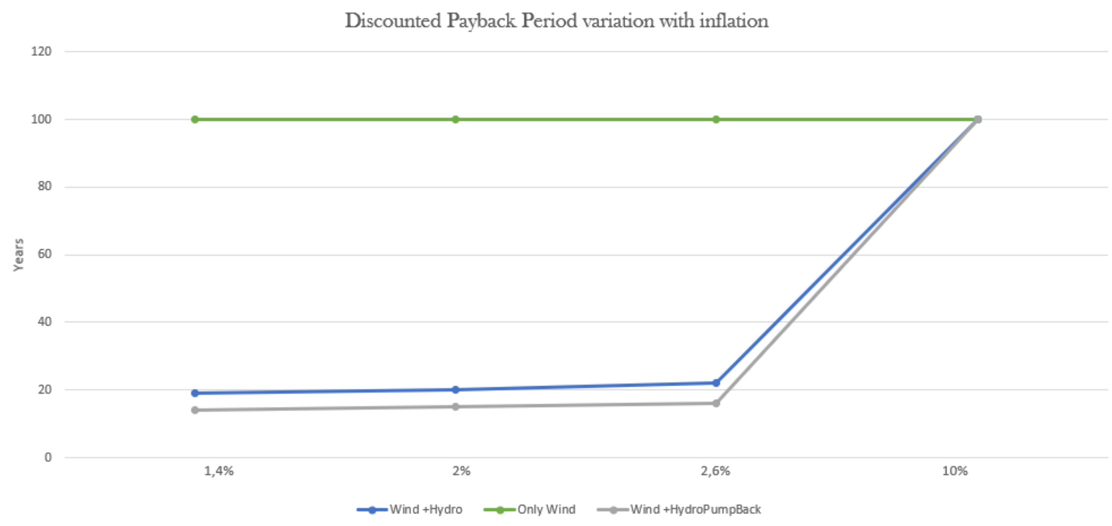


Figure 6.23. Discounted Payback Period variation with inflation

The Discounted Payback Period of the Hydro scenarios are both quite similar only becoming exceedingly high when the extreme inflation of 10% is presented. The Wind Scenario payback period is over 100 years with all inflation values studied.

Last but not least, the scenarios will be assessed at their worst and best situations to create the extremes on both sides of the baseline situation. The worst scenario takes into consideration the lowest hydrogen price, the incremented OPEX, CAPEX and inflation. Whereas the best case scenario takes into consideration hydrogen price of 3€/kg, reduced OPEX, CAPEX and inflation

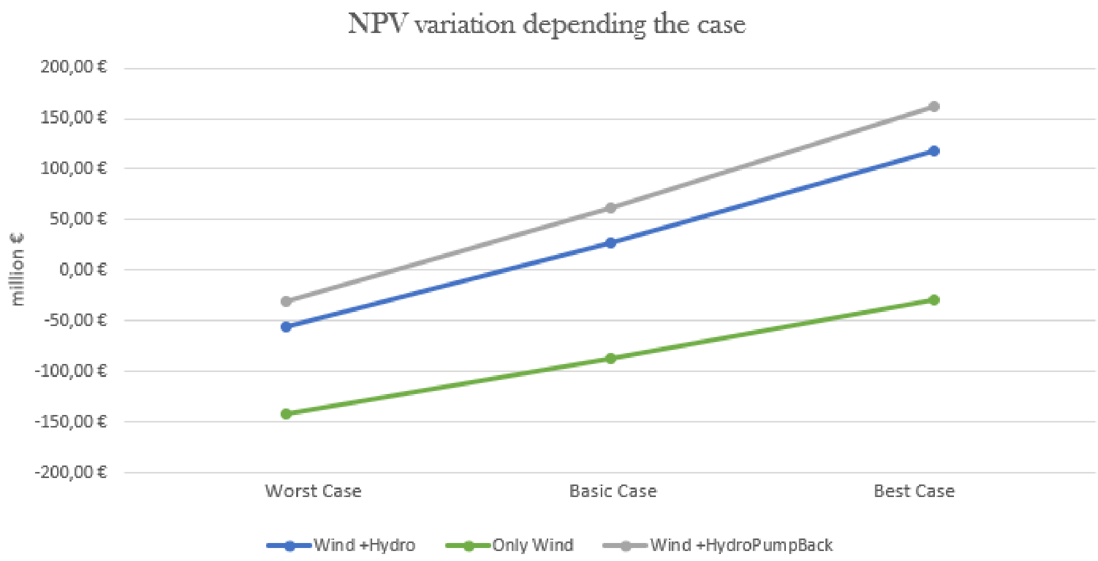


Figure 6.24. NPV variation depending the case

As expected the best case scenario NPV values are higher, however not even in the best case scenario the only wind scenario becomes beneficial.

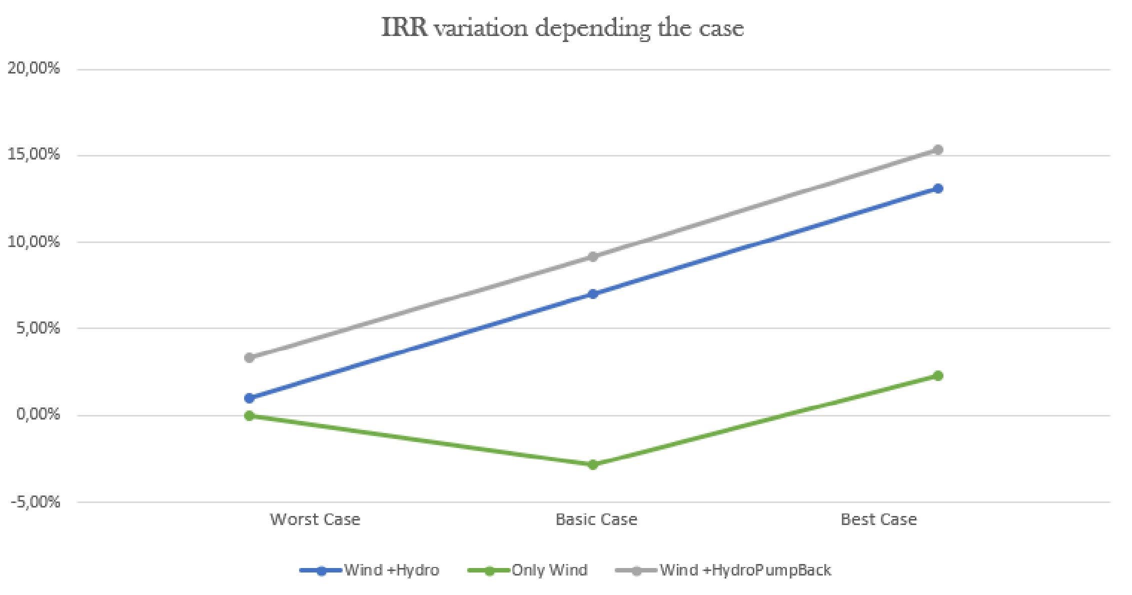


Figure 6.25. IRR variation depending the case

IRR values behave similarly to the NPV ones, in the worst case neither of the option's IRR is greater than the discount rate rendering them unviable options. The IRR value of the wind scenario in the worst case is not 0 as presented on the graph but rather it can not be calculated as the Cash Flow of some years is negative.

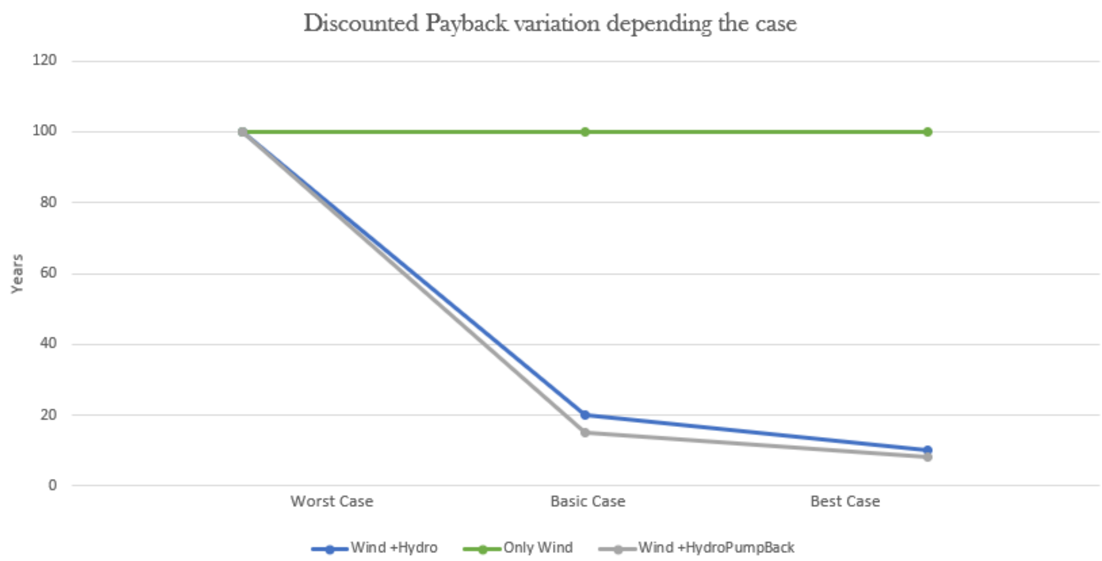


Figure 6.26. Discounted Payback variation depending on the case

As the wind scenario is not viable by any means the payback time is still above 100 years. Nevertheless, the other two scenarios' payback periods get lower and closer as the case improves.

For the Only Wind scenario to be viable the best case scenario parameters should be considered but changing the price of hydrogen sale up to 4€/kg, which leads to a NPV of 26,3 million €, an IRR of 6,6% and a discounted payback period of 21 years.

All in all, it can be seen that the best scenario is the Wind with Hydro PumpBack one as is the one that has better profitability and lesser payback time during all the cases presented proving to be more stable. This analysis leads to the conclusion that some scenarios would only be viable thanks to subsidies as can be seen with the less favourable scenario, only wind, which would require a hydrogen price of 4 €/kg. That hydrogen price is unlikely and would likely need to be subsided during operation to make it feasible. Furthermore, for the pump back scenario, the project remains feasible under several changes of circumstances except with some more extreme economic parameters which are deemed highly improbable and make it unfeasible, like with a 10% inflation. Moreover, subsidies in CAPEX can turn the scenario of hydro with wind into a really interesting option as the investment is reduced and so is the risk.

7 Environmental impact

In the following chapter a high-level overview of the environmental impact of the three facilities that encompass the scenario that has been deemed as the best alternative, wind with pump-back hydro will be performed. This could be used to target resources and focus on the most at-risk areas to avoid investment and efforts in low-risk impact areas.

7.1 Impact assessment

In this section, the main impacts of the different technologies will be described differentiating which facility produces them. Thereafter, a Leopold Matrix will be presented containing all the impacts from all facilities of the alternative selected in the previous chapter.

7.1.1 Impacts from the wind farm

- **Landscape.** This derives from two reasons, the contrast of the new installation due to color and contrast and the shadow flickering caused by the blades. The first one is perceived as the wind turbines modifying the natural landscape and overall view of the area. The shadow flickering encompasses two different events when the sun is reflected on the blades producing flashes and the moving shadow produced by the blades. These phenomena have impacts on both wildlife and human health.
- **Population and health safety** Which includes besides the one previously mentioned the following:
  - Noise pollution. Due to the wind flow the wind turbines can produce noises, the faster the wind and the bigger the wind turbine the louder the noise in different frequencies. The machinery inside the wind turbine can also cause noises during the operation.
  - Electromagnetic interference. Wind turbines produce electromagnetic radiation which affects radio and TV waves, however, if these radiations have any effect on health is not proven. Bats are also affected by this effect.
- **Fauna affections** Birds and bats are mainly affected by the blades of the wind turbines as they may collide with them. Moreover, other fauna species are also disturbed during construction and operation due to noises, air pollution and other effects. This can cause migrations and relocation of wildlife causing a decrease in biodiversity.
- **Vegetation.** To build these facilities the greenery has to be removed in the wind turbine and the surrounding area. Flora loss will cause the relocation or migration of wildlife decreasing the biodiversity of the area

- **Soil affections.** During construction works greenery is removed and the foundations and roads are built which can cause the soil to be damaged. As an example, soil damage can lead to degradation or landslides in the vicinity.
- **Water pollution.** During construction and operations leaks of contaminants may occur thus polluting not only surface water but also underground reservoirs.

[Sayed et al., 2020]

7.1.2 Impacts from the hydro-power station

- **Impact on Ecosystems.** Due to the reservoir, a huge area is flooded changing the existing ecosystem and affecting not only the flora and fauna of that area but also the aquatic ecosystem as the introduction of new factors may change the water's temperature and oxygen levels which can lead to aquatic life loss. Moreover, flora loss is huge in the area the reservoir is going to occupy. This also affects biodiversity as huge migrations happen.
- **Impact on aquatic fauna**. When a river's flow is interrupted by a damn some fish species can't migrate along the flow impacting their life cycle.
- **Changes in water quality**. The damn construction and subsequent water stagnation can cause harmful components to leak into the water. Temperature changes also can affect water quality and the life on it. Stored water can be the perfect opportunity for harmful microorganisms to proliferate raising the risk of infections in the surrounding area.
- **Land use**. The construction of the damn and subsequent reservoir takes up a lot of space leading to changes in land usage, which can also cause social unrest.
- **Impact on wildlife**. These changes in the ecosystem can affect migrations and other important wildlife activities leading to mass migration of species or extinction, ultimately biodiversity in the area can be severely reduced.
- **Impact on society**. If the new damn is located in the vicinity of a town it may cause the reservoir to flood the town, forcing the community to relocate elsewhere. Similarly, the flooded area may contain culturally significant sites, rendering them flooded, and creating a loss of heritage. As a positive impact, there will be job creation in the area and other economic benefits derived from the new industry.

[Sayed et al., 2020] [Green Living Answers, 2024]

7.1.3 Impacts from the hydrogen facility

- **Land use**. The land where the facility is going to be built will suffer a change in land usage from its current use to industrial use.
- **Biodiversity loss**. Whether from construction or operation certain species will be affected negatively and consequently will need to abandon the area.
- **Water use.** Due to the need for the electrolysis process of water, the facility will consume some water, which in areas that suffer from water stress levels could be an issue. Besides, certain contaminants may leak from the facility to the environment.

- **Noise pollution**. During the construction phase, some noise will be produced at given moments. Moreover, during operation, there also be noise emitted due to the ventilation and cooling systems.

[Blohm og Dettner, 2023]

7.1.4 Leopold Matrix

The following two graphs contain the magnitude and importance of the impacts caused by several actions in diverse environmental affections. The values can range from 1 to 3 being 1 a smaller impact and 3 being the most detrimental one.

LEOPOLD MATRIX FOR THE ASSESSMENT OF ENVIRONMENTAL IMPACTS (Magnitude)

1. ACTIONS THAT MAY CAUSE ENVIRONMENTAL EFFECTS

2. CHARACTERISTICS OR CONDITIONS OF THE ENVIRONMENT LIKELY TO BE ALTERED

			A. REGIMEN MODIFICATION							B. LAND TRANSFORMATION AND CONSTRUCTION						C. PROCESSES		D. CHANGES	E. ACCIDENTS		ASSESSMENTS	
		PROPOSED ACTIONS	A. Habitat modification	B. Land Cover Alteration	C. Alteration of hydrology	D. River control and flow modification	F. Canalization	G. Paving or resurfacing	H. Noise and vibration	A. Industrial sites and buildings	B. Roads and tracks	C. Transmission lines, pipelines and corridors	D. Dredging and channel reinforcement	E. Canals	F. Dams and reservoirs	A. Electric power generation	B. Chemical industry	A. Road traffic	A. Explosions or fire	B. Releases and leaks		
A. PHYSICAL AND CHEMICAL CHARACTERISTICS	1. SOIL	A. Construction materials					1	1		2	1	1		1	1						8	
		B. Soils	2	1		1	1	2		1	2	2	1	1	1				2	3	20	
		C. Magnetic fields and background radioactivity														2	2				4	32
	2. WATER	A. Continental	3		2	2	2							2	2	1				2	16	
		B. Underground			3	1		2					2	2	2					3	15	
		C. Quality			3	2	1	2					2	2	2	1	1		3	3	22	
		D. Temperature			1															2	3	56
	3. ATMOSPHERE	A. Quality (gases, particle)								2	2	2	1	2	2			1	3	3	18	18
	4. PROCESSES	A. Floods	2	2		1	1							1	2				2		11	
		B. Erosion	2	2	2	2	2	1		1				2	2				2		18	
		C. Deposition (Sedimentation and precipitation)			2	2	2	2						2	2				1		13	42
B. BIOLOGICAL CONDITIONS	1. FLORA	A. Trees	3	2	1	1	1	2		2	2	2	2	2	2				3	2	27	
		B. Shrubs	3	2	1	1	1	2		2	2	2	2	2	2				3	2	27	
		C. Other vegetation	3	2	1	1	1	2		2	2	2	2	2	2				3	2	27	
		D. Aquatic plants	3	2	1	1	1	2					2	2	2				3	2	21	102
	2. FAUNA	A. Birds	3	2	1	1	1	2	3	1	2	2	1	1	1	3		2	3	2	31	
		B. Terrestrial animals including reptiles	3	2	1	1	1	2	3	1	3	3	1	1	1	1		2	3	2	31	
		C. Fish and crustaceans	3	2	2	2	2	2	3				2	2	2	2				3	27	
		D. Insects	3	2	1	1	1	3	3	3	1	1	1	1	1	1				3	26	115
C. CULTURAL FACTORS	1. LAND USE	A. Open or wild spaces	3	2	1	2	1	3	1	3	3	3	3	3	3	3	3	1	3	3	44	44
	2. AESTHETIC	A. Panoramic views and landscapes	3	3	2	2	2	3	1	1	3	2	1	3	3	2			3	3	37	37
	3. CULTURAL LEVEL	A. Health and safety							3	1									3	3	10	
		B. Employment								1	1	1	1	1	1	1	1				8	2
D. ECOLOGICAL RELAT		A. Eutrophication																		3	3	3
ASSESSMENTS			39	26	25	24	22	33	17	22	23	22	23	34	35	16	6	6	40	46		
			186							159						22		6	86			

Figure 7.1. Leopold Matrix Magnitude of impacts

LEOPOLD MATRIX FOR THE ASSESSMENT OF ENVIRONMENTAL IMPACTS (Importance)

1. ACTIONS THAT MAY CAUSE ENVIRONMENTAL EFFECTS

2. CHARACTERISTICS OR CONDITIONS OF THE ENVIRONMENT LIKELY TO BE ALTERED			A. REGIMEN MODIFICATION							B. LAND TRANSFORMATION AND CONSTRUCTION						C. PROCESSES		D. CHANGES	E. ACCIDENTS		ASSESSMENTS	
		PROPOSED ACTIONS	A. Habitat modification	B. Land Cover Alteration	C. Alteration of hydrology	D. River control and flow modification	F. Canalization	G. Paving or resurfacing	H. Noise and vibration	A. Industrial sites and buildings	B. Roads and tracks	C. Transmission lines, pipelines and corridors	D. Dredging and channel reinforcement	E. Canals	F. Dams and reservoirs	A. Electric power generation	B. Chemical industry	A. Road traffic	A. Explosions or fire	B. Releases and leaks		
A. PHYSICAL AND CHEMICAL CHARACTERISTICS	1. SOIL	A. Construction materials					1	1		1	1	1		1	1						7	
		B. Soils	2	2		1	1	3		3	3	3	2	2	2				3	3	30	
		C. Magnetic fields and background radioactivity														3	2				5	42
	2. WATER	A. Continental	3		3	3	3							3	3	3				2	23	
		B. Underground			2	1		3					2	2	2					3	15	
		C. Quality			2	1	1	1					2	1	1	1	1		3	3	17	
		D. Temperature			1															2	3	58
	3. ATMOSPHERE	A. Quality (gases, particle)								3	3	3	1	2	2			1	3	3	21	21
	4. PROCESSES	A. Floods	3	3		2	2							1	1				1		13	
		B. Erosion	3	3	2	3	2	2		2				1	1				2		21	
		C. Deposition (Sedimentation and precipitation)			2	2	2	2						1	1				1		11	45
B. BIOLOGICAL CONDITIONS	1. FLORA	A. Trees	3	3	1	1	1	2		3	3	2	1	3	3				3	3	32	
		B. Shrubs	3	3	1	1	1	2		3	3	2	1	3	3				3	3	32	
		C. Other vegetation	3	3	1	1	1	2		3	3	2	1	3	3				3	3	32	
		D. Aquatic plants	3	3	1	1	1	2					1	3	3				3	3	24	120
	2. FAUNA	A. Birds	3	3	1	1	1	3	3	3	3	2	1	1	1	3		1	3	2	35	
		B. Terrestrial animals including reptiles	3	3	1	1	1	3	3	3	3	3	1	1	1	1		2	3	2	35	
		C. Fish and crustaceans	3	2	3	3	3	1	3				2	2	2	2				3	29	
		D. Insects	3	2	1	1	1	2	3	1	1	1	2	2	2	2				3	27	126
C. CULTURAL FACTORS	1. LAND USE	A. Open or wild spaces	3	3	1	2	2	3	1	3	3	3	3	3	3	3	2	1	3	3	45	45
	2. AESTHETIC	A. Panoramic views and landscapes	3	3	2	2	2	3	1	3	2	2	1	2	3	3			3	3	38	38
	3. CULTURAL LEVEL	A. Health and safety							3	1									3	3	10	
		B. Employment								1	1	1	1	1	1	1	1				8	2
D. ECOLOGICAL REL		A. Eutrophication																		3	3	3
ASSESSMENTS			41	36	25	27	26	35	17	32	28	24	21	37	38	21	5	5	40	50		
			207							180						26		5	90			

Figure 7.2. Leopold Matrix Importance of impacts

As it can be observed the consequences with greater magnitudes are those caused by habitat modifications mainly causing an impact on flora and fauna, the effects caused to the open or wild spaces by a great number of actions mainly in construction and the impacts caused by accidents weather explosion and fire or leaks. The main affected are the fauna followed closely by the flora and further by the water conditions. The importance of the impacts is focused mainly on the effects of the habitat modifications and the land cover alterations on flora, fauna and wild spaces, the consequences of the accidents and the impacts caused by construction affecting flora, fauna and wild spaces. Also important to mention the impact noise and vibrations have on fauna and human health, and the impact construction activities have on soils, air quality and continental waters. Furthermore, habitat modifications and land cover alterations also affect physical processes like floods, erosion and deposition. In addition, the impact caused by employment is considered positive in the activities carried out both in construction and in operation.

All in all the main impacts are focused on fauna and flora. Water and wild spaces will also be affected and even soils and some psychical processes too. The effects considered in case of accident are high however the probability of them materializing is low. Furthermore, employment affects positively the project.

7.2 Measures to decrease the environmental impact

To decrease some of the most important impacts that have just been mentioned, the following measures are presented.

As general actions for all facilities, the affected areas with temporary impacts should be restored to their initial condition after the construction work is finished. Moreover, habitat offsetting should be carried out for all of the areas with permanent impacts like wind turbine foundations. This entails producing all the flora and fauna present in the affected area in a new area to compensate for the effect and ensure the continuity of biodiversity. Furthermore, works should be limited when the fauna present in the area are in breeding or migrating season.[McGillivray, 2012]

In addition, the following measures for each of the facilities are also presented.

7.2.1 Measures to decrease the hydro-power station impact

- **Fish passages.** To allow fish migration these passages can be built parallel to the main flow river to allow fish to travel upstream and downstream without swimming across the hydro-power facility.
- **Flow Releases**. to ensure that the level of water downstream some flow is to be released to avoid damaging aquatic life and ecosystem downstream.
- **Sediment Management**. To increase the lifespan of the reservoir sediments must be removed also ensuring water quality is maintained.
- **Habitat restoration**. To compensate for the habitat loss, the present ecosystems are to be enhanced or new ones created.

[Green Living Answers, 2024]

7.2.2 Measures to decrease the wind farm impact

- **Noise cancellation**. By changing the design the noise produced by the wind on the wind turbine can be severely decreased and insulating the machinery can also decrease considerably that effect. However, it is still advised to leave 300m from any populated areas.
- **Birds and bats**. To avoid harming them the wind parks should be built outside of their migration paths and in areas where is considered safe.
- **Electromagnetic interference**. To avoid major interference on radio and other transmissions wind farms should not be installed in the vicinity of any broadcasting stations or communication hubs.
- **Stop of wind turbines at certain times (Curtailment)**. To decrease the impact on bats the angle of the blades can be adjusted during certain periods or stop the wind turbines in the periods when the bats are at high risk (certain hours at night when they are feeding and in breeding and migrating season) [Bat Conservation Trust, 2024]

[Sayed et al., 2020]

7.2.3 Measures to decrease the hydrogen plant impact

- **Noise avoidance**. To ensure that the noise produced by the hydrogen plant does not affect the public in any harmful way, there should be a buffer zone between the facility and the nearest populated areas.
- **Water use**. The hydrogen plant shouldn't be built in an area with draughts or any other water usage issues.
- **Biodiversity loss**. To avoid this effect the facility should not be built in protected areas so that the majority of the fauna is not affected.

[Blohm og Dettner, 2023]

7.3 Environmental monitoring

Besides the aforementioned measures to reduce impacts, several parameters need to be measured to ensure the environmental conditions remain between the limits. The main parameters that need to be carefully monitored are:

- soil erosion to avoid degradation
- water quality upstream and downstream of the facilities to ensure the correct characteristics and the well-being of aquatic life
- noise levels at certain distances from the facilities to avoid health implications and the well-being of fauna
- follow-up of the measures to save bats and birds to decrease the impact and minimize the casualties
- reforestation works progress until completion to ensure restoration of the areas impacted during construction

Monitoring does not only control the compliance of the mitigation actions and the approved design but it is also helpful to notice unforeseen impacts. As it can be noticed the monitoring efforts should be focused on the points with higher scores on the Leopold Matrix. In this case fauna, flora, water and soil and the negative effects of noise pollution.

[González, 2021]

Social Acceptance of the local community 8

8.1 Main complaints and concerns of the community

To assess the social acceptance of the alternative chosen which encompasses wind, hydro and the hydrogen production plant, the opinions of each of them will be considered.

Hydro-power has a long history in Iceland as it has been a major producer of electricity for the island through time. Small hydro plants don't offer that much information regarding their social acceptance in Iceland however there is a great deal of information regarding the major hydro projects of the last decades. There has been great support from the government to these projects, major hydro-power facilities, as well as lobby efforts from aluminium companies wanting to buy the electricity at cheap prices to produce their products. However, there have been great demonstrations and complaints from society to try to impede the construction of some of these projects. The reasons given were mainly focused on the environmental impact as well as the landscape changes in areas that were considered pristine and where the development was meant to happen. Plenty of environmental groups were also opposed to some projects due to the environmental impacts they considered unacceptable. Some of the communities' concerns were focused on a sentiment of unfairness based on the feeling that their country was being exploited for the gain of outside corporations without posing any benefit to them. Even though, some projects promised local jobs and stated that the economic benefits for the area would be great reality has been far from that. [Burns og Haraldsdóttir, 2019] [Schils, 2011] [Saving Iceland, 2005]

As for wind farms, that are not that developed in Iceland at the moment, the community focuses their complaints and concerns on the visual impact of the turbines and the loss of the original pristine landscape they have always been able to enjoy. Moreover, besides the local community, the tourism sector does not support these projects either as the visual impacts they produce can be detrimental to their business and they would suffer certain monetary loss as the demand for their services decreases.[Ólafsdóttir og Sæþórsdóttir, 2019] Some other concerns often raised in wind projects revolve around noise and health concerns that may arise due to the wind farms. [Ellis og Ferraro, 2016]

The hydrogen production facility may not face this kind of opposition as there are no plants built at the moment, thus there are no negative experiences already in the country. [Hafstað, 2020] There is awareness regarding its need throughout the country, nevertheless, local community support is not guaranteed as a general feeling does not mean support or acceptance for a specific project. Moreover, uncertainty can also play a role in social acceptance as there are no facilities built people may fear the unknown. [Harðardóttir, 2024]

Taking this into consideration it is possible that there is opposition to this project even though it is not a large-scale installation. Most of the issues from communities derive from massive projects which is not the case so fewer local opposition should be expected. Nevertheless, environmental groups may still oppose it as there is no project with zero environmental impact.

Nevertheless, the main concerns and source of opposition to renewable projects seem to be the fell of unfairness regardless the type of installation from the local communities as they perceive they are losing their natural landscapes (and a possible source of income from tourism) only for a big corporation to profit out of it. To tackle this concern there are several measures that could be taken to ensure the support of the local communities or at least their acceptance of the project.

8.2 Measures to improve social acceptance of the project

There are multiple approaches to transforming social resistance into social acceptance, all are based on the understanding is a dynamic process that has to evolve and adapt to the situation and the project.

One of the most important steps that seems to increase the acceptance of communities is public participation. There are several ways to involve the community with a variety of methods.

- Raising awareness in the community of all the benefits, false information and how the process will work. It can be done with newsletters or exhibitions
- Consultation, meaning asking the opinion of the people and hearing their concerns regarding any part of the process. There are several ways to achieve it such as meetings, surveys, and feedback forms.
- Community empowerment to show that the project can create positive impacts on the area and its inhabitants through job creation, the establishment of a local energy organisation, creation of a municipal fund for the community to enjoy.

[Ellis og Ferraro, 2016]

The key to being successful when interacting with the community is not to focus on one-way communication but rather a dialogue between all. This will enhance the feeling of being listened to and not he one of the outsiders coming to profit without giving anything back. Furthermore, linked with communication is transparency from the government, the process to follow, and the developer's intentions. Transparency is fundamental to gaining support from the community and increasing public acceptance. [Ellis og Ferraro, 2016]

Another key aspect is to focus on the planning aspect of the development to reduce impacts as best as possible and not rely on mitigation actions. This means avoiding protected environmental areas, areas with heritage or cultural value to locals, and areas with a direct line of view from population centres. In order to achieve this, it is necessary to engage in communication with the local community, as they are the most knowledgeable about the area in question. Consequently, the community will feel that they are being heard and will not oppose the development of the project. [Ellis og Ferraro, 2016]

Moreover, there is another way to increase social acceptance, co-ownership of the project with locals. This can be done by allowing them to buy shares of a private project, by developing the project for the community. This will decrease their sentiment of corporations taking advantage of locals without giving anything in exchange by sharing the profits somehow. In some areas, this is not that well seen by the community and they prefer funds from the developer to spend on the community. [Ellis og Ferraro, 2016]

Any solution proposed should be tailored to the project and the local community. All in all, communication is key as well as taking into consideration the community and their concerns. Besides, mutual profit should also be considered as giving something back to the community is key to gaining their support. [Ellis og Ferraro, 2016]

Discussion 9

9.1 Changes in the model and their effect on the feasibility

The sensitivity study in the analysis chapter focused on the internal parameters of the model. However, it is important to note that more overall parameters, such as size or the functioning of the electrolyzer, can also modify the feasibility of the project. In the following sections, the variations produced by such changes will be presented.

9.1.1 Establish a minimum capacity for the electrolyzer

As it has been explained before alkaline electrolyzers don't perform well when they need to constantly start and stop. To minimize the number of starts and stops and to not wear out the machinery further than needed, establishing a 20% minimum capacity for the electrolyzer to work is proposed. Furthermore, taking it further it is also proposed in the second scenario to add another parameter to the electrolyzer functioning, it will not start unless the working period is at least 2 hours.

In the following graph, it can be seen the variation these two new specifications have on the feasibility of the project in comparison with the baseline scenario.

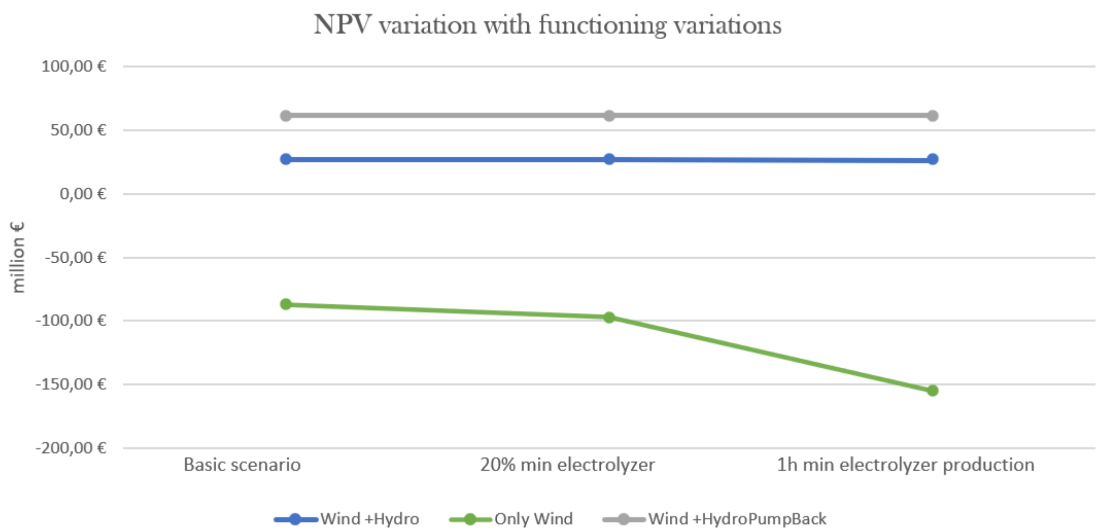


Figure 9.1. NPV variation considering different parameters for the electrolyzer

As it can be seen for the two scenarios with hydro there is no variation in the NPV, and the rest of the economic parameters behave in the same way. For the only wind scenario the feasibility decreases with these modifications and so does the IRR. Moreover, this last scenario IRR for the last modification proposed can not be calculated as the yearly cash flow is negative.

These results make sense as the scenarios depending mostly on hydro are more stable and don't suffer hourly variations or extreme peaks. However, the only wind scenario which is way more variable with huge peaks is negatively affected as there are times when certain production could happen but it is below the 20% cap.

As for the total hydrogen production, it decreases substantially in the only wind scenario. Notwithstanding, in the other two scenarios, the hydrogen production also decreases, although to a negligible extent, which does not affect the feasibility of the process.

9.1.2 Changing the size of the facilities

Besides changing the operational details of the electrolyzer, studying how the different sizes of facilities will change the feasibility also looks promising.

To study the effect the size of the facilities has on the feasibility a new energyPRO model has been created taking into account facilities 4 times bigger. This means an electrolyzer of 160MW, a hydro-power facility of 160MW and a wind farm of 200MW. Thus all CAPEX, OPEX and other parameters have been adjusted to the new size of the facility. Hereafter are the economic results of the basic scenario presented in the analysis chapter and the new scenario to compare feasibility.

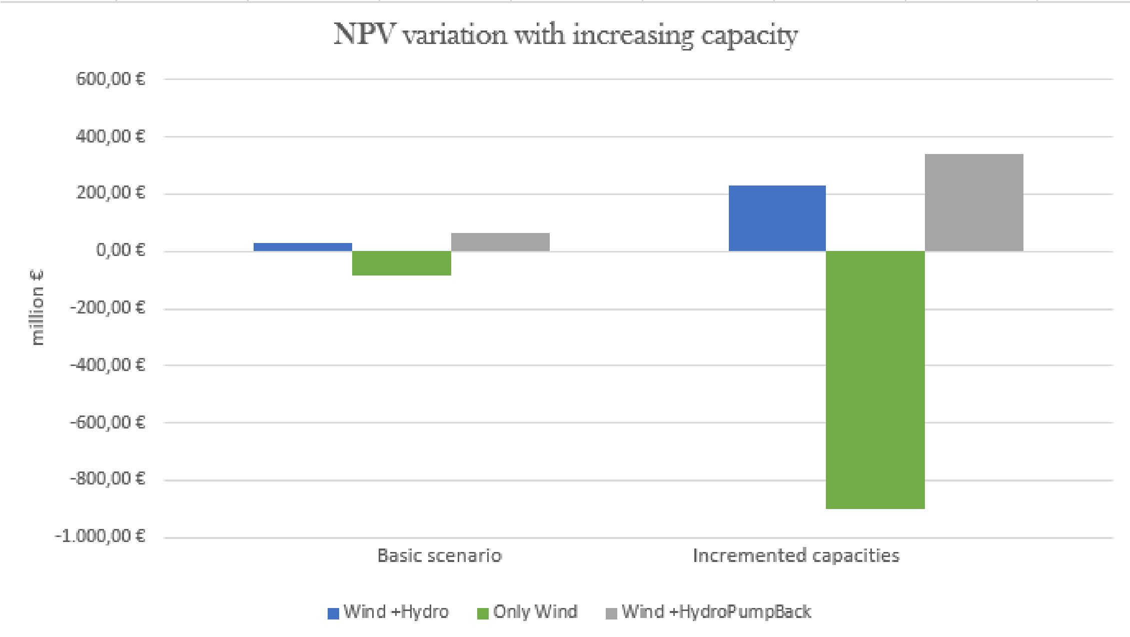


Figure 9.2. NPV variation with increasing capacity

As can be seen for the two scenarios that were already feasible, the feasibility increases for both. However, the wind scenario, which was already deemed unfeasible, has proven to be even more so.

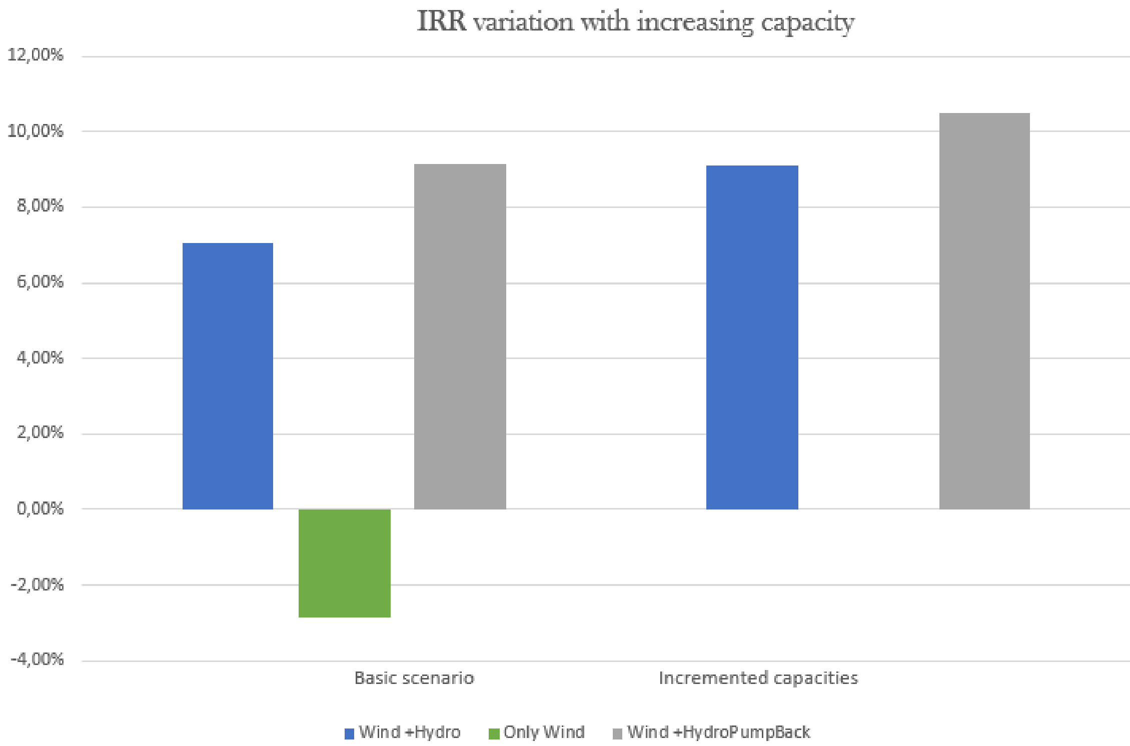


Figure 9.3. IRR variation with increasing capacity

As for the IRR, it behaves similarly as the NPV increases in both hydro scenarios, a bit more in the normal hydro one, mainly because the investments are lower. Furthermore, the IRR of the wind scenario in the new situation cannot be calculated as the yearly cash flow is negative making it the worst option viable.

The discounted payback time periods also decreased slightly reaching 15 years for the hydro and wind scenario when the basic situation was 20 years. Furthermore, it is reduced to 13 years for the pump-back hydro and wind scenario from the 15 years of the basic one. The only wind scenario surpasses the 100 years in both situations.

It can be seen that the feasibility of the previously feasible scenarios increases with the size of the facilities, due to the economies of scale phenomenon. While some of the costs do not increase at the same rate as the production of hydrogen does, the feasibility of different scenarios changes. It can be discussed that the IRR of the pump-back hydro scenario does not increase further as does normal hydro because either the electrolyzer should be even bigger for it to make sense or the extra investment for that facility makes the feasibility harder to achieve. Nevertheless, it must be highlighted that the pump-back scenario remains the most feasible during all the proposed variations even though the investment is slightly higher.

10 Conclusion

The techno-economic feasibility study of an off-grid project to produce green hydrogen has been performed, not only taking into account technical and economical parameters but also potential environmental and societal implications.

Green hydrogen has been identified as a pivotal component in the transition to a carbon-neutral economy, facilitating the electrification of challenging sectors and grid balancing through the integration of renewable energy.

After a comprehensive evaluation of electrolysis technologies, the alkaline electrolysis process emerged as a promising option for this project. The principal reasons for this conclusion are the maturity of the technology, the low CAPEX and OPEX, the low dependence on rare elements, and the low impact on the environment.

In order to ascertain the economic viability of the proposed project, three distinct scenarios were analysed: only wind, wind with hydro and wind with pump-back hydro. In addition, the market price of hydrogen and oxygen was analysed, along with the anticipated future changes. Furthermore, the availability of water for the process was investigated. In addition, the investment cost (CAPEX) and operational and maintenance costs (OPEX) for all the facilities are presented. The results of the economic analysis and the sensitivity analysis indicate that the pump-back hydro scenario is the most feasible and stable option taking into consideration the assumptions specified during the analysis chapters. The hydro and wind scenario is a viable option in the majority of circumstances. However, the only wind scenario is not a viable option in almost all circumstances.

The environmental impact of the facilities is primarily focused on fauna and flora, although water and soil are also affected, as are some physical processes. The impact of employment is beneficial, and the likelihood of accidents is minimal thus their effect on the environment. A number of strategies for reducing the impact of the project are outlined, including the ongoing monitoring of the situation.

The social acceptance of the project may be contingent upon whether the community perceives it to be beneficial to them or if they believe that the sole objective of the project is to enrich foreign corporations. In addition, a number of measures designed to ensure public acceptance are presented.

To conclude, the hydrogen project in Iceland is viable both technically and economically depending on the chosen scenario. Additionally, its environmental and societal impacts can be minimized and monitored to ensure real sustainability.

Bibliography

Accountinginside, 2024. Accountinginside. *Net Present Value (NPV) with Inflation.* https://accountinginside.com/net-present-value-npv-with-inflation/?utmcontent=cmp-true, 2024. Visited: 15-05-2024.

Aengenheyster et al., 2018. M. Aengenheyster, Q. Feng, F. Ploeg og H. Dijkstra. *The point of no return for climate action: effects of climate uncertainty and risk tolerance*, Earth System Dynamics, 2018.

Ahad et al., 2023. Md Tanvir Ahad, Md Monjur Hossain Bhuiyan, Ahmed Nazmus Sakib, Alfredo Becerril Corral og Zahed Siddique. *Challenges and Opportunities of Hydrogen Production*, Materials, 2023.

Ahmed et al., 2022. Khaja Wahab Ahmed, Myeong Je Jang, Moon Gyu Park, Zhongwei Chen og Michael Fowler. *Effect of Components and Operating Conditions on the Performance of PEM Electrolyzers: A Review*, Electrochem, 2022.

Airbus, 2024. Airbus. *Hydrogen An important decarbonisation pathway.* `https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen`, 2024. Visited: 18-03-2024.

Alverio et al., 2023. Gabriela Nagle Alverio, Jeannie Sowers og Erika Weinthal. *Displaced to Cities: Conflict, Climate Change, and Rural-to-Urban Migration.* `https://www.usip.org/publications/2023/06/displaced-cities-conflict-climate-change-and-rural-urban-migration`, 2023. Visited: 18-03-2024.

Aricò et al., 2012. A. S. Aricò, S. Siracusano, N. Briguglio, V. Baglio, A. Di Blasi og V. Antonucci. *Polymer electrolyte membrane water electrolysis: status of technologies and potential applications in combination with renewable power sources*, Electrochem, 2012.

Bade et al., 2024. Shree Om Bade, Olusegun Stanley Tomomewo, Ajan Meenakshisundaram, Patrick Ferron og Babalola Aisosa Oni. *Economic, social, and regulatory challenges of green hydrogen production and utilization in the US: A review*, Elsevier, 2024.

Balat, 2008. M. Balat. *Possible Methods for Hydrogen Production*, IRENA, 2008.

Barth et al., 2024. Adam Barth, David González, Jose Luis Gonzalez, Viktor Hanzlík, Gonçalo Pinheiro, Humayun Tai og Alexander Weiss. *How grid operators can integrate the coming wave of renewable energy.* `https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/how-grid-operators-can-integrate-the-coming-wave-of-renewable-energy`, 2024. Visited: 18-03-2024.

Bat Conservation Trust, **2024**. Bat Conservation Trust. *Wind farms and wind turbines.* https://www.bats.org.uk/about-bats/threats-to-bats/wind-farms-and-wind-turbines, 2024. Visited: 23-05-2024.

Beasley, **2023**. B. Alex Beasley. *Overview: The Oil Shocks of the 1970s.* https://energyhistory.yale.edu/the-oil-shocks-of-the-1970s/, 2023. Visited: 01-05-2024.

Bernuy-Lopez, **2023a**. Carlos Bernuy-Lopez. *Electrolysis technologies and LCOH: current state and prospects for 2030.* https://hydrogentechworld.com/electrolysis-technologies-and-lcoh-current-state-and-prospects-for-2030, 2023a. Visited: 01-05-2024.

Bernuy-Lopez, **2023b**. Carlos Bernuy-Lopez. *Electrolysis technologies and LCOH: current state and prospects for 2030*, Hydrogen World, 2023b.

Blohm og Dettner, **2023**. Marina Blohm og Franziska Dettner. *Green hydrogen production: Integrating environmental and social criteria to ensure sustainability*, Elsevier, 2023.

Bocanegra-Bernal og de la Torre, **2002**. M. H. Bocanegra-Bernal og S. Díaz de la Torre. *Phase transitions in zirconium dioxide and related materials for high performance engineering ceramics*, SpringerLink, 2002.

Brauns og Turek, **2020**. Jörn Brauns og Thomas Turek. *Alkaline Water Electrolysis Powered by Renewable Energy: A Review*, Processes, 2020.

Brynolf et al., **2018**. Selma Brynolf, Maria Taljegard, Maria Grahn og Julia Hansson. *Electrofuels for the transport sector: A review of production costs*, Elsevier, 2018.

Buis, **2022**. Alan Buis. *Steamy Relationships: How Atmospheric Water Vapor Amplifies Earth's Greenhouse Effect.* https://climate.nasa.gov/explore/ask-nasa-climate/3143/steamy-relationships-how-atmospheric-water-vapor-amplifies-earths\-greenhouse-effect/, 2022. Visited: 18-03-2024.

Burns og Haraldsdóttir, **2019**. Georgette Leah Burns og Laufey Haraldsdóttir. *Hydropower and tourism in Iceland: Visitor and operator perspectives on preferred use of natural areas*, Elsevier, 2019.

Carlson et al., **2023**. Ewa Lazarczyk Carlson, Kit Pickford og Honorata Nyga-Łukaszewska. *Green hydrogen and an evolving concept of energy security: Challenges and comparisons*, Elsevier, 2023.

CFI, **2015**. CFI. *Discounted Payback Period.* https://corporatefinanceinstitute.com/resources/valuation/discounted-payback-period/, 2015. Visited: 12-04-2024.

Chand og Paladino, **2023**. Kishore Chand og Ombretta Paladino. *Recent developments of membranes and electrocatalysts for the hydrogen production by anion exchange membrane water electrolysers: A review*, Arabian Journal of Chemistry, 2023.

Chaubey et al., 2013. Rashmi Chaubey, Satanand Sahu, Olusola O. James og Sudip Maity. *A review on development of industrial processes and emerging techniques for production of hydrogen from renewable and sustainable sources*, Elsevier, 2013.

Chauveau et al., 2010. F. Chauveau, J. Mougin, J.M. Bassat, F. Mauvy og J.C. Grenier. *A new anode material for solid oxide electrolyser: The neodymium nickelate Nd2NiO4*, Elsevier, 2010.

Chen, 2011. Alex C.C. Changand Hsin-Fu Changand Fon-Jou Linand Kuo-Hsin Linand Chi-Hung Chen. *Biomass gasification for hydrogen production*, Elsevier, 2011.

Chen et al., 2015. Shigang Chen, Kui Xie, Dehua Dong, Huaxin Li, Qingqing Qin, Yong Zhang og Yucheng Wu. *A composite cathode based on scandium-doped chromate for direct high-temperature steam electrolysis in a symmetric solid oxide electrolyzer*, Elsevier, 2015.

Chen et al., 2022. Yuhao Chen, Chaofan Liu, Jingcheng Xu, Chengfeng Xia, Ping Wang, Bao Yu Xia, Ya Yan og Xianying Wang. *Key Components and Design Strategy for a Proton Exchange Membrane Water Electrolyzer*, Wiley Library, 2022.

CIC Energigune, 2022. CIC Energigune. *HYDROGEN PRODUCTION METHODS AND ITS COLOURS.* https://cicenergigune.com/en/blog/hydrogen-production-methods-colours, 2022. Visited: 01-05-2024.

D et al., 2019. Le Bideau D, Mandin P, Benbouzid M, Kim M og Sellier M. *Review of necessary thermophysical properties and their sensivities with temperature and electrolyte mass fractions for alkaline water electrolysis multiphysics modelling*, Elsevier, 2019.

Dans, 2023. Enrique Dans. *El panorama de la energía en Europa.* https://www.enriquedans.com/2023/02/el-panorama-de-la-energia-en-europa.html, 2023. Visited: 18-03-2024.

Davenport og Saur, 2022. Zhiwen Maand Patrick Davenport og Genevieve Saur. *System and technoeconomic analysis of solar thermochemical hydrogen production*, Elsevier, 2022.

de Pee et al., 2018. Arnout de Pee, Dickon Pinner, Occo Roelofsen, Ken Somers, Eveline Speelman og Maaike Witteveen. *How industry can move toward a low-carbon future.* https://www.mckinsey.com/capabilities/sustainability/our-insights/how-industry-can-move-toward-a-low-carbon-future, 2018. Visited: 21-03-2024.

Department for Energy Security and Net Zero, 2023. Department for Energy Security and Net Zero. *Powering Up Britain: Energy Security Plan*, UK Government, 2023.

Department of Energy, 2022. Department of Energy. *DOE Releases First-Ever Comprehensive Strategy to Secure America's Clean Energy Supply Chain.* https://www.energy.gov/articles/

doe-releases-first-ever-comprehensive-strategy-secure-americas-clean-\ energy-supply-chain, 2022. Visited: 01-05-2024.

Du et al., 2023. Naiying Du, Claudie Roy, Retha Peach, Matthew Turnbull, Simon Thiele, og Christina Bock. *Anion-Exchange Membrane Water Electrolyzers*, American Chemical Society, 2023.

Dubouis og Grimaud, 2019. Nicolas Dubouis og Alexis Grimaud. *The hydrogen evolution reaction: from material to interfacial descriptors*, Royal Society of Chemestry, 2019.

Dubouis et al., 2024. Nicolas Dubouis, David Aymé-Perrot, Damien Degoulange, Alexis Grimaud og Hubert Girault. *Alkaline electrolyzers: Powering industries and overcoming fundamental challenges*, Joule, 2024.

EEA, 2023. EEA. *Progress and prospects for decarbonisation in the agriculture sector and beyond.* https://www.eea.europa.eu/publications/Progress-and-prospects-for-decarbonisation, 2023. Visited: 21-03-2024.

EEA, 2023a. EEA. *Total net greenhouse gas emission trends and projections in Europe.* https://www.eea.europa.eu/en/analysis/indicators/total-greenhouse-gas-emission-trends, 2023a. Visited: 18-03-2024.

EEA, 2018. EEA. *Progress of EU transport sector towards its environment and climate objectives.* https://www.eea.europa.eu/publications/progress-of-eu-transport-sector-1, 2018. Visited: 18-03-2024.

EEA, 2023b. EEA. *Soil, land and climate change.* https://www.eea.europa.eu/signals-archived/signals-2019-content-list/articles/soil-land-and-climate-change, 2023b. Visited: 18-03-2024.

EIA, 2022. EIA. *Greenhouse gases and the climate.* https://www.eia.gov/energyexplained/energy-and-the-environment/greenhouse-gases-and-the-climate.php, 2022. Visited: 18-03-2024.

EIA, 2023. EIA. *Use of energy explained.* https://www.eia.gov/energyexplained/use-of-energy/transportation.php, 2023. Visited: 18-03-2024.

El-Shafie, 2023. Mostafa El-Shafie. *Hydrogen production by water electrolysis technologies: A review*, Elsevier, 2023.

Ellis og Ferraro, 2016. Geraint Ellis og Gianluca Ferraro. *The social acceptance of wind energy*, European Commission, 2016.

EMBER, 2023. EMBER. *World A new era of falling emissions in the power sector.* https://ember-climate.org/countries-and-regions/regions/world/, 2023. Visited: 18-03-2024.

Emerson et al., 2014. Sean C. Emerson, Tianli Zhuand Timothy D. Davis, Amra Peles, Ying She, Rhonda R. Willigan, Thomas H. Vanderspurt, Michael Swanson og Daniel A. Laudal. *Liquid phase reforming of woody biomass to hydrogen*, Elsevier, 2014.

Emodi et al., 2021. Nnaemeka Vincent Emodi, Heather Lovell, Clinton Levitt og Evan Franklin. *A systematic literature review of societal acceptance and stakeholders' perception of hydrogen technologies*, Elsevier, 2021.

EMSA, 2024. EMSA. *Alternative Sources of Power.* https://www.emsa.europa.eu/sustainable-shipping/alternative-fuels.html, 2024. Visited: 18-03-2024.

EPA, 2021a. EPA. *Climate Change Indicators: Permafrost.* https://www.epa.gov/climate-indicators/climate-change-indicators-permafrost#:~:text=A%20thawing%20permafrost%20layer%20can,be%20damaged%20as%20permafrost%20thaws., 2021a. Visited: 18-03-2024.

EPA, 2021b. EPA. *Climate Change Indicators: Ice Sheets.* https://www.epa.gov/climate-indicators/climate-change-indicators-ice-sheets, 2021b. Visited: 18-03-2024.

EPA, 2024. EPA. *GHG Reduction Programs and Strategies.* https://www.epa.gov/climateleadership/ghg-reduction-programs-strategies, 2024. Visited: 18-03-2024.

European Commision, 2023. European Commision. *The EU budget ensures European energy independence through REPowerEU.* https://commission.europa.eu/strategy-and-policy/eu-budget/motion/focus/eu-budget-ensures-european-energy-independence-through-repowereu, 2023. Visited: 01-05-2024.

European Commission, 2024a. European Commission. *2050 long-term strategy.* https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy, 2024a. Visited: 21-03-2024.

European Commission, 2024b. European Commission. *2050 long-term strategy.* https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy, 2024b. Visited: 18-03-2024.

European Commission, 2023a. European Commission. *Renewable hydrogen production: new rules formally adopted.* https://energy.ec.europa.eu/news/renewable-hydrogen-production-new-rules-formally-adopted-2023-06-20, 2023a. Visited: 01-05-2024.

European Commission, 2013. European Commission. *A hydrogen strategy for a climate-neutral Europe*, European Commission, 2013.

European Commission, 2023b. European Commission. *EU energy in figures – Statistical pocketbook 2023*, Publications Office of the European Union, 2023b.

European Commission, 2024c. European Commission. *Hydrogen.* https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen, 2024c. Visited: 21-03-2024.

European Commission, 2022. European Commission. *Methane emissions.* https://energy.ec.europa.eu/topics/oil-gas-and-coal/methane-emissions, 2022. Visited: 18-03-2024.

European Commission, 2024d. European Commission. *European Hydrogen Bank.* https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen/european-hydrogen-bank, 2024d. Visited: 30-05-2024.

European Council, 2024. European Council. *European Green Deal.* https://www.consilium.europa.eu/en/policies/green-deal/#initiatives, 2024. Visited: 18-03-2024.

European Parliment, 2023. European Parliment. *Reducing carbon emissions: EU targets and policies.* https://www.europarl.europa.eu/topics/en/article/20180305STO99003/reducing-carbon-emissions-eu-targets-and-policies, 2023. Visited: 18-03-2024.

Falcão og Pinto, 2020. D.S. Falcão og A.M.F.R. Pinto. *A review on PEM electrolyzer modelling: Guidelines for beginners*, Elsevier, 2020.

Faunce et al., 2018. Thomas A. Faunce, James Prest, Dawei Su, Sean J. Hearne og Francesca Iacopi. *On-grid batteries for large-scale energy storage: Challenges and opportunities for policy and technology*, Cambridge University Press, 2018.

Ferrero et al., 2013a. Domenico Ferrero, Andrea Lanzini, Massimo Santarelli og Pierluigi Leone. *A comparative assessment on hydrogen production from low- and high-temperature electrolysis*, Elsevier, 2013a.

Ferrero et al., 2013b. Domenico Ferrero, Andrea Lanzini, Massimo Santarelli og Pierluigi Leone. *A comparative assessment on hydrogen production from low- and high-temperature electrolysis*, Elsevier, 2013b.

Gaille, 2018. Louise Gaille. *18 Biggest Hydrogen Energy Pros and Cons.* https://vittana.org/18-biggest-hydrogen-energy-pros-and-cons, 2018. Visited: 21-03-2024.

Ghirardi et al., 2008. Maria Lucia Ghirardi, Alexandra Dubini, Jianping Yu og Pin-Ching Maness. *Photobiological hydrogen-producing systems*, Royal Society of Chemestry, 2008.

González, 2021. Ainhoa González. *Strategic environmental assessment monitoring: the enduring forgotten sibling*, Impact Assessment and Project Appraisal, 2021.

Graversen et al., 2014. Rune G. Graversen, Peter L. Langen og Thorsten Mauritsen. *Polar Amplification in CCSM4: Contributions from the Lapse Rate and Surface Albedo Feedbacks*, American Meteorological Society, 2014.

Green Living Answers, **2024**. Green Living Answers. *Hydroelectric Power Environmental Impact.* https://www.greenlivinganswers.com/hydroelectric/environmental-impact, 2024. Visited: 22-05-2024.

Gross, **2020**. Samantha Gross. *THE CHALLENGE OF DECARBONIZING HEAVY TRANSPORT*, Brookings, 2020.

Gustavsson et al., **2023**. Mathias Gustavsson, Mirjam Särnbratt, Theo Nyberg, Maria Hernández Leal, Olga Lysenko, Magnus Karlsson, Linus Karlsson, Linda Önnby, Erik Östling, Elin Lindblad, Mikael Elevant og Kenneth Lundkvist. *POTENTIAL USE AND MARKET OF OXYGEN AS A BY-PRODUCT FROM HYDROGEN PRODUCTION*, Energiforsk, 2023.

Hafstað, **2020**. Vala Hafstað. *Will Hydrogen Be Produced in Iceland for Export?* $https : //icelandmonitor.mbl.is/news/news/2020/10/23/will_{h}ydrogen_{b}e_{p}roduced_{i}n_{i}celand_{f}or_{e}xport/$, 2020. Visited: 28-05-2024.

Hall, **2019**. David Hall. *Climate explained: why some people still think climate change isn't real.* `https://theconversation.com/climate-explained-why-some-people-still-think-climate-change-isnt-real-124763`, 2019. Visited: 18-03-2024.

Haoran et al., **2024**. Cheng Haoran, Yanghong Xia, Wei Wei, Zhou Yongzhi, Zhao Bo og Zhang Leiqi. *Safety and efficiency problems of hydrogen production from alkaline water electrolyzers driven by renewable energy sources*, Elsevier, 2024.

Harðardóttir, **2024**. Dröfn Harðardóttir. *Hydrogen and electrofuels.* https://www.landsvirkjun.com/hydrogen, 2024. Visited: 28-05-2024.

Hayes, **2023**. Adam Hayes. *Cost of Capital: What It Is, Why It Matters, Formula, and Example.* https://www.investopedia.com/terms/c/costofcapital.asp, 2023. Visited: 15-05-2024.

Hydrogen Europe, **2021**. Hydrogen Europe. *Use of Hydrogen in Buildings*, Hydrogen Europe, 2021.

Iberdrola, **2024**. Iberdrola. *DECARBONIZE THE ELECTRICITY SECTOR.* `https://www.iberdrola.com/about-us/decarbonized-economy-principles-regulatory-actions/decarbonisation-electricity-sector`, 2024. Visited: 18-03-2024.

IEA, **2017**. IEA. *Short-term energy outlook*, IEA, 2017.

IEA, **2022a**. IEA. *Global Hydrogen Review 2022- Executive summary.* `https://www.iea.org/reports/global-hydrogen-review-2022/executive-summary`, 2022a. Visited: 21-03-2024.

IEA, **2023**. IEA. *Global Hydrogen Review 2023*, IEA, 2023.

IEA, **2021**. IEA. *How rapidly will the global electricity storage market grow by 2026?* https://www.iea.org/articles/how-rapidly-will-the-global-electricity-storage-market-grow-by-2026, 2021. Visited: 21-03-2024.

IEA, **2022b**. IEA. *An updated roadmap to Net Zero Emissions by 2050.* https://www.iea.org/reports/world-energy-outlook-2022/an-updated-roadmap-to-net-zero-emissions-by-2050, 2022b. Visited: 21-03-2024.

IEA, **2023**. IEA. *World Energy Outlook 2023*, IEA, 2023.

IEA-ETSAP og IRENA, **2015**. IEA-ETSAP og IRENA. *Renewable Energy Integration in Power Grids*, IEA-ETSAP and IRENA, 2015.

Incer-Valverde et al., **2022**. Jimena Incer-Valverde, Laura J. Patiño-Arévalo, George Tsatsaronis og Tatiana Morosuk. *Hydrogen-driven Power-to-X: State of the art and multicriteria evaluation of a study case*, Elsevier, 2022.

Ioras et al., **2014**. Florin Ioras, Indrachapa Bandara og Chris Kemp. *Introduction to Climate Change and Land Degradation*, 2014.

IPCC, **2024**. IPCC. *Future Climate Changes, Risks and Impacts.* https://ar5-syr.ipcc.ch/topic$_futurechanges.php, 2024. Visited: 18-03-2024.

IPCC, **2018**. IPCC. *Summary for Policymakers*, IPCC, 2018.

IRENA, **2020**. IRENA. *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5C Climate Goal*, IRENA, 2020.

IRENA, **2022**. IRENA. *Geopolitics of the Energy Transformation*, IRENA, 2022.

IRENA, **2023**. IRENA. *Renewables Competitiveness Accelerates, Despite Cost Inflation.* https://www.irena.org/News/pressreleases/2023/Aug/Renewables-Competitiveness-Accelerates-Despite-Cost-Inflation, 2023. Visited: 01-05-2024.

IRENA, **2023**. IRENA. *Renewable power generation costs in 2022*, IRENA, 2023.

Jing et al., **2022**. Liang Jing, Hassan M. El-Houjeiri, Jean-Christophe Monfort, James Littlefield, Amjaad Al-Qahtani, Yash Dixit, Raymond L. Speth, Adam R. Brandt, Mohammad S. Masnadi, Heather L. MacLean, William Peltier, Deborah Gordon og Joule A. Bergerson. *Understanding variability in petroleum jet fuel life cycle greenhouse gas emissions to inform aviation decarbonization*, Nature Communications, 2022.

Khan et al., **2021**. Mohd Adnan Khan, Cameron Young og David B. Layzell. *The TechnoEconomics of Hydrogen Pipelines TECHNICAL BRIEF*, Transition Accelerator Technical Briefs, 2021.

Kiemel et al., **2021**. Steffen Kiemel, Tom Smolinka, Franz Lehner, Johannes Full, Alexander Sauer og Robert Miehe. *Critical materials for water electrolysers at the example of the energy transition in Germany*, International Journal of Energy Research, 2021.

Kim og Sarkar, 2017. Bokhwa Kim og Sudipta Sarkar. *Impact of wildfires on some greenhouse gases over continental USA: A study based on satellite data*, Elsevier, 2017.

Kolb, 2020. Stefan Schneiderand Siegfried Bajohrand Frank Grafand Thomas Kolb. *State of the Art of Hydrogen Production via Pyrolysis of Natural Gas*, Wiley Library, 2020.

Krishnan et al., 2023. Subramani Krishnan, Vinzenz Koning, Matheus Theodorus de Groot, Arend de Groot, Paola Granados Mendoza, Martin Junginger og Gert Jan Kramer. *Present and future cost of alkaline and PEM electrolyser stacks*, Elsevier, 2023.

Kumar og Lim, 2022. S. Shiva Kumar og Hankwon Lim. *An overview of water electrolysis technologies for green hydrogen production*, Elsevier, 2022.

Kyriakopoulos og Arabatzis, 2016a. Grigorios L. Kyriakopoulos og Garyfallos Arabatzis. *Electrical energy storage systems in electricity generation: Energy policies, innovative technologies, and regulatory regimes*, Elsevier, 2016a.

Kyriakopoulos og Arabatzis, 2016b. Grigorios L. Kyriakopoulos og Garyfallos Arabatzis. *Electrical energy storage systems in electricity generation: Energy policies, innovative technologies, and regulatory regimes*, Elsevier, 2016b.

Lakshmanan og Bhati, 2024. Sandhiya Lakshmanan og Madhulika Bhati. *Unravelling the atmospheric and climate implications of hydrogen leakage*, Elsevier, 2024.

Lee et al., 2020. Hae In Lee, Muhammad Mehdi, Sang Kyung Kim, Hyun Seok Cho, Min Joong Kim, Won Chul Cho, Young Woo Rhee og Chang Hee Kim. *Advanced Zirfon-type porous separator for a high-rate alkaline electrolyser operating in a dynamic mode*, Elsevier, 2020.

Leopold et al., 1971. Luna B. Leopold, Frank E. Clarke, Bruce B. Hanshaw og James R. Balsley. *A Procedure for Evaluating Environmental Impact*, GEOLOGICAL SURVEY CIRCULAR 645, 1971.

Lind et al., 2022. Mikael Lind, Wolfgang Lehmacher, Sara Åhlén Björk, Sandra Haraldson, Christopher Pålsson, Risto Penttilä, Kirsi Tikka og Richard T. Watson. *Decarbonizing the maritime sector: Mobilizing coordinated action in the industry using an ecosystems approach.* https://unctad.org/news/decarbonizing-maritime-sector-mobilizing-coordinated-action-industry-using\-ecosystems-approach, 2022. Visited: 18-03-2024.

MacMillan og Turrentine, 2021. Amanda MacMillan og Jeff Turrentine. *Global Warming 101.* https://www.nrdc.org/stories/global-warming-101#warming, 2021. Visited: 18-03-2024.

Mantero et al., 2020. Giulia Mantero, Donato Morresi, Raffaella Marzano, Renzo Motta, David J. Mladenoff og Matteo Garbarino. *The influence of land abandonment on forest disturbance regimes: a global review*, Landscape Ecology, 2020.

Martin, **2023**. Polly Martin. *Hydrogen vehicles in Denmark left without fuel as all commercial refuelling stations shuttered.* https://www.hydrogeninsight.com/transport/hydrogen-vehicles-in-denmark-left-without-fuel-as-all-commercial-refuelling\-stations-shuttered/2-1-1519914, 2023. Visited: 21-03-2024.

Masson-Delmotte et al., **2018**. Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor og T. Waterfield. *SPECIAL REPORT: GLOBAL WARMING OF 1.5 ºC*, IPCC, 2018.

McGillivray, **2012**. Donald McGillivray. *Compensating Biodiversity Loss: The EU Commission's Approach to Compensation under Article 6 of the Habitats Directive*, Journal of Environmental Law, 2012.

McNall, **2011**. Scott G. McNall. *Rapid Climate Change: Causes, Consequences, and Solutions.* Routledge, 2011. Taylor and Francis Group.

Midilli et al., **2021**. Adnan Midilli, Haydar Kucuk, Muhammed Emin Topal, Ugur Akbulut og Ibrahim Dincer. *A comprehensive review on hydrogen production from coal gasification: Challenges and Opportunities*, Elsevier, 2021.

Miller et al., **2020**. Hamish Andrew Miller, Karel Bouzek, Jaromir Hnat, Stefan Loos, Christian Immanuel Bernäcker, Thomas Weißgärber, Lars Röntzschc og Jochen Meier-Haackd. *Green hydrogen from anion exchange membrane water electrolysis: a review of recent developments in critical materials and operating conditions*, Sustainable Energy Fuels, 2020.

Ministry of the Environment, Energy and Climate, **2024**. Ministry of the Environment, Energy and Climate. *Hydrogen and E-fuels Roadmap for Iceland*, Government of Iceland, 2024.

Mo et al., **2016**. Jingke Mo, Ryan R. Dehoff, William H. Peter, Todd J. Toops og Johney B. Green Jr. v Feng-Yuan Zhang. *Additive manufacturing of liquid/gas diffusion layers for low-cost and high-efficiency hydrogen production*, Elsevier, 2016.

Moahmmed, **2021**. Chnar Mustafa Moahmmed. *Literature Review as a Research Methodology: An overview and guidelines*, ResearchGate, 2021.

Montuori, **2011**. A Montuori. *Systems Approach*, Elsevier, 2011.

Mordor Intelligence, **2022**. Mordor Intelligence. *Oxygen Market Size and Share Analysis, Growth Trends and Forecasts (2024 2029).* https://www.mordorintelligence.com/industry-reports/oxygen-market, 2022. Visited: 03-05-2024.

Mudhoo et al., **2018**. Ackmez Mudhoo, Paulo C. Torres-Mayanga, Tânia Forster-Carneiro, Periyasamy Sivagurunathan, Gopalakrishnan Kumar, Dimitrios Komilis og Antoni Sánchez. *A review of research trends in the enhancement of biomass-to-hydrogen conversion*, Elsevier, 2018.

Musmarra, 2016. Antonio Molinoand Simeone Chianeseand Dino Musmarra. *Biomass gasification technology: The state of the art overview*, Elsevier, 2016.

NASA, 2019. NASA. *What Is the Sun's Role in Climate Change?* https://climate.nasa.gov/explore/ask-nasa-climate/2910/what-is-the-suns-role-in-climate-change/#:~:text=Warming%20from%20increased%20levels%20of,0.1%20percent%20during%20that%20period., 2019. Visited: 18-03-2024.

NASA, 2024. NASA. *What do volcanoes have to do with climate change?* https://climate.nasa.gov/faq/42/what-do-volcanoes-have-to-do-with-climate-change/, 2024. Visited: 18-03-2024.

National Academies, 2016. National Academies. *Attribution of Extreme Weather Events in the Context of Climate Change - New Report.* https://www.nationalacademies.org/news/2016/03/attribution-of-extreme-weather-events-in-the-context-of-climate-change-new-report, 2016. Visited: 18-03-2024.

National Geographic, 2024. National Geographic. *Ocean Currents and Climate.* https://education.nationalgeographic.org/resource/ocean-currents-and-climate/, 2024. Visited: 18-03-2024.

Ni et al., 2008. Meng Ni, Michael K.H. Leung og Dennis Y.C. Leung. *Technological development of hydrogen production by solid oxide electrolyzer cell (SOEC)*, Elsevier, 2008.

Niblett et al., 2024. Daniel Niblett, Mostafa Delpisheh, Shanmugam Ramakrishnan og Mohamed Mamlouk. *Review of next generation hydrogen production from offshore wind using water electrolysis*, Elsevier, 2024.

Nicita et al., 2020. A. Nicita, G. Maggio, A.P.F. Andaloro og G. Squadrito. *Green hydrogen as feedstock: Financial analysis of a photovoltaic-powered electrolysis plant*, Elsevier, 2020.

Nijs et al., 2021. W. Nijs, D. Tarvydasand og A. Toleikyte. *EU challenges of reducing fossil fuel use in buildings*, European Commission, 2021.

Oldenburg, 2022. Fabio Oldenburg. *Key electrolyzer technologies and their roles in the future green hydrogen project landscape.* https://apricum-group.com/which-horse-to-bet-on-key-electrolyzer-technologies-and-their-roles-in-the-future-green-hydrogen-project-landscape/, 2022. Visited: 01-05-2024.

Ozcan et al., 2023. Hasan Ozcan, Rami S. El-Emam og Bahman Amini Horri. *Thermochemical looping technologies for clean hydrogen production – Current status and recent advances*, Elsevier, 2023.

Prosperi, 2021. Prosperi. *Factors to Consider in an Economic Feasibility Study.* https://blog.prosperiglobal.com/economic-feasibility-study/, 2021. Visited: 12-04-2024.

Psaraftis og Kontovas, **2021**. Harilaos N. Psaraftis og Christos A. Kontovas. *Decarbonization of Maritime Transport: Is There Light at the End of the Tunnel?*, Sustainability, 2021.

Randers og Goluke, **2020**. Jorgen Randers og Ulrich Goluke. *An earth system model shows self-sustained thawing of permafrost even if all man-made GHG emissions stop in 2020*, Scientific Reports volume, 2020.

Ritchie og Rosado, **2024**. Hannah Ritchie og Pablo Rosado. *Explore data on where our electricity comes from, and how this is changing.* https://ourworldindata.org/electricity-mix, 2024. Visited: 18-03-2024.

Ritchie et al., **2024a**. Hannah Ritchie, Pablo Rosado og Max Roser. *Emissions by sector: where do greenhouse gases come from?* https://ourworldindata.org/emissions-by-sector, 2024a. Visited: 18-03-2024.

Ritchie et al., **2024b**. Hannah Ritchie, Pablo Rosado og Max Roser. *Greenhouse gas emissions.* https://ourworldindata.org/greenhouse-gas-emissions, 2024b. Visited: 24-03-2024.

Roberts, **2024**. Sienna Roberts. *What is a Feasibility Study?* https://www.theknowledgeacademy.com/blog/feasibility-study/#:~:text=7%20Steps%20to%20do%20a%20Feasibility%20Study%201,data%20...%207%207%29%20Make%20a%20go%2FNo-go%20decision, 2024. Visited: 12-04-2024.

Santos et al., **2013**. Diogo M. F. Santos, César A. C. Sequeira og José L. Figueiredo. *Hydrogen production by alkaline water electrolysis*, Quim. Nova , 2013.

Saving Iceland, **2005**. Saving Iceland. *Environmental Impact of the Kárahnjúkar Dams.* https://www.savingiceland.org/2005/02/environmental-impact-of-the-karahnjukar-dams/, 2005. Visited: 30-05-2024.

Sayed et al., **2020**. Enas Taha Sayed, Tabbi Wilberforce, Khaled Elsaid, Malek Kamal Hussien Rabaia, Mohammad Ali Abdelkareem, Kyu-Jung Chae og A.G. Olabi. *A critical review on environmental impacts of renewable energy systems and mitigation strategies: Wind, hydro, biomass and geothermal*, Elsevier, 2020.

Scheepers et al., **2021**. Fabian Scheepers, Markus Stähler, Andrea Stähler, Edward Rauls, Martin Müller, Marcelo Carmo og Werner Lehnert. *Temperature optimization for improving polymer electrolyte membrane-water electrolysis system efficiency*, Elsevier, 2021.

Schils, **2011**. Nathalie Schils. *Icelanders protest Karahnjukar Hydropower Project, 2000-2006.* https://nvdatabase.swarthmore.edu/content/icelanders-protest-karahnjukar-hydropower-project-2000-2006, 2011. Visited: 30-05-2024.

Scientific American, **2009**. Scientific American. *The Role of Sunspots and Solar Winds in Climate Change.* https://www.scientificamerican.com/article/sun-spots-and-climate-change/, 2009. Visited: 18-03-2024.

Sea Level Rise, 2024. Sea Level Rise. *The Future of Sea Level Rise.* https://sealevelrise.org/forecast/, 2024. Visited: 18-03-2024.

Selysos, 2023. Selysos. *Solid Oxide Electrolysis Cells (SOECs).* http://selysos.iceht.forth.gr/index.php/solid-oxide-electrolysis-cells-soecs, 2023. Visited: 01-05-2024.

Semenov og Stratonovitch, 2010. Mikhail A. Semenov og Pierre Stratonovitch. *Use of multi-model ensembles from global climate models for assessment of climate change impacts*, Climate Research, 2010.

Shen et al., 2018. Xiaojun Shen, Xiaoyun Zhang, Guojie Li, Tek Tjing Lie og Hong Lv. *Experimental study on the external electrical thermal and dynamic power characteristics of alkaline water electrolyzer*, International Journal of Energy Research, 2018.

Skov og Schneider, 2022. Iva Ridjan Skov og Noémi Schneider. *Incentive structures for power-to-X and e-fuel pathways for transport in EU and member states*, Elsevier, 2022.

SLOCAT, 2021. SLOCAT. *Transport and Climate Change Global Status Report – 2nd edition*, SLOCAT, 2021.

Spiller et al., 2023. Beia Spiller, Nafisa Lohawala og Emma DeAngeli. *Medium- and Heavy-Duty Vehicle Electrification: Challenges, Policy Solutions, and Open Research Questions*, Resources for the Future, 2023.

Tashie-Lewis og Nnabuife, 2021. Bernard Chukwudi Tashie-Lewis og Somtochukwu Godfrey Nnabuife. *Hydrogen Production, Distribution, Storage and Power Conversion in a Hydrogen Economy - A Technology Review*, Elsevier, 2021.

The Royal Society, 2019. The Royal Society. *Sustainable synthetic carbon based fuels for transport*, The Royal Society, 2019.

Tüysüz, 2024. Harun Tüysüz. *Alkaline Water Electrolysis for Green Hydrogen Production*, American Chemical Society, 2024.

UIG, 2003. UIG. *Oxygen (O2) Properties, Uses and Applications Oxygen Gas and Liquid Oxygen.* https://www.uigi.com/oxygen.html, 2003. Visited: 03-05-2024.

UN, 2024. UN. *THE 17 GOALS.* https://sdgs.un.org/goals, 2024. Visited: 18-03-2024.

UNFCCC, 2024. UNFCCC. *The Paris Agreement.* https://unfccc.int/process-and-meetings/the-paris-agreement, 2024. Visited: 18-03-2024.

Ursúa et al., 2013. Alfredo Ursúa, Idoia San Martin, Ernesto L. Barrios og Pablo Sanchis. *Stand-alone operation of an alkaline water electrolyser fed by wind and photovoltaic systems*, International Journal of Hydrogen Energy, 2013.

Ursúa et al., 2016. Alfredo Ursúa, Julio Pascual, Idoia San Martin, Ernesto L. Barrios og Pablo Sanchis. *Integration of commercial alkaline water electrolysers with renewable energies: Limitations and improvements*, Elsevier, 2016.

U.S. Department of Energy, **2024a**. U.S. Department of Energy. *Hydrogen Production: Biomass Gasification.* https://www.energy.gov/eere/fuelcells/hydrogen-production-biomass-gasification, 2024a. Visited: 01-05-2024.

U.S. Department of Energy, **2024b**. U.S. Department of Energy. *Hydrogen Production: Photoelectrochemical Water Splitting.* https://www.energy.gov/eere/fuelcells/hydrogen-production-photoelectrochemical-water-splitting, 2024b. Visited: 01-05-2024.

Vinodh et al., **2023**. Rajangam Vinodh, Shankara Sharanappa Kalanur, Sadesh Kumar Natarajan og Bruno G. Pollet. *Recent Advancements of Polymeric Membranes in Anion Exchange Membrane Water Electrolyzer (AEMWE): A Critical Review*, Polymers, 2023.

Weiland, **2009**. Peter Weiland. *Biogas production: current state and perspectives*, Appl Microbiol Biotechnol, 2009.

World Economic Forum, **2023**. World Economic Forum. *The 1.5C climate threshold: What it means and why it matters.* https://www.weforum.org/agenda/2023/09/prevent-1-5-degrees-celsius-climate-threshold/, 2023. Visited: 18-03-2024.

Xiao et al., **2023**. Ze Xiao, Xi Lin, Wenhua Feng, Binyi Chen, Qingwei Meng og Tiejun Wang. *Efficient Hydrogen Production from the Aqueous-Phase Reforming of Biomass-Derived Oxygenated Hydrocarbons over an Ultrafine Pt Nanocatalyst*, Catalysts, 2023.

Xu et al., **2013**. Li Xu, Wei Li, Shaoxing Zhang Yan You og Yingchun Zhao. *Polysulfone and zirconia composite separators for alkaline water electrolysis*, Springer Nature, 2013.

Yang et al., **2021**. Juchan Yang, Myeong Je Jang, Xiaojun Zeng, Yoo Sei Park, Jooyoung Lee, Sung Mook Choi og Yadong Yin. *Non-precious electrocatalysts for oxygen evolution reaction in anion exchange membrane water electrolysis: A mini review*, Elsevier, 2021.

Yoro og Daramola, **2020**. Kelvin O. Yoro og Michael O. Daramola. *Chapter 1 - CO2 emission sources, greenhouse gases, and the global warming effect*, Woodshed Publishing, 2020.

Yu et al., **2021**. Mingquan Yu, Eko Budiyanto og Harun Tüysüz. *Principles of Water Electrolysis and Recent Progress in Cobalt-, Nickel-, and Iron-Based Oxides for the Oxygen Evolution Reaction*, Wiley Library, 2021.

Yue et al., **2021**. Meiling Yue, Hugo Lambert, Elodie Pahon, Robin Roche, Samir Jemei og Daniel Hissel. *Hydrogen energy systems: A critical review of technologies, applications, trends and challenges*, Elsevier, 2021.

Zandalinas et al., **2021**. Sara I. Zandalinas, Felix B. Fritschi og Ron Mittler. *Global Warming, Climate Change, and Environmental Pollution: Recipe for a Multifactorial Stress Combination Disaster*, CellPress, 2021.

Zhang et al., **2022**. Ting Zhang, Dongfeng Li, Amy E. East, Desmond E. Walling, Stuart Lane, Irina Overeem, Achim A. Beylich, Michèle Koppes og Xixi Lu. *Warming-driven erosion and sediment transport in cold regions*, Nature Reviews Earth and Environment, 2022.

Zhao et al., **2021**. Yongming Zhao, Huaqing Xue, Xu Jin, Bo Xiong, Renhe Liu, Yong Peng, Luyang Jiang og Guohua Tian. *System level heat integration and efficiency analysis of hydrogen production process based on solid oxide electrolysis cells*, Elsevier, 2021.

Ólafsdóttir og Sæþórsdóttir, **2019**. Rannveig Ólafsdóttir og Anna Dóra Sæþórsdóttir. *Wind farms in the Icelandic highlands: Attitudes of local residents and tourism service providers*, Elsevier, 2019.

Østergaard et al., **2022**. Poul Alberg Østergaard, Anders N. Andersen og Peter Sorknæs. *The business-economic energy system modelling tool energyPRO*, Elsevier, 2022.