MASTER’S DEGREE PROGRAM IN SUSTAINABILITY SCIENCE AND SOLUTIONS

Life Cycle Assessment of Green hydrogen: Wind-based hydrogen vs Solar-based hydrogen

LUT School of Energy Systems

Master’s thesis

2023

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Examiner(s): Junior Researcher Lauri Leppakoski

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ABSTRACT

Lappeenranta University of Technology LUT

LUT School of Energy Systems

Degree Program in Sustainability Science and Solutions

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The success of the European Commission's green deal is highly dependent on the rate of scaling up green technologies, especially in sectors like the power industry, whose ability to meet future demand through renewable energy sources will be subjected to massive development of wind and Solar Photovoltaic (PV) technologies. The decision of the EU to pursue hydrogen as an alternative energy source with projections of being able to produce 10 million tonnes in 2030 creates many uncertainties, especially in material markets. In this thesis, an LCA study is conducted to evaluate the environmental burdens of producing 10 million tonnes of hydrogen using renewable electricity. Hydrogen production is very sustainable when renewable energy sources are used for electricity supply. However, there is a need to understand the environmental footprint of producing these large quantities of hydrogen since they also carry environmental burdens in ecosystems. The study uses an attributional approach to assess the environmental impacts of producing these quantities under different energy scenarios using 50kW electrolysers: Alkaline Water and Proton electrolyte Membrane electrolysers. The results reveal that solar is the most sustainable energy source for hydrogen production compared to wind energy. Furthermore, the results also established an Alkaline water electrolyser to have the most minor environmental burdens compared to the Proton Electrolyte Membrane electrolyser when producing vast quantities of hydrogen.

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SYMBOLS AND ABBREVIATIONS

List of symbols and Units

^oC	Degrees Celsius
GW	Gigawatts
MW_{el}	Megawatts (electric Units)
kW	Kilowatts
h/a	Hours per Annum
Kg	Kilogram
%	Percentage
H_2O	Water
H_2	Hydrogen
OH-	ions
KOH	Potassium hydroxide
e^-	electron
O_2	Oxygen
H^+	hydrogen atoms

List of abbreviations

GHG	Greenhouse gases
IPCC	Intergovernmental Panel on Climate Change
CO_2	carbon dioxide
EU	European Union
EC	European Commission
IEA	International Energy Agency
UN	United Nations

UNSDGs	United Nations Sustainable Development Goals
IRENA	International Renewable Energy Agency
PEM	Proton Electrolyte Membrane
PEME	Proton Electrolyte Membrane Electrolyser
SMR	Steam Methane Reforming
GWP	Global Warming Potential
CU-CI	Copper-chlorine cycle
NOx	Nitrogen Oxides
AWARE	Available Water Remaining
SOEC	Solid Oxide Electrolyte Cell
FCEV	Fuel Cell Electric Vehicle
LT PEMFC	Low-Temperature Proton Electron Membrane Fuel Cell
HT PEMFC	High-Temperature Proton Electron Membrane Fuel Cell
BOP	Balance Of Plant
PM2.5	Particulate Matter 2.5
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life cycle Impact Assessment
JRC-IES	Joint Research Centre – Institute for Environment and Sustainability
PV	Photovoltaic
IPHE	International Partnership for Hydrogen Economy
c-SI	Crystalline Silicon
FU	Functional Unit

TM	Transitional Metals
PGM	Platinum Group Metals
PCOP	Photochemical Ozone potential
CC	Climate change
FD	Fossil Depletion
FPMF	Fine Particulate Matter Formation
FWEP	Freshwater Eutrophication Potential
MD	Metal Depletion
LU	Land Use
FWC	Fresh Water consumption

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Abstract

(Acknowledgements)

(Symbols and abbreviations)

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1. Introduction

This section gives a brief background and description of the formulated research objectives. Furthermore, the justification of conducting this research study is also presented in this chapter.

1.1. Research Background

In 2015, 195 country representatives agreed to increase focus on reducing GHG emissions to raise their emission reduction efforts towards net zero emissions from all sectors throughout 30yrs (Sharifi *et al.,* 2019). According to an Intergovernmental panel on climate Change report (IPCC), the global net anthropogenic CO_2 emissions would need to reach zero emissions by 2050;- that's if a pathway consistent with limiting global temperatures to 1.5^oC is adopted(IPCC, 2018). With this in perspective, the EU adopted this objective for its member states under a Road Map to 2050 climate targets. Hydrogen is considered one of the pathways to achieve these environmental targets of reducing GHG emissions(European Commission, 2018; European Commission, 2020a). This chapter will introduce the environmental impacts of green hydrogen by discussing the background of green hydrogen and the context in which solar energy sources and Wind energy sources are at the centre of its production, followed by the research problem, research aims, objectives and questions, the significance of this study and finally the limitations.

1.2. Research Aim

This thesis research aims to investigate the Life Cycle Assessment of the environmental impacts of producing green hydrogen by comparing wind and solar energy mix Scenarios. The study aims to put into perspective the hydrogen economy potential of Europe concerning the European energy transition road map with adaption to the use of renewable energy sources in its energy mix to meet the requirements of the EU hydrogen road map and substantial contribution to decarbonisation targets relayed in the Paris agreement 2015.

According to the European Commission, (2020) to meet the global climate targets, the European Union must mainly implement the green deal as a recovery strategy to increase sustainable energy transition and energy security of the block. The EU green deal strategy highlights rolling out renewable energy projects, mainly focusing on Wind and solar to facilitate a clean hydrogen economy (European Commission, 2020a).

To be able to achieve the aim of this research, an objective examination/study will be taken on critical aspects contributing to the aspects of the green deal: The study will focus on the material intensity required to produce renewable electricity, electrolyser technologies for producing these quantities of hydrogen. Finally, a life cycle assessment concept will be applied to determine and quantify the effects of producing this category of hydrogen using renewable electricity using GaBi Software.

1.3. Research Questions

The main Research questions that will be discussed in this study include the following:

1. What is the carbon emission footprint of producing 10 million tonnes of hydrogen?

Under this question, the study will investigate the emission footprint of mass-producing hydrogen using renewable electricity as anticipated by the EU hydrogen roadmap. The study should be able to establish a link with changes in material intensity of increasing renewables and the effect on associated impact categories that will be affected as a scaling up these technologies.

2. How does the production of 10 million tonnes of hydrogen affect different midpoint indicators?

Under this question the study will try to establish quantitative estimates of environmental impact categories that are risk of being greatly affected by these systems of hydrogen production technologies.

2. Literature Review

This section uses a chronological review of the literature to establish existing knowledge about producing green hydrogen and life cycle assessment concept in hydrogen production.

2.1. Hydrogen Economy

Recently, a considerable amount of literature has grown up around the themes of symbolic growing environmental risks relating to increasing in average global temperatures, increase in GHG concentrations and increase in GHG emission levels, which is further reinforced by numerous reports of climatic disparities all over the globe with coral reefs being identified as the first planetary ecosystem under the risk of significant destruction (Steffen *et al.*, 2018). The Paris agreement was a fundamental step towards identifying and creating a united energy policy that highlighted fossil fuel related GHG emissions as a significant contributor/cause of global warming, thus classifying the use of fossil fuel energy sources as a significant threat to the future of human existence (IEA, 2019). Global leaders and societies under the IPCC identified the need for a transition towards sustainable energy systems, thus increasing the interest and focus on pathways that emphasise energy storage technologies and renewable energy systems(Bogdanov *et al.*, 2019).

Hydrogen was recognised as one of the primary energy pathways to achieve a green transition for energy storage and utilisation in addition to increasing utilisation of other renewable energy sources through a development framework under the IEA(European Commission, 2018). EC defines hydrogen based on its possibility to be used as a feedstock, fuel or energy carrier and storage that has many possible applications across multiple sectors, including industries, transport systems, power, and building systems (European Commission, 2020b). Currently, the world is left with less than 50 years of fossil fuel energy reserves; thus, hydrogen seems to have been selected as the potential alternative source of energy by the international energy agency, including many other world governments, because it does not emit CO_2 and when used it does not pollute the air. The increasing momentum of hydrogen is also facilitated by the desperate measures and means that need to be taken to decarbonise a massive range of sectors to meet the international climate targets the UN set under UNSDGs for its member states in 2018 (IEA, 2019). The EU aims to use hydrogen as support to transition from a fossil fuel-based energy system to a renewable-based energy system. To achieve this radical transition, energy storage technologies like batteries and hydrogen are at the centre of this transition(Bogdanov *et al.*, 2019). Over the past five years, there have been increased hydrogen studies and collaborations among countries worldwide. These studies give a green light signal for the projected transition of the world economies to a hydrogen economy. To understand the extent of acceptance of the hydrogen economy, the study scouts the Scopus database for publications related to keywords that include " hydrogen economy, Transition, pathway, and energy" and using VOS viewer software for analysis of the Bibliography coupling of the results.

The visual[1] analysis of bibliographical relationships and average citations of the documents between countries[2] from data retrieved.

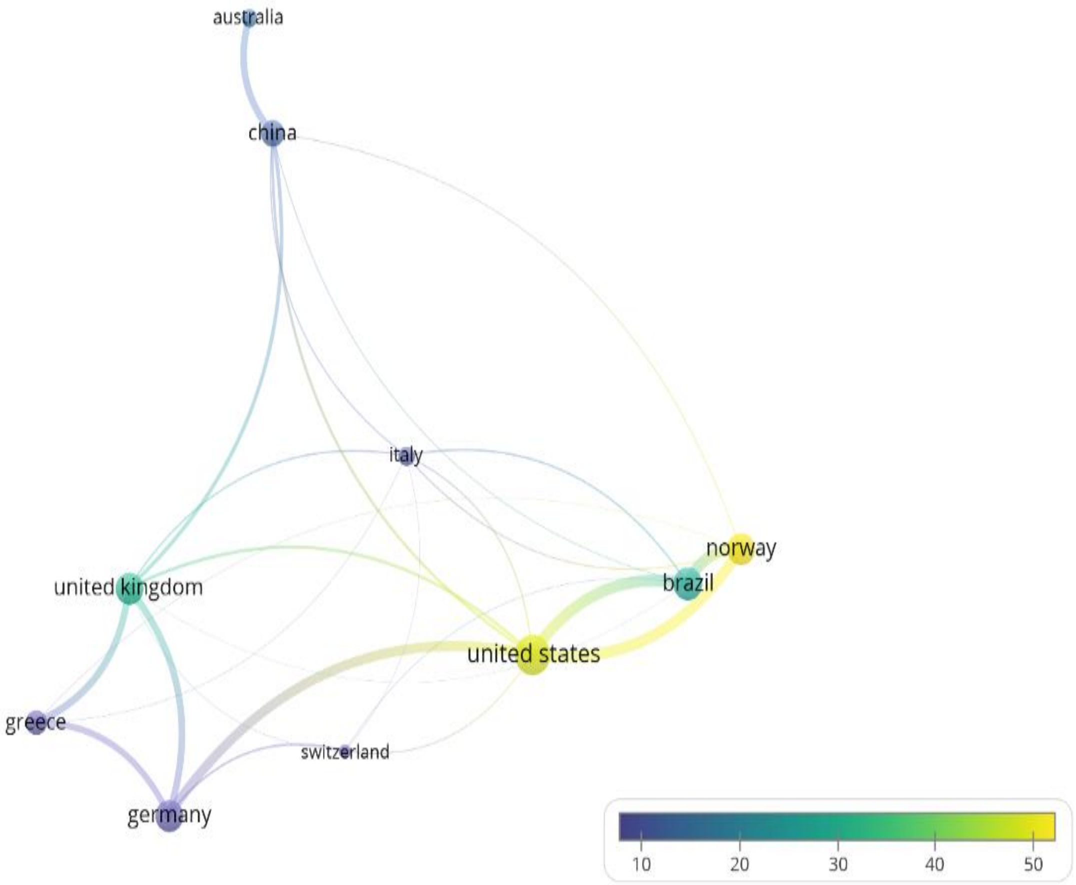

Figure 1 : relationships of hydrogen publications

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[1] The Visual colouring varies by number of average citations and number of publications by countries

[2] The bibliographical relationships are stronger among European countries like Norway, Germany, and United Kingdom, with average citations greater than 50 among partner countries like the United States. Countries Like Brazil, China and Italy have bibliographical relationships with the United States. However, the intensity of publications is relatively lower when compared to the relationships with the European Union Countries.

The data from Scopus shows that at least 54 documents were published between 2017 and 2022 containing the keywords of interest. Among these documents, 53% were articles, 27.9% were reviewed articles, 11.6% were conference papers, and books were 2.3%. These documents originated from 15 countries, and 6 of the top 10 countries under this search are from European region.

Furthermore, the data showed that the critical subject areas of the published documents were centred on energy, with a percentage of 31.5% of the documents.

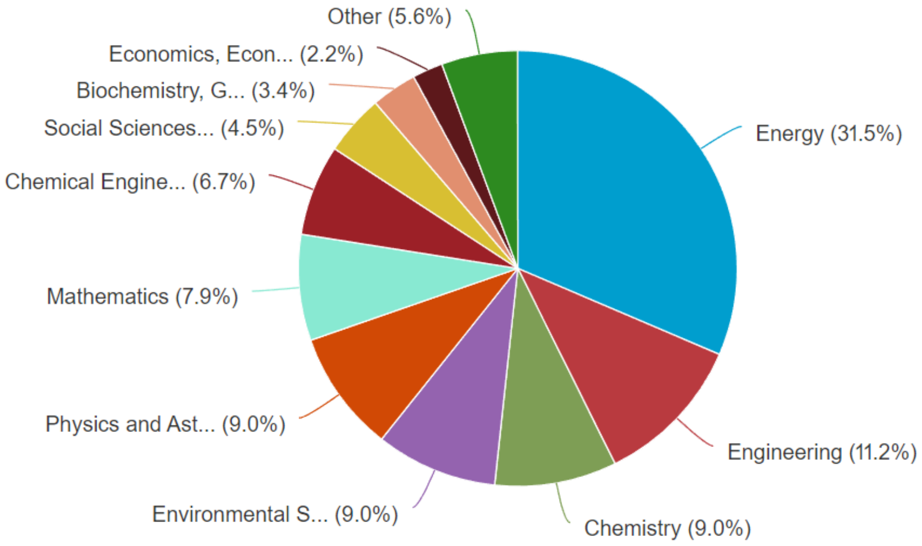


Figure 2. Share of hydrogen publications by school faculty.

Hydrogen can be produced from many feedstocks using different chemical, electrochemical and biological process technologies, but some of these production methods are also associated with emissions and cost implications. In the last decade, low carbon economy hydrogen (hydrocarbons) has achieved much attention from both scientists and Policymakers as an energy carrier with a production capacity output of 120 Mt/a in 2020 and expected to rise to 530 Mt/a in the year 2050 (Hermesmann and Müller, 2022). However, currently, these hydrogen production methods are primarily dominated by fossil fuel sources of energy like steam reforming of natural gas (76%) and gasification of hydrocarbon sources like coal (23%) which are non-renewable energy sources which imply they are associated with emission of GHG (IEA, 2019). The critical aspect of this research is centred on electricity-based hydrogen. Electricity-based hydrogen is produced through water electrolysis with electricity regardless of the electricity source(European Commission, 2020b). Furthermore, hydrogen can be further clustered into colour codes representing the energy source used to produce the hydrogen. These cluster types include green, blue, grey, and turquoise hydrogen (Hermesmann and Müller, 2022).

2.1.1. Hydrogen types

There are many processes to produce hydrogen varying on the desired colour code of the final type of hydrogen produced. IRENA describes the existence of many processes and energy sources where the colour code nomenclature is becoming commonly used with an emphasis on the measure of the impact on the life-cycle greenhouse gas (GHG) emission during these hydrogen production methods (IRENA, 2021b). The authors define different types of hydrogen respective to the colour coding as follows;

Grey Hydrogen

This is the hydrogen produced with fossil fuels and mainly produced from methane using steam reforming or coal gasification(Hermesmann and Müller, 2022). This type of hydrogen is involved with CO2 emissions, which makes these technologies unsuitable for a path toward net-zero emissions(International and Agency, 2021; Ji and Wang, 2021; Hermesmann and Müller, 2022).

Blue Hydrogen

This type can be produced by incorporating carbon capture and storage (CCS) processes during the early stages of energy transition within grey hydrogen production methods. However, it is significantly limited by social acceptance due to issues associated with additional CO2 storage, monitoring, and transportation costs. In addition, blue hydrogen is affected by the uncertainty and infinite nature of the fossil fuel resources like price fluctuations which affect sustainability(pidjoe, 2019; Koj *et al.*, 2017; Mehmeti *et al.*, 2018; Hermesmann and Müller, 2022).

Turquoise Hydrogen

This type is associated with using natural gas as a feedstock with no CO2 emission during methane pyrolysis. Under this process, turquoise hydrogen is produced when methane (the main component of natural gas) is directly split into hydrogen and carbon(Koj *et al.,* 2017; Hermesmann and Müller, 2022). This is critically important because the carbon in the methane generated during this procedure turns into a solid called carbon black. This makes turquoise hydrogen a viable option because it is easy to store solid carbon than the gaseous CO2; however, this procedure is still in the pilot stage (Hu, 2021; Hermesmann and Müller, 2022).

Green Hydrogen

This is the type of hydrogen produced from renewable energy, and this type of hydrogen is the most suitable for a fully sustainable energy transition (IRENA, 2019). To generate this type of Hydrogen currently, you need to use the water electrolysis method fuelled by renewable electricity(Mehmeti *et al.*, 2018).

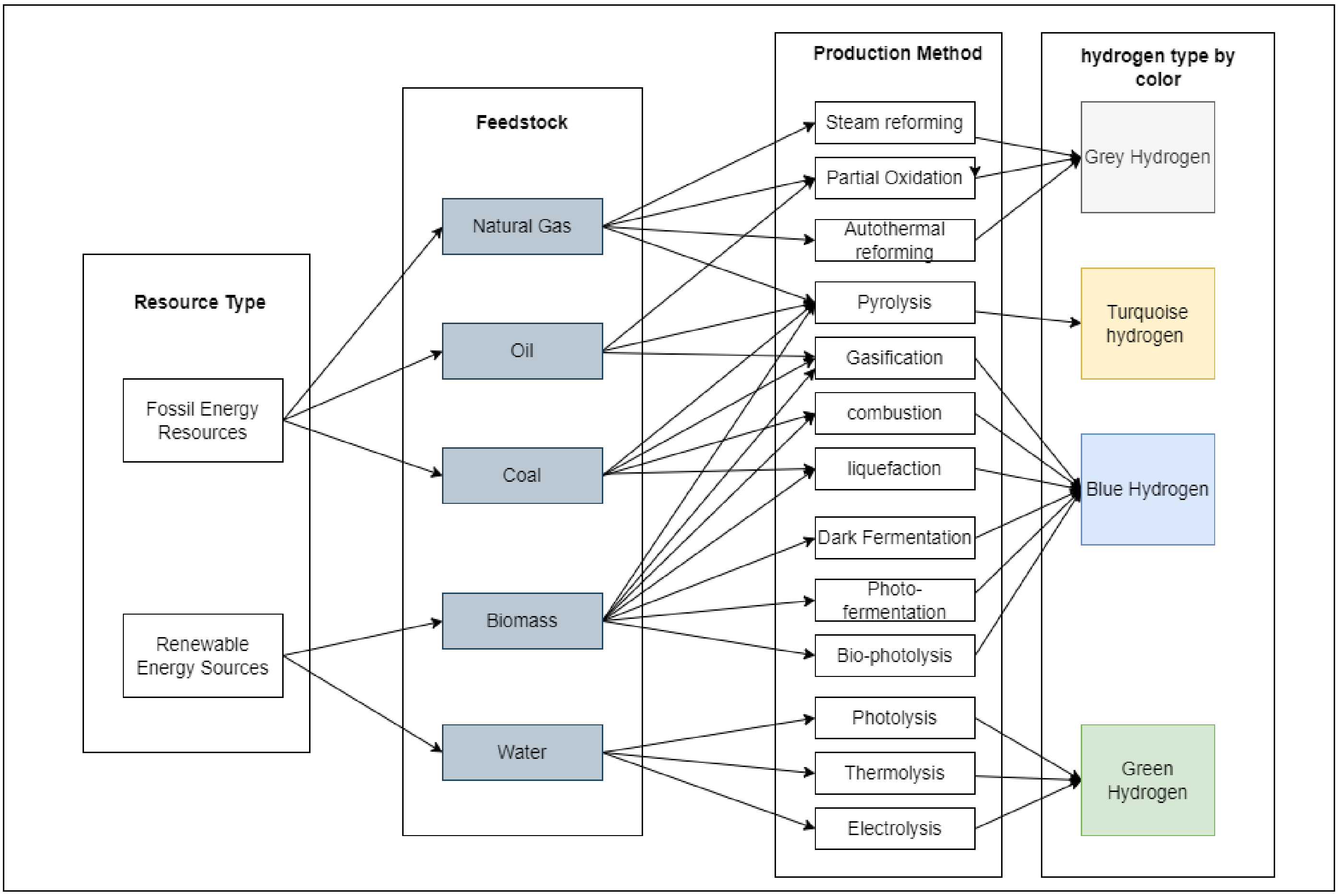


Figure 3. Hydrogen production methods and Pathways

2.1.2. **Renewable Sources of Hydrogen**

This research focuses on the green cluster of hydrogen, which can be produced from renewable electricity sources of energy. These energy sources are mainly considered to be hydropower energy, solar-based energy, wind energy sources, or biogas reforming, which also combines the use of bio-chemical conversion of biomass(European Commission, 2020b). This process involves different methods of generating green hydrogen, and some of them include:

Biomass conversion:- Valente,. et al define biomass conversion as a thermos-chemical and biochemical conversion depending on whether gasification or decomposition processes are employed to cause a chain reaction of the feedstock fuel and catalysts (Arzamendi, Die and Gandı, 2013). However, it should be noted that both processes can be used to generate hydrogen much as one is associated with emissions of CO_2 (Valente, Iribarren and Dufour, 2021). Furthermore, Arzamendi et.al, (2013) highlight the possibility of producing hydrogen from organic waste using low valorization much as this pathway faces low production rates as there biggest challenge making it an undesirable option (Arzamendi, Die and Gandı, 2013). Under this pathway, the major conversion technologies/processes include Gasification, reforming/partial oxidation and anerobic fermentation as shown in figure 5 below.

Solar conversion - Recent studies describe this as a process of thermolysis through which Hydrogen is produced using solar-generated heat for the high-temperature chemical cycle Hydrogen (photolysis). This method uses photons in a biological or an electrochemical system to produce Hydrogen (Hu, 2021).This method has the most preferred hydrogen type, i.e green hydrogen, which does not produce CO2 as a byproduct during the production process. Other processes under this pathway include photocatalytic water splitting, Bio-photolysis, and photo-electrolysis.

Hydrogen from Electrolysis also known as electrolytic hydrogen; - Electric current is used to split water molecules into hydrogen and oxygen atoms in the presence of a catalyst known as an electrolyte, thus completing a process called electrolysis (Imperiyka and Eman, 2017). Many sources can provide the necessary electricity. However, reducing greenhouse gas emissions requires producing electricity using clean energy technologies, such as wind, solar, geothermal and hydropower, nuclear or carbon-sequestrated coal and gas. Nuclear heat can be employed to increase water electrolysis performance in producing hydrogen. By increasing water temperature, hydrogen and oxygen need less power, which decreases energy consumption (Imperiyka and Eman, 2017). It should be clearly understood that hydrogen only qualifies to be labelled green hydrogen/renewable hydrogen if renewable energy technologies are employed as a source of electricity. This research paper's methodology section will discuss electrolysis technology more.

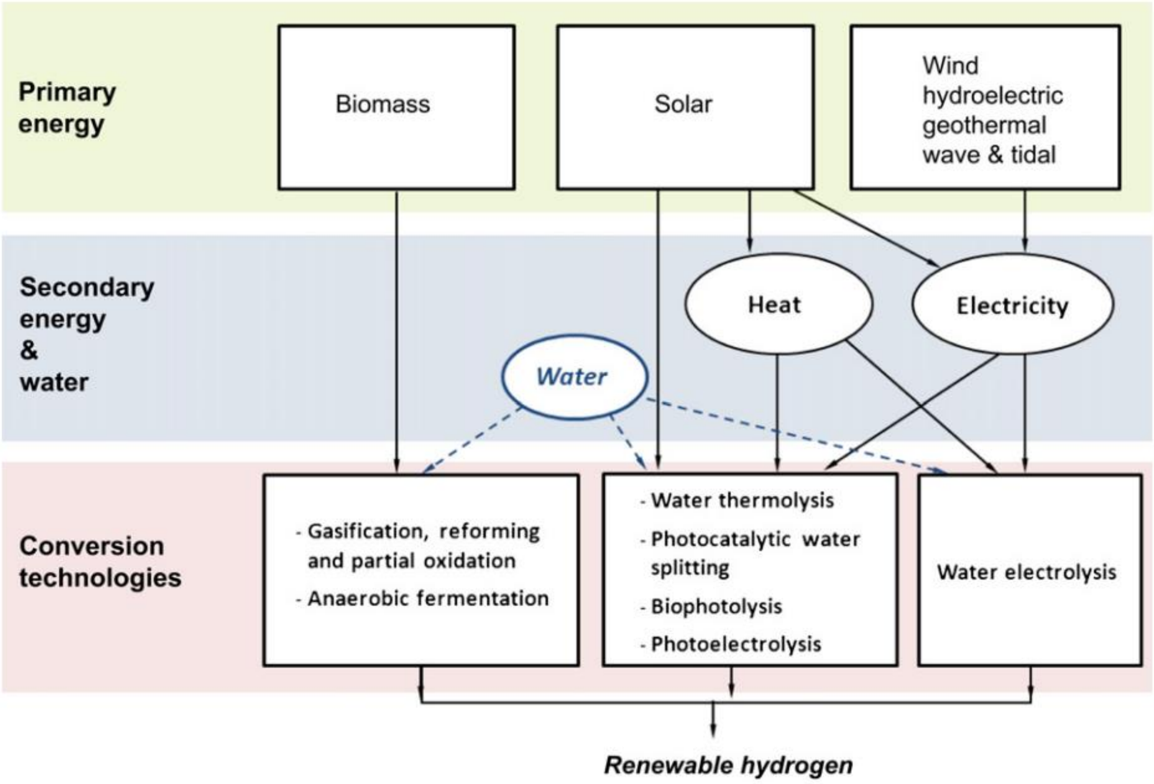


Figure 4. Production pathways of Renewable hydrogen: adapted from (Arzamendi, Die and Gandı, 2013)

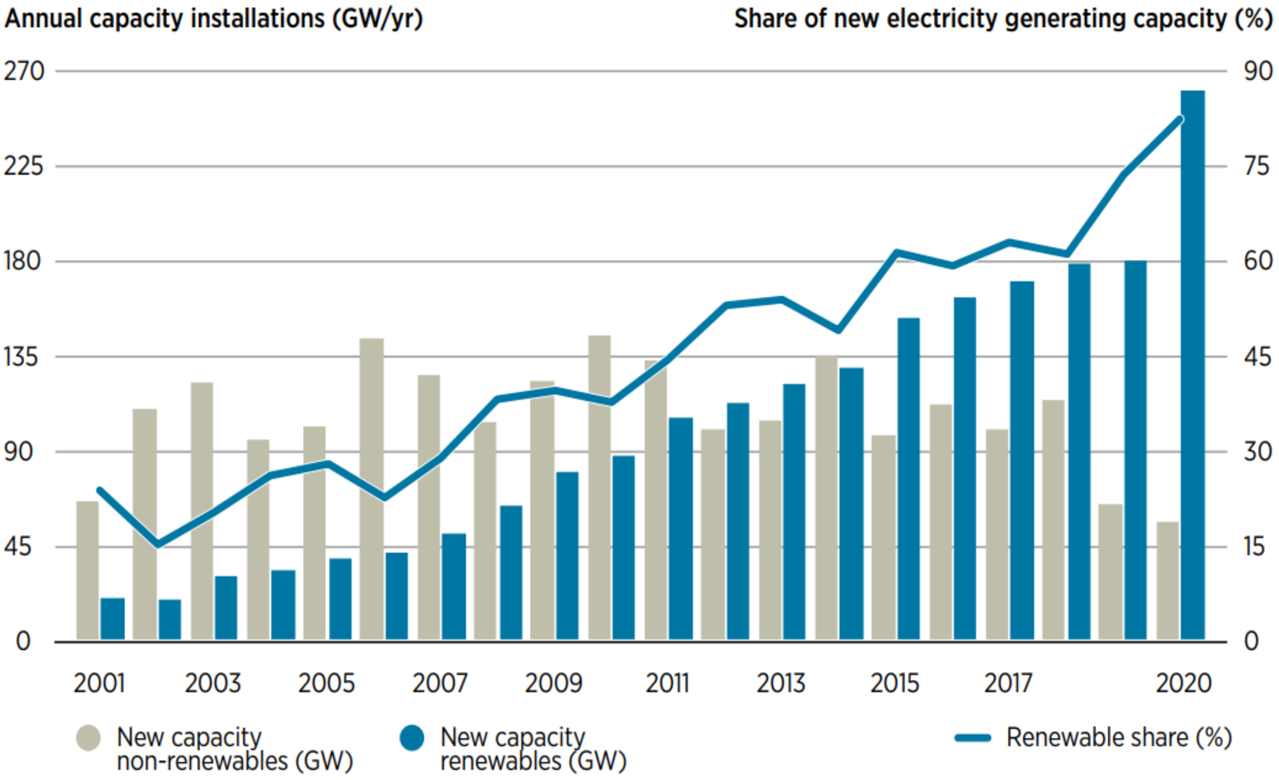
2.2. Renewable Energy

Renewable energy is energy derived from natural processes/sources which can be continuously replenished. There are many definitions of renewable energy. However, most of these definitions share a common opinion on renewable energy sources' continuously replenishable and abundant nature. Renewable energy can be used in many sectors, including space and water heating, electricity generation, cooling, and transportation. Furthermore, renewable energy sources have existed since humanity’s evolution, but they got tremendous attention for power harnessing in the last three decades. These sources include solar energy derived from the sun, bioenergy derived from biomass/forestry, geothermal energy derived from earth crust heating elements, wind energy derived from wind currents and hydroelectric power derived from water runoffs streams like rivers as well as tidal energy from water currents in big oceans and seas. It should be noted that most of the time, these renewable energy sources are associated with green and clean energy, and only some of these sources are sustainable. This can be attributed to the volatile nature of these renewable energy source types. Thus, their efficiency/effectiveness depends greatly on the natural parametric distinctiveness of the energy source type. Our study focuses mainly on two kinds of renewable energy sources, which have been at the centre of the current energy transition trends in the last decade, i.e. wind energy and solar energy.

The current global energy transition is highly aimed at a strategic trajectory to increase the Renewable energy share of the total primary energy supply to grow from 14% to 74% under the 1.5^{o}C scenario by the IPCC between the years 2018 to 2050 (Kent, 2018). Recent developments identified by IRENA are remarkable developments in the application of renewable energy sources in the power sector (IRENA, 2021b). The authors highlight the significant increase in global renewable energy capacity installations (130%) compared to the rise in non-renewables, which grew by 24% in the last decade(IRENA, 2021a). This also implies that in 2021, the total installed capacity of renewable electricity reached its highest, i.e. 3064 GW, generating an estimated electric power of 8000 TWh of electricity (IRENA, 2021b). The significant increase in installations between the years 2010-2021 has been mainly witnessed in solar PV installations with a cumulative installed capacity reaching 843 GWh globally, while wind energy growth also got a significant change with onshore wind cumulative capacity reaching 769 GWh and Off-shore wind installations still being low with a cumulative capacity of 56GW as of 2021 (IRENA, 2021a). Furthermore, it should be known that in 2021 hydropower continued to be the largest share of renewable energy at 1230 GWh [40%] while other power technologies like geothermal, solar thermal, and bioenergy reached a capacity of 166 GWh [86% was bioenergy power]. Other significant contributors, like wind and solar, were 46% collectively (IRENA, 2021b).

Figure 6 below shows the global annual new electricity capacity installations between the years 2001 and 2020, comparing non-renewable energy installations and renewable energy installations.

The differences in annual electricity capacity additions can be observed in figure 6 with new renewable capacity installation having a linear incremental curve whereas the new capacity installations show gradual reductions between the years 2001 and 2020.



Based on IRENA's renewable energy statistics.

Note: GW = gigawatt.

Figure 5. Source: Adopted from IRENA report- Renewables 2021

2.3. Previous LCA studies

A considerable amount of literature has been published on LCA of hydrogen production methods. These studies highlighted many interesting findings ranging from investigating which feedstocks are more sustainable for hydrogen production in the context of minimal associated emissions to which technology combinations produce the highest hydrogen quality in the current state. A short review of some of these pieces of literature will be included in this section highlighting some of the crucial parameters, functional units, systems boundaries, conversion technologies and impact categories considered under these studies by different authors.

2.3.1. **LCA about PEME technologies**

Bareiß *et al.,(2019)* performed an LCA on the effectiveness of reducing greenhouse gas emissions by producing hydrogen using PEM water electrolysis compared with Steam methane reforming (SMR). The authors considered a future 2050 base-load scenario for in-depth modelling of the electrolyser components and electricity production was assumed to be renewable energy mix from Germany. The study covered four hydrogen production methods i.e hydrocarbon reforming, hydrocarbon pyrolysis, biomass processing and water splitting. However, the only technologies modelled for this study were SMR technology among hydrocarbon technologies and Electrolysis using PEM technology water splitting. The authors used an attributional approach to model a cradle-to-gate system with a boundary system that included all processes and flows for a standalone PEME system with a 1MW stack (Total Active area $37m^2$) and sub-components of the system. The Authors chose a functional unit of 1kg of dried hydrogen at the gate with a standard quality of 5.0, 30bar pressure at 60^0C operating temperature(Bareiß *et al.*, 2019). The authors used foreground data collected from different sources, including literature from laboratory experiments, industrial partners and data for background system as taken from the ecoinvent v3.3 database. The findings of this study reveal that an environmentally friendly electricity mix is crucial for reducing greenhouse gases for electrolytic hydrogen with a capability to reduce emissions from 29.5kg CO_2 equivalent per Kg of hydrogen produced to 11.5kg CO_2 equivalent per Kg of hydrogen if renewable energy sources are used for electricity supply (Bareiß *et al.*, 2019). Furthermore, the authors reveal that the PEM system and its components have a very insignificant contribution to the greenhouse gas emissions of the entire system, thus recommending electrolytic hydrogen production to be powered by renewable energy sources to minimise the emissions associated with hydrogen production(Bareiß *et al.*, 2019).

A study by *Iberia and Dincer,(2022)* used an attributional life cycle impact analysis methodology to assess the implementation of hydrogen energy projects for mobility systems (Fuel cell electric buses) using renewable and nuclear-based energies (Iberia and Dincer, 2022). The authors selected three water electrolysis technologies for this study, i.e AWE , PEME and the Copper-chlorine (CU-CI) cycle technologies as clean hydrogen production technologies and a cradle-to-grave system was used, to begin with the generation of energy/electricity and end with hydrogen utilisation by electric buses. The functional unit used in the study was production of 200kg of hydrogen / day transported 100 kilometres to the fuelling station. It was structured to investigate the potential environmental effects of using hydrogen in fuel-cell electric buses compared to diesel buses (Iberia and Dincer, 2022). The system boundary included the evaluation of processes starting from energy production (electricity generation), energy demand for hydrogen production, hydrogen transportation and utilisation of hydrogen at hydrogen refuelling stations. The energy scenarios used under this study was the energy mix from the province of Ontario which compared utilization of 100% nuclear energy against utilization of 100% renewable energy mix with a composition of 70.1% electricity from Hydro, 24.4% from wind and 5.6% from solar PV. The authors analysed that for GWP impact category indicator, CU-CI using renewable energy sources provided relevant results when compared to conventional hydrogen production methods with an emission footprint of 0.87 kg CO_2 per kilogram of hydrogen produced using CU-CI technology which is significantly lower than 7.95kg CO_2 per kilogram of hydrogen produced using conventional methods. The study further revealed that PM2.5 almost doubled under nuclear energy source which could be attributed to use uranium fuel with indicator measurement of 0.017kg NOx per kilogram of hydrogen which is much higher than the conventional sources of hydrogen at 0.011kg kg NOx per kilogram of hydrogen produced (Iberia and Dincer, 2022).

In a different study, Mehmeti *et al.*(2018) conducted a life cycle assessment that can be considered leaning more to the water footprint of hydrogen production methods. The authors used a mid-point methodology to investigate the effects of different hydrogen pathways which were later used in assessing the impacts these pathways have on natures' ecosystems like water through use of Available Water Remaining (AWARE) methodology to determine water scarcity risk arising from these pathways (Mehmeti *et al.*, 2018). The authors chose 7 pathways for this study i.e steam methane reforming, coal gasification, water electrolysis using PEME, Solid Oxide Cell (SOEC), biomass gasification and dark fermentation of lignocellulosic and a function unit of 1kg of hydrogen at the plant gate was selected for reference. The authors applied an attributional approach using a cradle to gate system that entails all reference flows from the energy source for each pathway until hydrogen is delivered at the gate (Mehmeti *et al.*, 2018). It should be noted that just like the previous LCA studies, this study also declared electrolysis as the least harmful pathway only if renewable energies are used as a source of electricity for hydrogen production. According to the authors Mehmeti *et al.,(2018)* the results werent able to pinpoint an optimal solution. However, they proved that hydrogen from non fossil fuel sources (SMR and electrolysis) were less harmful to the environment than fossil based hydrogen pathways like coal gasification(Mehmeti *et al.*, 2018).

2.3.2. **LCA about AWE technologies**

Koj *et al.*, (2017) Conducted a comparative LCA of industrial hydrogen production by alkaline electrolysers of a 6 MW scale in three countries. The countries where these studies were conducted included Austria, Germany, and Spain. The authors chose a functional unit of producing 1kg of hydrogen at 33 bars of atmospheric pressure and temperature of 40^0C at a purity level of 99% (Koj *et al.*, 2017). Furthermore, the impact categories chosen for the study included, Acidification Potential, Climate change, Eutrophication Freshwater, Eutrophication Marine, Eutrophication Terrestrial, Ozone depletion, Particulate Matter, Photochemical Ozone formation and depletion of abiotic resources (Koj *et al.*, 2017). The authors evaluated impacts of these systems at different life cycles including Impacts caused by the electricity supply system (operation phase), Impacts caused by construction phase, and the impacts caused by electricity system transformation and stack replacement (Koj *et al.*, 2017). The results presented operation of Alkaline Electrolysers in Austria hard the suitable results with electrolysers in Spain having the impacts category results for all categories understudy (Koj *et al.*, 2017). Germanys results were three times higher than results from Austria because there electricity grid mix is dominated mainly by coal power plants thus having high emissions associated with electricity generation. The authors further recommended reducing cell material usage since the most increased emission contributions were from cell materials like nickel and polytetrafluoroethylene, thus calling for advance research on these cell part designs (Koj *et al.*, 2017).

Another study about AWE was conducted by Burkhardt *et al.* (2016). The study considered state of the art hydrogen refuelling station with an on-site alkaline electrolyser station in Berlin Germany for this analysis (Burkhardt *et al.*, 2016). The study employs an attributional approach for the assessment and the system boundary includes a 2.0 MW_{el} wind turbine, AWE, hydrogen compressor, storage, and dispenser (Burkhardt *et al.*, 2016). The functional unit used for this system was production of 1kg of hydrogen gas at 700 bars of atmospheric pressure at -40 ^{0}C temperature at a hydrogen refuelling station. According to Burkhardt et. al, (2016) the results show that the hydrogen system has a solid potential to lower greenhouse gas emissions compared to conventional fuels with FCEV reducing emissions by 86% to 89%. The authors further reveal that 74% of the primary energy input for the system is consumed by construction phase of the wind plant. Hydrogen production GHG emissions can be decreased by 30% if the electrolyser's operational time is increased from 3000 h/a to 6000 h/a (Burkhardt *et al.*, 2016).

Lotrič *et al.*(2021) conducted an LCA on hydrogen technologies, assessing four critical technologies at the forefront of the hydrogen transition i.e AWE, PEME, high temperature and low temperature fuel cells (Lotrič *et al.*, 2021). The study was conducted with a focus on critical raw materials needs of these technologies, end-of-life strategies for the EU and functional unit was 50 KW system for both PEME and AWE whereas for the fuel cell technologies, 5 KW for HT PEMFC and 1 KW for the LT PEMFC (Lotrič *et al.*, 2021). The authors modelled the AWE as an outdoor system with a functional unit of producing 1.4kg of hydrogen per hour and the system boundary considered was gate to gate model. This means all processes under the electrolyser technology and its subcomponents were included to produce hydrogen at the gate ready for pumping to distribute through a pipeline or storage(Lotrič *et al.*, 2021). The results revealed that PEME system had a more significant environmental impact than AWE due to some components made from platinum. HT PEMFC had a larger environmental footprint than LT PEMFC due to the BOP components that increase total mass of the system (Lotrič *et al.*, 2021).

2.3.3. **Other LCAs**

Ji and Wang, (2021) conducted a comparative LCA of hydrogen production methods, the technologies under study were fossil-based hydrogen technologies (SMR) and renewable based hydrogen technologies (Sodium Chloride cycle, Mercury Cell) (Ji and Wang, 2021). The authors used an attributional approach with a functional unit of producing 1 kg of hydrogen at the gate (Ji and Wang, 2021). The authors reveal that much as SMR has the highest emission footprint in the process of producing hydrogen, it also has the highest quantity output compared to the other renewable based hydrogen production methods. The authors were able to establish that SMR had a global warming potential of 12 kg of CO_2 per kilogram of hydrogen produced which is the highest when compared to 1.05 kg of CO_2 and 0.909kg of CO_2 per kilogram of hydrogen using mercury cell and diaphragm cell respectively. Furthermore, authors were able also to quantify the global Warming potential of solar based hydrogen to be 0.37 kg of CO_2 per kilogram of hydrogen produced (Ji and Wang, 2021). In comparison, 0.325 kg of CO_2 per kilogram of hydrogen produced was the figure for wind-based hydrogen (Ji and Wang, 2021).

Most LCAs compare environmental impacts of conventional methods of hydrogen production with renewable hydrogen production methods. However, much as various analyses have been conducted to investigate the impact of hydrogen production under different parameters, the common point of consensus with most of these pieces of literature is that electrolytic hydrogen has the least environmental burden. It also becomes more environmentally friendly when the source of electricity is wind or solar since other renewable energies like nuclear are associated with increased PM2.5 pollutants (Acar and Dincer, 2015; Burkhardt *et al.*, 2016; Mehmeti *et al.*, 2018; Bareiß *et al.*, 2019; Lotrič *et al.*, 2021). Furthermore, most of the LCAs are conducted with rationalised functional units of producing 1kg of hydrogen at the gate thus it becomes difficult to understand the whole system effects if these technologies are scaled up. The impact category of GWP is the most studied impact category used by these studies.

3. Methodology

This chapter introduces the concept of Life Cycle Assessment (LCA) and how it is applied in a context related to our research questions. The study uses a holistic approach to investigate the impact of scaling up green hydrogen production to meet the EU's hydrogen strategic targets of producing 10 million of green hydrogen in 2030. Furthermore, the study uses quantitative data from existing LCAs of different renewable energy systems, electrolyser technologies and hydrogen production methods to explore and shed light on the potential impact categories that might be affected by scaling up green hydrogen production.

3.1. LCA concept

There are many definitions of LCA; however, according to Sfs-En Iso 14044 Environmental ,(2021), LCA is the systematic compilation and evaluation of a product systems inputs, outputs, and the potential environmental impacts of that product system throughout its entire life cycle.

LCA is a study tool used to evaluate environmental burdens associated with a product, process, or service by identifying energy and materials used with respective emissions released to the environment and further identifying opportunities for environmental improvement (Finkbeiner et al., 2006). Therefore, LCA introduces product systems thinking approach methodology to enable decision-makers to be aware of the potential shift of burdens that may arise when implementing different solutions to different problems. In our case, hydrogen production is the product being implemented as a carbon-free energy carrier in many sectors of the economy (Lozanovski et al, 2011). Furthermore, LCA methodology follows systematic procedures/guidelines issued and stipulated by the ISO14044:20006 and ISO 14040 framework, thus transforming LCA into a methodological tool that can be used to quantitatively assess, evaluate, and analyse the activities of a product at different levels of its life cycle to ascertain the impact of the product on the environment.

Typically, there are four phases in an LCA, as shown in the figure below: goal and scope definition, life cycle inventory analysis (LCI) comprised of data collection about energy, material flows and emissions to the environment, life cycle impact assessment (LCIA) which is related to the identified forms of resource use and environmental emissions, interpretation of results from the previous phases of the study concerning the study objectives (Finkbeiner et al., 2006). Carrying out this assessment of hydrogen systems follows the Fuel Cell-

Hydrogen guide, which provides detailed technical guidance on the procedures that should be followed while conducting LCA for fuel Cells and hydrogen production technologies under the ISO 14040 and ISO 14044 framework (Lozanovski, Schuller and Faltenbacher, 2011). These technical guidelines are referenced with the International Life Cycle Data sets (ILCD) provided by the European Platform on LCA under the Joint Research Centre – Institute for Environment and Sustainability (JRC-IES), which are intended for hydrogen production systems technology developers (pidjoe, 2019; Lozanovski, Schuller and Faltenbacher, 2011).

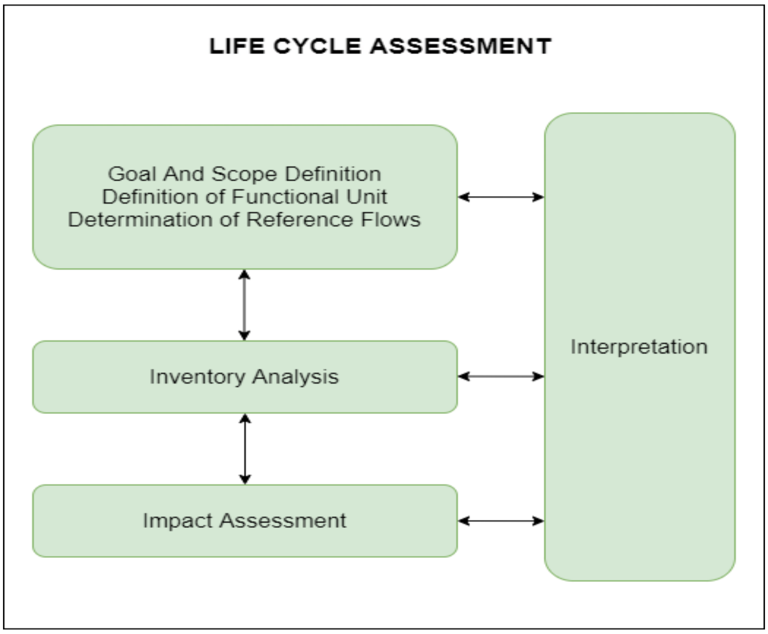


Figure 6: Stages of conducting an LCA. Source (ISO 14044 : 2006)

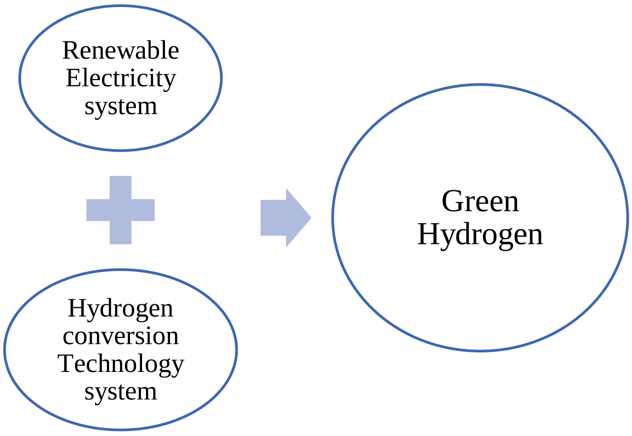
3.2. Goal And Scope Definition

The primary goal of this assessment is to provide insights into the environmental impacts of producing 10 million tonnes of renewable/green hydrogen as stated by the EU hydrogen road map 2030 adopted in 2020 (European Commission, 2020). To achieve this goal, midpoint ReCiPe2016 life cycle assessment methodology is applied, and the carbon footprint of the hydrogen technologies used to produce this quantity will be compared under this method. It should be noted that central to hydrogen adoption is the need for safe, sustainable, low carbon and clean hydrogen systems since various energy sources can produce hydrogen (International and Agency, 2021). Thus, in the context of emission reduction, the environmental footprint of each hydrogen production method varies considerably based on the geographical region and processes used (European Commission, 2018; From *et al.*, 2020; International and Agency, 2021).

The study further focuses on establishing the exact deviations that might arise in scaling up hydrogen technologies using wind and solar energy sources as primary energy/electricity sources comparatively using the two commercially available electrolysis Technologies (AWE and PEME) that are already being rolled out to meet the growing hydrogen demand needs in the EU region.

3.2.1. **Scope of Study**

The scope of the study follows an attributional LCA approach to model a cradle-to-gate assessment with emphasis on the production phase and processes of hydrogen incorporating all material inputs of the renewable electricity system and the electrolysis technology system. This means that the hydrogen system has to be clustered into two independent sub-systems, i.e. renewable electricity supply system (wind and solar technologies) and hydrogen conversion system (AWE and PEME electrolysis systems), which are necessary for the production of emission-free hydrogen also referred to as green hydrogen. Since our primary goal of this LCA is understanding the potential impacts of scaling up hydrogen technologies, the functional unit chosen for this study is the production of 10 million tonnes of hydrogen with a purity rate of 100% in gaseous form.



3.2.2. **Renewable energy System in Europe**

The past decade has seen rapid developments in the EU energy mix, specifically in the share of renewables, whose share value has increased from as low as 6.4% to 15.8% between 2009 and 2019 (IRENA, 2021a). This increased share value can be attributed to the additional policy changes implemented among member states which have resulted in substantial cost reductions and increased subsidies for clean energy technologies under the EU green deal (European Commission, 2018). The second strategic building block of the road to a net-zero greenhouse gas economy aims to maximise the deployment of renewable energy and the use of renewable electricity in the European energy mix. Subsequently, Europe also looks at using these energy sources to drive down its energy import dependence on oil and gas from its neighbouring states, which is currently at 55% of its total energy consumption to an estimated 20% by 2050 (European Commission, 2018).

In the second phase of the hydrogen strategy roll-out plan (2024-2030), the European Union commission's objective is to install at least 40 GW of renewable hydrogen electrolyser by 2030 (European Commission, 2020). This objective targets the production of up to 10 million tonnes of renewable hydrogen within the EU block itself, and to achieve that, the commission looks at increasing investments in critical technologies and value chains that may aggregate from €180 to €470 billion by 2050 (European Commission, 2020). Before the covid 19 Pandemic, the entire EU member states had committed to increasing the share of renewable energy (to 32%) in their national energy mix, including submission of plans to achieve this by 2030 (IEA, 2022). However, due to the disruptions of the pandemic, there was a sense that these targets would not be achieved. This resulted in the commission releasing a €750 billion recovery fund, emphasising that at least 30% is devoted to climate change mitigation and adaptation (IEA, 2022).

According to (Kent, 2018), the total installed wind and PV capacity expansions will surpass coal by 2025. This is because the renewable energy technologies market is undergoing favourable cost reductions and sustainable policy reforms within the European market, which are forecasted to effect a decline in utility-scale solar PV generation costs by 36% and a 26% average annual growth of onshore wind forecast(IEA, 2022). The authors further forecast the average solar PV capacity additions to contribute 60% of the renewable energy expansion from 2023 to 2025 in a range of 130 GW to 165 GW(IEA, 2022). The Figure below shows the changes in the Renewable generation capacity of EU 27 from 2009 to 2019 (Solar PV, Onshore wind, and Offshore wind).

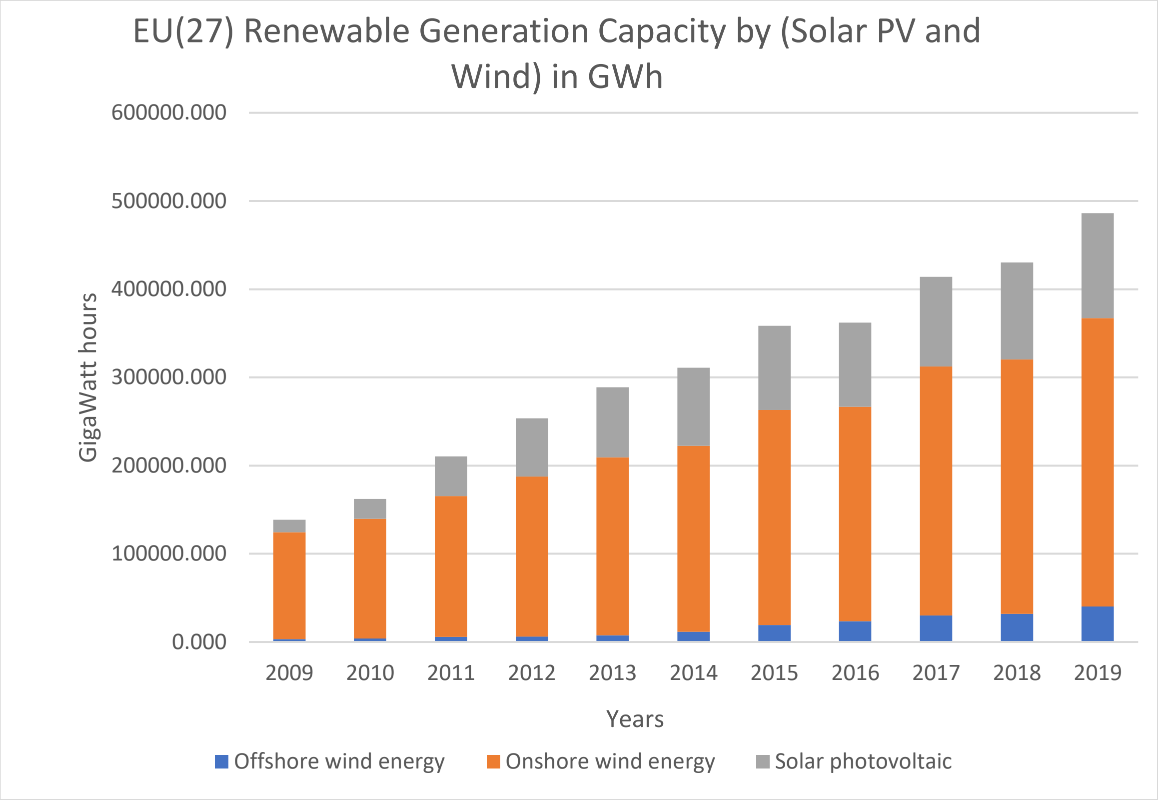


Figure 7: Data Source: IRENA (2021), Renewable Energy Statistics

There is a need to thoroughly understand the renewable energy technologies currently being scaled up to meet the forecasted future electricity demand. This study considers two renewable energy technologies (wind energy and solar PV) as the sole sources of renewable electricity for hydrogen conversion technologies. The data to be collected should cover the most technologically successful and mature technologies that have received acceptance and the capacity outputs of these technologies alongside material quantities consumed for manufacturing these technologies.

Morden wind power technologies designs deviate on drive mechanisms, drive systems and generator designs for both onshore and offshore applications. This deviation will be catered for by benching marking material consumption data for building these technologies, emphasising the latest wind turbine profiles developed by leading wind technology firms like Vestas. The deviations exist on the choices of either wind turbines that employ a gearbox configuration or wind turbines that utilise direct-drive structures for the generator mechanism as shown in the table 1 below. Each type of generator system has different advantages over the other however, currently the most preferred wind turbines are direct drive wind turbine systems due to the reductions in size that arise from using permanent magnets. This implies that by eliminating the gearbox, the overall weight of the turbine reduces but also replaces mechanical failure prone gearbox with simpler designs that are easy to operate and maintain thus becoming more efficient for offshore applications (Dias et al, 2020).

Table 1: Parameters for wind energy technologies. Sources: (Dias et al, 2020)

Type of Generator	***Type of Turbine***	***Application***
Direct Drive	High Temperature Superconductors (HTS)	offshore
Direct Drive	Electrically Excited Synchronous generator (EESG)	onshore
Direct Drive	Permanent magnet Synchronous Generator (PMSG)	onshore and offshore
Gearbox	Permanent magnet Synchronous Generator (PMSG)	onshore and offshore
Gearbox	Double-Fed Induction Generator (DFIG)	onshore and offshore
Gear box	Squirrel Cage Induction Generator (SCIG) - without total converter	offshore

PV systems are currently classified on four technologies, as shown in the table below. Much as the present market share of these systems is dominated by silicon-based wafer technologies; there is a growing perspective that the silicone-based PV systems will be replaced by thin-film technologies due to high performance efficiencies in abilities to absorb light 10 -100 times more efficient than the later. The problem of low irradiation levels on significant geographical landscapes of the EU greatly hinders the critical challenges with using PV systems in the EU region. Previous studies have reported that the solar irradiation in Europe are estimated to be under 1kwh/m^2/d during winter times for a fixed panels PV model, however areas like north Africa have solar irradiation ranging beyond 6$^+$ kWh/m^2/d (Trainer, 2013). With a 15% solar panel efficiency North Africa would produce 0.9kwh/m^2/d, which implies 75% more PV electricity can be generated from Africa instead of Europe. This can also be seen taking effect under the EUs hydrogen strategy which points out the establishment of the International Partnership for a Hydrogen Economy (IPHE) and Africa being recognised as potential cost competitive renewable hydrogen supplier to Europe (European Commission, 2020).

Table 2: Solar PV plant technologies market share: Source: (Dias et al, 2020)

	Type of PV technology	*Market Share*
1	wafer-based crystalline silicon (c-Si), either single-crystalline or multi-crystalline silicon (no distinction between the two will be made in this study)	c-Si. 95.4%.
2	cadmium telluride (CdTe);	CdTe. 2.4%.
3	copper indium gallium diselenide (CIGS)	CIGS. 1.9%.
4	amorphous silicon (a-Si).	a-Si. 0.3%.

3.2.3. Hydrogen Conversion technologies

Many conversion technologies use different methods to produce hydrogen however, the chosen technologies highlighted by the EUs hydrogen Strategy are water electrolysis technologies with the announcement of having a target to install 40 GW around the EU by 2030 (European Commission, 2020). Data from several studies suggests that the most established electrolysis technology ready for commercialization are alkaline water electrolyser (AWE) and proton electrolyte membrane electrolyser (PEME) with MW scale capacity plants operational in countries like Canada and other regions worldwide (Okunlola, Davis and Kumar, 2022).

Water electrolysis

Water electrolysis is the method of separating water into Hydrogen and oxygen by electrical application. There are two types of technologies commonly used in water electrolysis, i.e. Alkaline Electrolysis and Polymer Electrolyte Membrane (PEM)(Lamy, 2016).

$$H_2O + electricity \rightarrow \frac{1}{2}O_2 + H_2$$

The energy needed to electrolyse increases marginally at a high temperature while the electrical power needed decreases. Therefore, if waste heat from other processes is implemented, the high-temperature electrolysis process becomes preferable.

Technical Scope

The current electrolysis technology market is dominated by two technologies with a mature status for commercial hydrogen production. The technical parameters of these technologies are protected by proprietary rights, however some of the assumed technical parameters of

AWE and PEME are obtained from secondary literature sources. And the data gathered from these articles is presented in table 3.

Table 3: technical parameters of Current PEME and AWE;- Sources: (Lamy, 2016; Ji and Wang, 2021; Lotrič *et al.*, 2021)

Parameter	*Units*	*AWE*	*PEME*
Cell voltage level	V	1.8 - 2.4	1.8 - 2.2
Current density	A/cm^2	0.2 - 0.4	1 - 2
Power density	W/cm^2	Up to 1.0	2.7
Power of system	KW	50	50
Anode Ir. loading	mg/cm^2	3	2
Cathode Pt. loading	mg/cm^2	0.2	0.2
Charge carriers		OH	H+
Electrolyte	type	NaOH	Polymers
capacity	Kg/H_2/H	1.46	1.46
Stack lifetime	years	7 - 10	7 - 10
BOP lifetime	years	20	20

Alkaline electrolysis

Under Alkaline Electrolysis, the reaction occurs between two electrodes submerged in a solution comprised of water and a liquid electrolyte. When Voltage is applied to the electrodes, water molecules take electrons to make $OH-$ ions and H_2 molecule. The $OH-$ ions move through the solution towards the anode ,where they combine with extra electrons to make water, electrons and O_2 (Millet and Grigoriev, 2013; Lotrič *et al.*, 2021).

Alkaline electrolytes are an electrolyte that usually circulates through the electrolytic cells using an aqueous KOH (caustic) solution (Koj *et al.*, 2017). Alkaline electrolysers can be used stationary and can be used at operating pressures of up to 2.5 MPa (Millet and Grigoriev, 2013; Lamy, 2016). Alkaline electrical electrolysis is a proven technique with a significant industrial record allowing for remote operation. In the alkaline electrolysis cell, the following reactions are performed as follows (Millet and Grigoriev, 2013; Lotrič *et al.*, 2021):

Electrolyte $4H_2O \rightarrow 4H^+ + OH^-$

Cathode: $4H^+ + 4e^- \rightarrow 2H_2$

Anode: $4OH + O_2 \rightarrow 2H_2O + 4e^-$

Sum: $2H_2O \rightarrow 2H_2 + O_2$

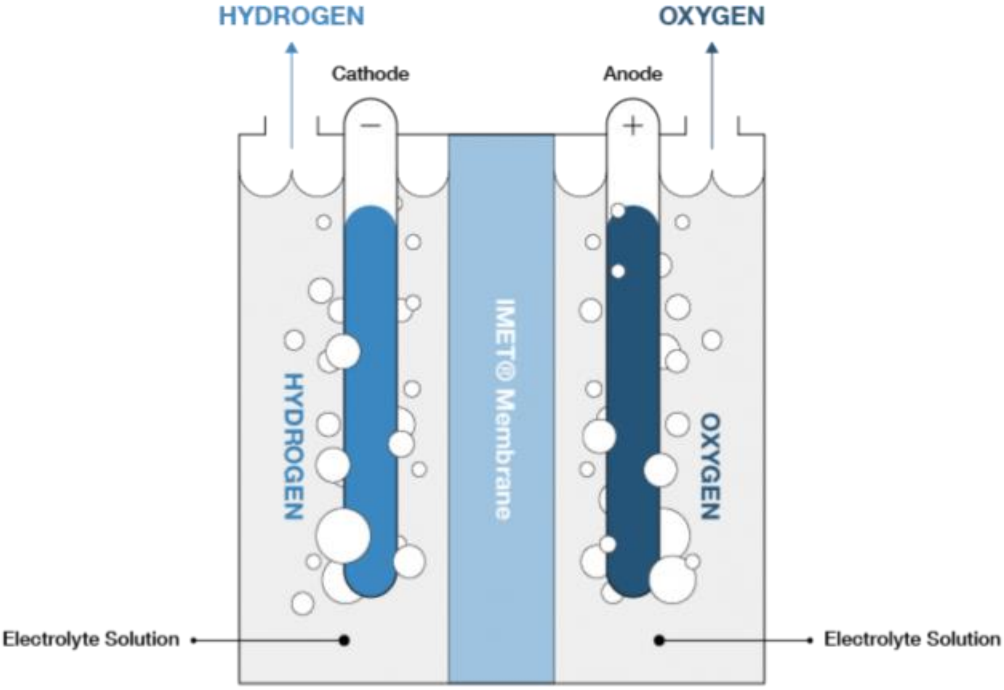


Figure 8 : Schematic Diagram of an Alkaline Water Electrolyser ; Adapted from (Cummins, 2022)

Polymer electrolyte membrane (PEM) electrolysers

PEM Electrolysers creates a chemical reaction using conductive ions of a solid polymer rather than a liquid (Cummins, 2022). Voltage is applied to the two electrodes resulting in the movement of splitting of the water molecules into protons and electrons and thus O_2 moving to the anode (Millet and Grigoriev, 2013; Bareiß *et al.*, 2019). The $H+$ ions move through the proton conducting cathode where the electrons become neutral H atoms commonly known as hydrogen (Millet and Grigoriev, 2013; Valente, Iribarren and Dufour, 2021).

PEM electrolysers do not need a fluid electrolyte which significantly simplifies construction(Bareiß *et al.*, 2019; Lotrič *et al.*, 2021). The electrolyte is a polymer membrane of acidic acid (Cummins, 2022). PEM electrolysers can be engineered for operating pressures of up to several hundred bars and are suitable for mobile and stationary purposes

(Mehmeti *et al.*, 2018; Bareiß *et al.*, 2019). The downside of this technique is the polymer electrolyte's short life span. Compared to AWE, the key advantages of PEME are its compression operation cycle, improved stack protection due to lack of KOH electrolytes, lightweight size due to higher densities and higher operating pressures (Millet and Grigoriev, 2013; Mehmeti *et al.*, 2018; Bareiß *et al.*, 2019; Ji and Wang, 2021). However, PEM electrolysers available on the global market at presnet are not as advanced as AWEs (Ji and Wang, 2021; Hermesmann and Müller, 2022).

Anode: $4H_2 \rightarrow O_2 + 2H^+ + 2e^-$

Cathode: $2H^+ + 2e^- \rightarrow H_2$

High-temperature electrolysis

Electrolysis of high temperatures is dependent on high-temperature fuel cell technology (Valente et al, 2021). For dissociating water at 100°C, the electric energy is greater than in 1000°C (Lotrič *et al.*, 2021). This ensures that the electrolyser with high temperatures can work more efficiently than those with low temperature electrolysers (Lotrič *et al.*, 2021). A regular technology used is the solid oxide electrolyser cell (SOEC). This electrolyser is built on a solid oxide fuel cell, which operates at temperatures ranging from 700 to 1000 °C (Millet and Grigoriev, 2013; Bhandari, Trudewind and Zapp, 2014; Lamy, 2016; Valente et al, 2021).

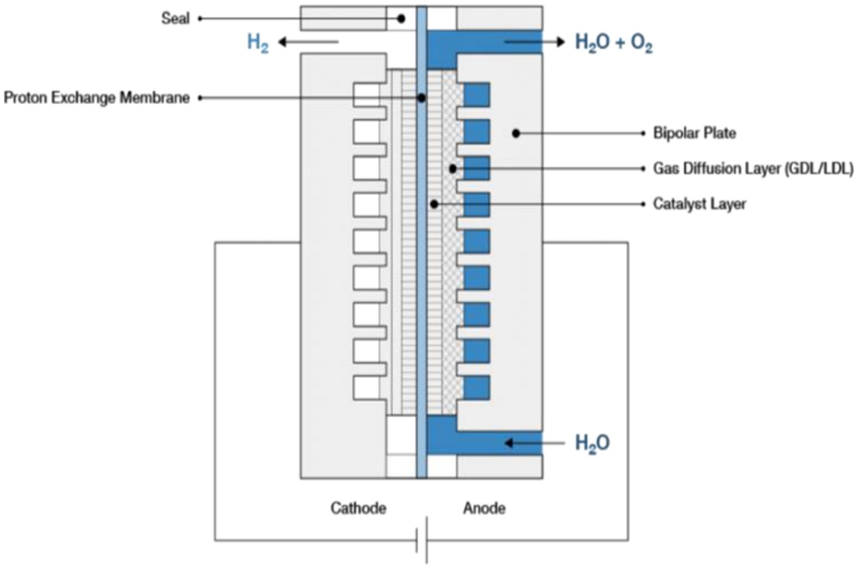


Figure 9: Schematic Diagram of PEM electrolysis process. Adopted from (Cummins, 2022)

3.3. System boundary

The study uses a cradle-to-gate system to examine the effects of material withdrawal for green hydrogen production. The hydrogen conversion technology is assumed to rely only on electricity from renewable sources to be more specific wind and solar electricity systems. The system boundary covers all processes, energy and material flows undertaken for the wind, solar PV, balance of plant construction and energy output from these systems during operational phases. However, transport processes are not included since the model does not consider the geographical placement of these electrolyser technologies in the EU region.

The hydrogen conversion technologies considered under this study are AWE and PEME with a production output capacity of 300 tonnes hydrogen per year. The system boundary also includes the material consumption for building these conversion technologies and energy consumption during the operation phase to produce hydrogen. However, since there is limited data on location placement of these technologies, transport of these materials was not included. Hydrogen systems are assumed to fit in 20 feet container size specifications connected to all their subsystems necessary for producing hydrogen at the gate. These subsystems include Chiller, Control Panel, Demi water Supply, Instrument Air systems, Nitrogen panel, Cell stack (Gas generation system), closed-loop cooling, hydrogen Purification systems and outdoor housing. The energy input into the manufacturing stages of renewable electricity and hydrogen conversion systems was not included. The hydrogen distribution systems like pipeline networks and storage tanks are not included. Furthermore, the co-products of hydrogen like oxygen and thermal heat produced by the electrolyser systems are not recovered or utilised thus assumed to be released to the atmosphere. However, only quantified outputs are tracked because of co-generation.

Averaged figures for renewable electricity plants in units of mass per unit output of electricity will be used to model the renewable electricity supply system needed by the hydrogen conversion technologies.

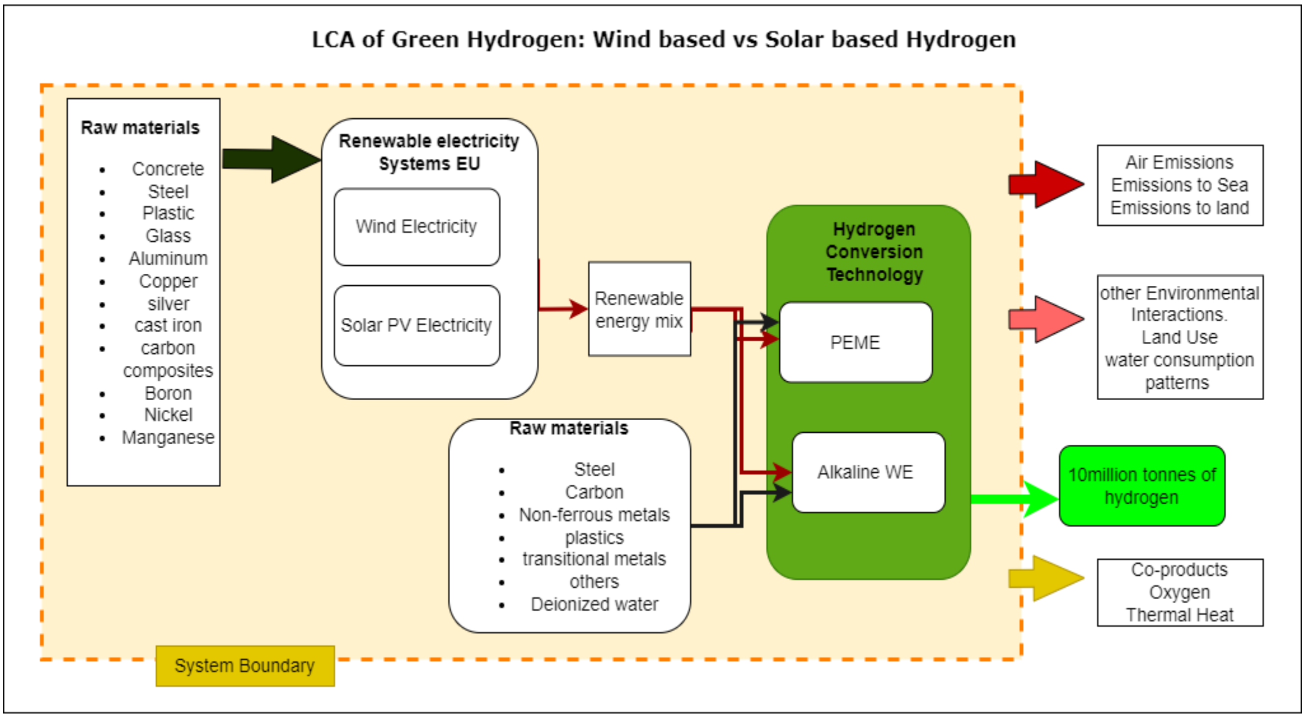


Figure 10: system boundary of green hydrogen

3.4. Energy Scenarios

The theory of scaling renewable-based electricity in Europe is intended to support a network of decentralised renewable hydrogen valleys (International Energy Agency, 2021). This network is central to keeping hydrogen supply chains constant for local industrial and transport systems and determining the impacts of scaling up these technologies is necessary for forecasting potential global bottlenecks and shortages in material markets. Further to this, International Energy Agency, (2021) explains the importance of having short transport distances for energy, thus calling for critical choices on significant infrastructure developments needed to facilitate the quick and efficient flow of volumetric energy densities with lower transport losses (IEA, 2021).

With this in mind, four scenarios will be considered for this study as shown in the table below. To facilitate a comprehensive environmental assessment, the performance of renewable electricity and hydrogen conversion technologies (Electrolyser technology) will be investigated under these scenarios. The assumptions used to design the scenarios adopted follow the following:

Baseline Scenario;

- Under the baseline scenario the study adopts a comparative assessment of producing 10million tonnes of hydrogen using two hydrogen conversion technologies i.e AWE and PEME. Therefore, the study will consider producing of these quantities using AWE as a stand-alone system and further produce the same quantities using PEME as a stand-alone as well.
- The electricity supply for both hydrogen conversion technologies will be assumed to be equal contributions from both wind and solar PV electrical system which is supplied to the renewable energy grid mix.

Scenario 1: Under this scenario, there is need to investigate the effects of renewable energy sources on these stand-alone hydrogen conversion technologies modelled in the baseline scenario. Furthermore, the scepticism for designing the renewable grid mix under this scenario is rooted from negative cases that highlight EU region having higher potential of producing wind-based electricity compared to electricity generation using solar PV. Therefor the scenario 1 parameters include the following.

- Just as the baseline scenario, the study will adopt a comparative assessment of producing 10 million tonnes of hydrogen using AWE as a stand-alone system and the same quantities for a stand-alone system of PEME. Therefore, each hydrogen conversion system produces 10 million tonnes of hydrogen independently.
- The highest renewable electricity share will be generated using wind plant, probably three quarters of the needed electricity and the rest will be generated using solar PV.

Scenario 2: Under this scenario, the study investigates the effects of producing portions of the targeted hydrogen quantities using both hydrogen conversion technologies. The assumptions considered under this scenario include the following.

- Under this scenario, the majority of the 10million tonnes of hydrogen will be produced using AWE whereas the rest will be produced using PEME. This means that both technologies are deployed for hydrogen production co-currently.
- The renewable electricity mix will be same as the base scenario, and therefore each of the technologies contributes 50% to the electricity needed by the hydrogen conversion technologies.

Scenario 3: Under this scenario, similar assumptions on the renewable electricity are applied as the assumption in scenario 2. However, the main difference is that under this scenario, the majority of the 10 million tonnes of hydrogen will be produced using PEME whereas the rest will be produced using AWE. Therefore, the assumptions considered under this scenario include the following.

- PEME produces the biggest quantities of the required hydrogen quantities.
- AWE produces the rest of the hydrogen quantities
- The renewable electricity mix is assumed to be comprised of 50% contribution from each renewable source under this study i.e 50% of electricity needed by the conversion technologies comes from wind and the other 50% is supplied using solar PV plant.

Table 4:Data for modelling technologies under different scenarios

Scenarios	***Renewable electricity Source***		***Electrolyser Technology***	***Hydrogen output** (tonnes)*
Baseline Scenario	50%	50%	AWE	10m
			PEME	10m
Scenario 1	75%	25%	AWE	10m
			PEME	10m
Scenario 2	50%	50%	AWE	7m
			PEME	3m
Scenario 3	50%	50%	AWE	4m
			PEME	6m

Grouping of Scenario models and Rationale of Results

Group 1:Baseline Scenario and Scenario 1: The base line scenario will be modelled to investigate the carbon footprint of producing 10million tonnes of green hydrogen using AWE technology and PEME both as standalone hydrogen systems. The assumptions under this scenario are that the electricity used for both technologies is 50% from wind technology and 50% from Solar PV electricity systems. Furthermore, in scenario 1 the emission footprint of producing 10 million tonnes of green hydrogen will again be simulated with 75% electricity input from wind technology and 25% from Solar PV. This will facilitate the investigations on how the sources of electricity affect the emissions on both electrolyser technologies.

Group 2: Scenarios 2 and 3:

Under these two scenarios, emphasis will be put on investigating the performance of joint production hydrogen using the two hydrogen conversion technologies (electrolyser technologies) understudy. Under scenarios 2 and 3, the total hydrogen production is 10 million tonnes of green hydrogen using a combination of both PEME and AWE. Scenario 2 will assume 70% of the green hydrogen being produced by AWE, and PEME will deliver the rest 30%. In comparison, Scenario 3 will take that 40% of the overall quantity of green hydrogen will be produced using AWE, and the rest 60% will be produced using PEME. Both scenarios have a total hydrogen output production of 10million tonnes of hydrogen.

3.5. Environmental Impact Categories

Conducting an LCA is dominated mainly by quantifying emissions and resource use by a product (ISO 14044:2006). To understand how these product activities affect or interact with the environment, it is necessary to choose a characterisation model/method per the stated goals and scope of the study (Lozanovski, Schuller and Faltenbacher, 2011). Bearing in mind that characterisation factors are derived using a midpoint level or endpoint point level method of impact category identification to assess the impact of a products activities on the areas of protection (Huijbregts *et al.*, 2017). According to Walter et. al, (2014) an impact category of an LCA can be defined as a cluster of environmental issues of concern also known as areas of protection. Using Life Cycle Inventory Analysis results, quantifiable impact category indicator representations can be assigned to determine a product's contribution to the selected impact categories.

The ISO 14044:2006 classifies life cycle impact assessment into mandatory and optional elements. The mandatory elements include selection of impact categories, category indicators and characterisation models, allocation of the LCI results also known as classification and computation of category indicator results (characterisation) which are generated following the scientific rules for the study being conducted (Walter et al, 2014). In contrast, the optional elements comprise normalisation, grouping and weighting procedures which can be justified scientifically but only in parts (Walter et al, 2014).

However, much as the ISO 14044 does not recommend or provide a list of impact categories to select from, the choice of which impact categories to consider for a study is left to the authors of the LCA (ISO14044). Furthermore, some recommendations are given to use sample categories, indicators models from the technical guidelines under the ISO 14047

(Walter et al, 2014). Irrespective of that, ISO 14044 emphasises the need to provide comprehensive information about the selection procedures for impact categories, indicators models, characterisation factors, and category indicators to be based on internationally acceptable literature sources, which can also be found under the EUs electronically published handbook for conducting LCA. With that in perceptive the table 5 below presents the selected impact categories and characterisation factors that have been considered for this study.

This study will use mid-point level characterisation factors to analyse LCI results as provided by the ReCiPe2016 methodology. The following 8 impact categories were selected to be suitable for this study out of the 17 midpoint impact categories under the ReCiPe 2016 model. The selected impact categories are considered to be the of critical import due to their relationship with resource withdraw partners within most critical material markets. This implies that their usage patterns are directly proportional to their withdrawal activities like mining, transportation which are as well linked to carbon emissions.

Table 5: List of impact categories selected for this study

Environmental Impact Category	*Unit of characterisation*	*Method*
Climate change (CC)	Kg CO_2 eq	Mid-point
Photochemical Ozone potential (PCOP)	Kg NOx eq.	Mid-point
Fossil Depletion(FD)	kg oil eq.	Mid-point
Fine Particulate Matter Formation(FPMF)	kg PM2.5 eq	Mid-point
Fresh water Eutrophication Potential (FWEP)	Kg Phoshate eq	Mid-point
Metal Depletion(MD)	kg Cu eq	Mid-point

Land Use (LU)	m^2 yr annual crop eq	Mid-point
Fresh Water consumption (FWC)	m^3	Mid-point

Climate Change

This is the most cited mid-point category of interest considered to arise due to environmental pressures exerted by Greenhouse gas emissions leading to atmospheric temperature changes, thus contributing to climate change (Allinson, 2013; Lozanovski, Schuller and Faltenbacher, 2011; Huijbregts *et al.*, 2017). The characterisation factor widely used for this indicator is Global warming Potential (GWP) and often measured with regards to integrated infrared radiative, and a category indicator result of kilograms of CO_2-equivalent per function unit of a product under study (Walter et al, 2014).

Photochemical Ozone potential

This mid-point category deals with the accumulation of ground-level ozone resulting from chemical reactions with Nitrogen dioxides, air pollutants like hydrocarbons and radiation from the sun leading to the creation of photochemical ozone layer in the stratosphere (Allinson, 2013). The characterisation factor for photochemical ozone creation is expressed in Kilograms of Nitrogen Oxides equivalent Per functional unit (Kg NOx eq./FU) of the product under study (Walter et al, 2014).

Fine Particle Matter Formation

The mid-point category of fine particle matter formation deals with the accumulation of chemical substances composed chiefly of primary and secondary particles which can lead to respiratory complications (Allinson, 2013). The characterisation factor used for this category indicator is expressed in Kilograms of ambient Particulate Matter 2.5 equivalent per Functional Unit of a product under study (Huijbregts *et al.*, 2017).

Freshwater Consumption

Water Use or water consumption at mid-point category deals with the amount of water withdrawn from hydrological cycle by activities related to producing a product under study (Hoekstra *et al.*, 2011). The characterisation factor used for this category at midpoint is cubic metres of water consumed per functional unit (m^3/FU) of the product under study (Huijbregts *et al.*, 2017).

Land Use

Land use mid-point impact category deals with environmental pressures from increased competition for land by different human activities thus resulting to relative species loss due to the destruction of their natural habitat (Allinson, 2013). The characterization indicator of this category is presented in square meters of land used in years annual crop equivalent per functional unit (m^2 yr annual crop eq/FU) of the product under study (Huijbregts *et al.*, 2017).

Freshwater Eutrophication Potential

Accumulating significant amounts of nutrients (such as nitrates and phosphates) in nature's ecosystems leads to Eutrophication. This impact category affects areas of protection like fresh water sources as result of pollution from surface run offs to water bodies and its category characterisation factors are expressed in kilograms of phosphorus to freshwater equivalents per functional unit (Kg P eq/ FU) of the product under study (Allinson, 2013).

Metal Depletion

This mid-point impact category deals with mineral resource scarcity as result of increased primary resource extraction due to activities related to a particular product. Since most mineral ores are finite, increased resource extraction increases depletion of mineral ore deposits and thus also reduces the ore grade resources worldwide (Huijbregts *et al.*, 2017). The characterisation factor used for this impact category is expressed in Kilograms of Copper equivalent per functional unit (Kg CU eq/FU) of the product under study (Huijbregts *et al.*, 2017; Allinson, 2013).

Abiotic Resource Depletion (Fossil Depletion)

According to studies by Allinson, abiotic resource depletion deals with reductions in available stocks of fossil fuels, metal ores and other material shortages on the global markets as result of increased resource exploration and extraction. This impact category can be subdivided into abiotic depletion elements whos' characterisation factor is expressed in kilograms of antimony equivalents per functional unit (Kg Sb eq / FU) and abiotic depletion fossil whos' characterisation factor is defined as kilograms of fossil fuel per functional unit

(Kg Oil eq/ FU) or in units of energy mega joules equivalent per functional Unit (MJ) of the product under study (Huijbregts *et al.*, 2017; Allinson, 2013).

3.6. Limitations of the research

The most significant limitations of this research are related to the hydrogen conversion technologies, and they include the following:

- The Hydrogen conversion systems/electrolysers are limited to a power 50 kW system with assumed 30 start-ups per year. Data for MW scale electrolysers was not comprehensive enough for this study. Given that the EU hydrogen strategy is anticipated to have a decentralised network of hydrogen valleys, these small modular electrolysers were deemed fit for this study.
- Maximum production capacity of these conversion technologies is 1.46KgH2/h with an average load of 30% per year.
- This study is limited to the operational stage of these electrolyser systems and does not consider the end-of-life stage of these technologies.
- Only two conversion technologies are included in this study (AWE and PEME).
- The operational life of these technologies is assumed to be 20 years with cell stacks lasting 7-10 years.
- The spare parts consumed per year by these technologies are included in the material consumed during the construction phase of the electrolysers.

Limitations to energy systems

- Only two Renewable electricity sources are considered for this study i.e wind electricity sources and solar PV electricity.
- The electricity produced by each renewable electricity is assumed to be transmitted to the renewable electricity grid mix which into fed the hydrogen conversion technologies.
- The models used do not include energy used for component manufacturing, transportation and decommissioning.
- All data used for modelling the wind plant and solar PV plant is represented in material input per unit of electricity output for each source of renewable electricity.

- The assumption is that all electricity used for hydrogen conversion technologies is supplied solely by the renewable electricity sources otherwise, the colour code of hydrogen produced changes from green hydrogen.
- Modelling does not include or account for electricity produced by renewable sources for other purposes other than hydrogen production.
- For Wind plant design and modelling, only 4 types of wind technologies have been included for the study as referred to table 1 in section 3.2.1 above. This is because there are many studies that predict these specific types of technology to be the leading technologies for future wind plants/farms. Furthermore, these technology types account for both on-shore wind technologies and off-shore wind technologies.
- For solar PV plant, only one PV technology was considered for this study due to its superiority in the PV market with a market share of over 95%. However, there some forecasts of some changes in the market share of these technologies much as these changes are still lucking concrete data to back their analysis.

3.7. Data Collection

To address the uncertainties around green hydrogen production in Europe, there is a need to explore the material demand changes from electricity needs for hydrogen systems and technology specific material requirements for electrolytic hydrogen conversion technologies. The data collected takes a critical review of the raw material demand for structural and technology-specific materials for offshore wind, onshore wind and solar photovoltaic using 2018 as a base year to forecast the demand for these materials for these technologies in a 2030 scenario. Through this, material consumption profiles for each technology will be studied using the available literature from different authors interested in this area (Dias et. al, 2020).

The choices in data collection for these hydrogen production technologies needed to consider the variations in intra-technology alternatives, material intensity variations across different technologies and material efficiency due to the rapid innovation changes which contribute to reductions in material usage in these technologies per unit of service output. This study will use quantitative data from secondary literature sources to explore the market share of successful sub-technologies and asses the estimated amounts in tonnes of materials embedded per GW utility-scale of these renewable technologies' installed capacity. The data collected will be put through a brief evaluation on the completeness and consistency based on the study requirements presented in the table 6.

Table 6: data collection execution plan: sources: (Okunlola et al, 2022: ISO 14044: 2006b)

Parameter	*Description*	*Requirement*
Time-related coverage	Desired age of data and the minimum length of time over with data should be collected.	Data should represent data commercial technologies forecasted to play an essential role between 2018 and 2050. As specified in the EU hydrogen economy roadmap.
Geographical coverage	Area from which data for unit processes should be collected.(EU)	Data should be representative of the EU hydrogen technologies and renewable energy technologies.
Technology coverage	Technology mix.	Technologies under study are Renewable energies: Wind energy and Solar Energy, Hydrogen conversion technologies: AWE, PEME
Precision	Measure of the variability of the data values for each data category expressed. Should follow LCA guidelines under ISO 14044:2006	Should be able to cover 100% material intensity requirements for the technologies under study
Completeness	Assessment of whether all relevant input and output data are included for a unit process data set.	Specific datasets will be compared with literature data and databases, where applicable.
Representativeness	Degree to which the data represents the identified time-related, geographicallocation	The data should fulfil the defined time-related, geographical and technological scope.
Consistency	The study methodology has been consistent with different components of the analysis.	The study methodology will be applied to all the components of the analysis.
Reproducibility	Assessment of the methodology and data, and whether an independent practitioner can reproduce the results.	The information about the methodology and the data values should allow an independent practitioner to reproduce the results reported in the study.
Sources of the data	Secondary literature, or Primary literature	Data will be derived from credible sources and databases.

4. Life Cycle Inventory Analysis

The ISO 14044: 2006 defines Life cycle inventory analysis as “a phase of life cycle assessment that involves compilation and quantifying inputs and outputs for a product under study throughout its entire life cycle”. This section details the different processes within the boundary system of the product understudy. The data collected was secondary data from previous LCA, company publications and other literature sources. The inventory data for the renewable energy systems and hydrogen conversion technologies is presented alongside this study's main assumptions and research goals.

4.1. Data for Renewable energy systems

Data for renewable energy systems is taken from Dias et al, (2020) where the authors provided insights and future demand estimates for raw materials necessary for both wind and solar PV plant development under various decarbonisation scenarios for both the EU market and the global markets. The Authors assessed different policy-relevant electricity generations for the EU and the rest of the world on an account of these four major factors: Power generation capacities, plant life time, sub-technology market share and material intensity (Dias et al, 2020). The authors used these factors to model scenarios to be used in the assessment which included, baseline scenario also referred to as medium demand scenario (MDS) and the other two were modelled as extreme scenarios where material demand is assumed to be high (High Demand Scenario-HDS) or low (*low Demand Scenario-LDS*) (Dias et al, 2020). This study adopted data for low demand scenario and the material intensity details of specific mass consumption of raw materials per unit of installed capacity of these technologies, as explained in detail in the next section.

4.1.1. **Data for Wind Technologies**

The data presented in the table below represents 4 wind turbine technologies (see table 7) for both onshore and offshore power generation activities. These technologies include 2 gearbox mechanism wind turbines and 2 direct drive mechanisms however three other technologies were not included as they were assumed to be in technological phase out stage thus regarded not to be relevant for our study.

Material usage estimates in t/GW for different wind turbine types

Material	DD-EESG	DD-PMSG	GB-PMSG	GB-DFIG	Averages
Concrete	369000.00	243000.00	413000.00	355000.00	**345,000**
Steel	132000.00	119500.00	107000.00	113000.00	**117,875**
Polymers	4600.00	4600.00	4600.00	4600.00	**4,600**
Glass/carbon composites	8100.00	8100.00	8400.00	7700.00	**8,075**
Aluminium (Al)	700.00	500.00	1600.00	1400.00	**1,050**
Boron (B)	0.00	6.00	1.00	0.00	**2**
Chromium (Cr)	525.00	525.00	580.00	470.00	**525**
Copper (Cu)	5000.00	3000.00	950.00	1400.00	**2,588**
Dysprosium (Dy)	6.00	17.00	6.00	2.00	**8**
Iron (cast) (Fe)	20100.00	20100.00	20800.00	18000.00	**19,750**
Manganese (Mn)	790.00	790.00	800.00	780.00	**790**
Molybdenum (Mo)	109.00	109.00	119.00	99.00	**109**
Neodymium (Nd)	28.00	180.00	51.00	12.00	**68**
Nickel (Ni)	340.00	240.00	440.00	430.00	**363**
Praseodymium (Pr)	9.00	35.00	4.00	0.00	**12**
Terbium (Tb)	1.00	7.00	1.00	0.00	**2**
Zinc (Zn)	5500.00	5500.00	5500.00	5500.00	**5,500**

Table 7: Data for Wind plant. Source: (Dias et al., 2020)

The wind plant data includes all material consumption for building structural components and technology-specific materials. The wind plant process boundary is assumed to be at a point until electrical energy is supplied to the existing grid. However due to the limitation on geographical placement of wind farms in EU, the transmission infrastructure is not included in the process boundary for wind plant. Since its difficult to find data on future wind farm distribution by type, the average figures from the above wind technologies were used in wind plant process modelling in Gabi software.

The assumptions on classications material intensity usage in wind turbine is based of the critical supply chains, and abundance of the materials used (Dias et al., 2020). The material usage is classified in two groups i.e structural materials and technology-specific materials.

Structural materials make up 95% of mass of materials consumed in wind plant development and include concrete, steel, plastic, glass/carbon composites, aluminium, chromium, copper, iron, manganese, molybdenum, nickel and zinc (Dias et al., 2020). Technology-specific materials contribute approximately 5% of the mass and comprise boron, dysprosium, neodymium, praseodymium and terbium (Dias et al., 2020). The components of wind plant are grouped into central systems below:

Rotor system: This system is made of blades, hub, Pitch system and connected to the nacelle.

Nacelle system: comprised of both electrical components and mechanical components. These components include main shaft, gearbox/direct drive magnets, generator, and control systems (Garrett and Razdan, 2017). The nacelle system assembly is then connected to the tower.

Tower: This elevates the nacelle and rotor systems to the required heights above the ground. It’s mainly made of sizeable tubular steel or even sometimes concrete sections rooted on mostly concrete foundations.

Ground Systems: Ground systems comprise the foundation concrete for the site and sometimes in conventional wind firms includes transformers, switch gears and cables for transmission of the generated electricity(Garrett and Razdan, 2017: Materials Research Society, 2010).

Table 8: Wind plant mass distribution Source: (Dias et al., 2020)

Mass distribution of a wind plant

Part	% Share	Mass (t/GW)
Foundation	75.0	379,736.63
Turbine	23.00	116,452.57
site cables, switch gears, transformers	2	10,126.31
Total	**100.00**	**506,315.50**

Dias et al.(2020) describes that mass distribution of a typical wind plant, the authors approximate the greatest(75% of the total mass) portion of mass to be utilized by the foundation, site cabels and transformers account for less than 2 % of the mass as shown in the table 8 above.

Table 9 Wind turbine Mass distribution Source: (Dias et al., 2020)

Mass distribution of a turbine

Part	% Share	Mass (t/GW)
Tower	59	68,707.01
Nacelle	22	25,619.56
Rotor	19	22,125.99
Total	**100**	**116,452.57**

The table 9 above shows the mass distribution of a typical turbine. The percentages used were collected from Dias et al and other lituratures.

4.1.2. **Data for Solar PV plant**

The data used in modelling Solar PV plant was collected from secondary literature sources and presented in material intensity input per electricty unit output. As described in previous chapter, the current global Solar PV market is dominated by Wafer-based crystaline silicon (C-Si) technologies with a 95% market share compared to the other three solar PV technologies. Futhermore, C-Si technology has variations based on the panel cell thickness and these technological variants include Single-crystaline PV (made of one single grain of crystalline cells), Multi-crystaline Solar PV technology (made of more than one cell with a cell width of 1cm^2) (Dias et al., 2020). The data in the table below is taken from Dias et al., and it represents forcasted C-Si Solar PV material intensity used in manufacture of solar plant components from Silcon cells to the plant foundation for the EU region in 2030(Dias et al., 2020).

Table 10 Solar PV data Source: (Dias et al., 2020)

Material usage estimates in t/MW for C-Si Solar PV plant

Material	**t/MW**
concrete	56.2
Steel	62.8
Plastic	7.9
Glass	42.9
Aluminium	6.9
copper	4.3
Silicon	2
Silver	4

Manufacturing c-Si solar PV plant materials are also classified into technology-specific and general/structural materials. Technology-specific make up 3% of the total mass of the c-Si PV plant materials and are comprised of silicon silver. In comparison, the general/structural materials make up approximately 97% of the total c-Si PV plant include concrete, steel, plastic, glass, aluminium and copper.

4.2. Data for Hydrogen conversion Technologies/Electrolysers.

The data used in this section was obtained from secondary literature sources from different authors. Due to the senstivity of technical information, critical details of data protected by proprietary restrictions are not included. The data presented in the next section details all calculated material and energy inputs and out puts of a life cycle of electrolyser technology operational phase. This data covers only two electrolytic technologies which include AWE and PEME, all assumptions under these technology evaluation will be presented alongside the data.

4.2.1. Data for Alkaline Water Electrolyser (AWE).

AWE data was obtained from Mitja M. *et al. (2019),*it includes all material mass, energy inputs, outputs for the manufacturing and operational phases of a 50 kW alkaline electrolyser system with a production capacity of 1.46Kg H_2/h (Mitja M. *et al.*, 2019). The data includes all masses for auxilary systems(Sub-systems) as described in the table 11 below. The system is modeled as an outdoor AWE system that can fit in standard 20 feet container.

Table 11: Material distribution for AWE Source: (Mitja M. *et al.*, 2019)

Mass Distribution of An Alkaline Water Electrolyser

	Mass, Kg	**Mass, %**
Chiller	140.979	1.5
Closed Loop Cooling	624.9698	6.5
Control Panel	950	9.9
Demi Water Supply	146.5075	1.5
Gas Generation System – Cell Stack	1463.76	15.3
Hydrogen Purification System	303.4905	3.2
Instrument Air	95.5009	1.0
Nitrogen Panel	11.63204	0.1
Outdoor Housing	5811.717	60.9
Grand Total	9548.557	100.0

The data for material consumption used for manufacturing 50 kW alkaline electrolyser including spare parts consumed during 1 year of operation is presented in table 12 attached in the appendix of this document.

Assmuptions considered about modelling AWE system include the following,

- The AWE is modeled a single process in GaBi include all sub-systems i.e Chiller, Closed loop, Hydrogen purification system, instrument Air, Nitroge panel, Outdoor housing, stack/Gas generation system, demi water supply, control panel.
- The system annual operation capacity was left the same, 30% average load per year producing 1.46 kg H_2/h.
- The spare parts material consumed in one year of operation are included in the unit process
- An aqueous potassium hydroxide (KOH) and cooling water is assumed to have a concentration of 25% w/w. Furthermore, the KOH is assumed to have a 10 year usage time before it is replaced.
- End of life stage of the electrolyser is not included in the assessment, however the electrolyser lifetime is assumed to be 20 years.
- Critical materials like Transitional metals (TM) and Platinum group metals (PGM) are aggregated since there considered industry proprietory sensitive data. TM were modeled as titainum alloys while PGM are modelled as Platinum alloys.

4.2.2. Data for Proton Electrolyte Membrane Electrolyser(PEME)

The data for PEME was obtained from Mitja M. *et al.,(2019)* it includes all material usage for all sub-systems to produce hydrogen at the gate. The electrolyser model is an outdoor 50 kW with a production capacity of 1.46 kg H_2/h(Mitja M. *et al.*, 2019).

Table 12: Mass distribution in PEME Source: (Mitja M. *et al.*, 2019)

Mass Distribution of a Proton Electrolyte Membrane Electrolyser (PEME)

	Mass, Kg	**Mass, %**
Analyzer	13.47525	0.15
Chiller	140.979	1.60
Closed Loop Cooling	624.9698	7.08
Control Panel	1200	13.60
Demi Water Supply	41.31558	0.47
Gas Generation System	580.4279	6.58
Hydrogen Purification System	303.4905	3.44
Instrument Air	95.5009	1.08
Nitrogen Panel	11.63204	0.13
Outdoor Housing	5811.717	65.87
Grand Total	8823.508	100.00

The table 14 attached in the appedix 8.3 below presents the material input for PEME for both manufacturing and operational phases.

The assumptions include in PEME unit process modelling include the following;

- The PEME is modeled as a single unit process including all Subsystems necessary for producing hydrogen at the gate. The modeled subsystems include Analyser, Chiller, Hydrogen Purification, Instrument Air, Nitrogen panel, Outdoor Housing, Closed loop, and gas generation system (Stack).
- The PEME is a 50 kW system, with a production capacity of 1.46 kg H_2/h and the asssumed average load annually is 30%.
- Transitional metals were modeled as Titanium Alloys whereas PGM where modeled as Platinum Alloys.
- The System is assumed to be an outdoor electrolyser thus mass and paint of the outside chousing is included in the unit process boundary.
- The PEME foundation materials of the plant are not modeled due to lack of standardised data.

4.3. Input and Output flows

The input flows for green hydrogen production processes and output flows of baseline scenario, and scenario1 are presented in the table below.

Table 13: Life cycle Results of input and Output flows - first group of results. Source: calculated results from GaBi software

		Baseline Scenario		***Scenario 1***	
	Units	**PEME**	**AWE**	**PEME**	**AWE**
Inputs					
Material Resources	kg	5.39E+17	1.65E+17	5.74E+17	1.92E+17
Energy Resources	kg	7.43E+13	5.74E+13	8.14E+13	6.28E+13
Electricity from wind plant	TWh	394.45	305.5	591.667	458.33
Electricity from Solar PV	TWh	394.45	305.5	197.5	152.5
Output					
Total Emissions		2.14E+17	1.65E+17	2.49E+17	1.92E+17
H2	***kg***	***1.00E+10***	***1.00E+10***	***1.00E+10***	***1.00E+10***
Emissions to air	kg	2.60E+15	2.05E+15	2.98E+15	2.30E+15
emissions to freshwater	kg	2.09E+17	5.19E+11	2.43E+17	1.88E+17
emissions to seawater	kg	5.46E+14	4.22E+14	6.30E+14	4.86E+14

The input flows were computed based on mass weight of the consumed resources to produce the desired quantities of green hydrogen. However input flows of electricity were computed from energy inputs in TWh of electricity from renewable sources as shown in the table 15 above.

Table 14; Life cycle Results of input and Output flows - Second group of results- source calculated from Gabi

		Scenario 2			***Scenario 3***		
	Units	**PEME**	**AWE**	**Total Sc2**	**PEME**	**AWE**	**Total Sc3**
Inputs							
Material Resources	kg	1.62E+17	1.16E+17	**2.78E+17**	3.23E+17	6.61E+16	**3.89E+17**
Energy Resources	kg	2.23E+13	4.02E+13	**6.25E+13**	4.46E+13	2.30E+13	**6.76E+13**
Electricity from wind plant	TWh	118.611	213.611	**332**	236.944	121.944	**359**
Electricity from Solar PV	TWh	118.611	213.611	**332**	236.944	121.944	**359**
Output							
Total Emissions		6.41E+16	1.15E+17	**1.79E+17**	1.28E+17	6.60E+16	**1.94E+17**
H2	kg	3.00E+09	7.00E+09	**1.00E+10**	6.00E+09	4.00E+09	**1.00E+10**
Emissions to air	kg	7.96E+14	1.43E+15	**2.23E+15**	2.96E+09	8.20E+14	**8.20E+14**
emissions to freshwater	kg	6.27E+16	1.13E+17	**1.76E+17**	1.25E+17	6.45E+16	**1.90E+17**
emissions to seawater	kg	1.64E+14	2.95E+14	**4.59E+14**	3.28E+14	1.69E+14	**4.97E+14**

Table 16 presents inputs and output flow for scenario 2 and 3 for green hydrogen production.

5. Life cycle Impact Assessment (LCIA)

The ISO 14044:2006 emphasizes the importance of tailoring this phase of LCIA to previous stages of the study to achieve the stated goals and scope. This chapter presents the results of the analyses modelled under different Scenarios as briefly described in section 3.2. The results obtained by simulation of these scenarios using GaBi software and the model chosen for this study was ReCiPe 2016. The model ReCiPe 2016 employs methodology that study's 18 mid-point impact categories linked to damage pathways and how they affect the 3 end-point protection areas as shown in the table below. For our study 8 impact categories were selected to be studied, under different scenarios to evaluate the impact of producing 10 million tonnes of hydrogen. The authors Huijbregts *et al.*, (2017) describe the operationalisation of the ReCiPe216 methodology and implementation of characterisation factors at different levels of national scale or continental scale of assessments (Huijbregts *et al.*, 2017).

The difference between mid-point impact categories and endpoint impact categories is that midpoint impact categories focus on a single environmental problem for instance in climate change. Whereas endpoint impact categories indicators reveal the environmental impact of systems/product under study on the areas of protection by aggregating the results into 3 higher levels i.e 1. Effect on Human Health, 2. Effect on Biodiversity/ecosystems and 3. Effect on resource scarcity (Iv and Fiche, 2021).

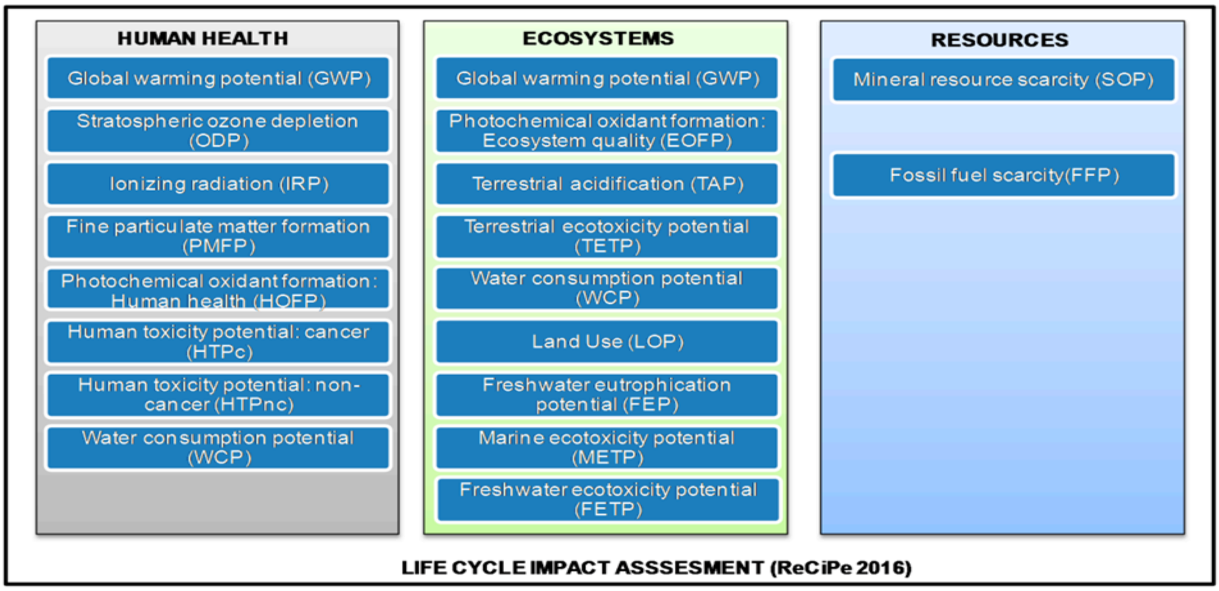


Figure 10 Source: (Mehmeti et al., 2018)

5.1. Results

The results are grouped in two groups i.e first grouped results are results from the baseline scenario and scenario 1. Second group is comprised of results for scenarios 2 and 3. Results from the first group are used to evaluate the impact of renewable energy mix on the whole system of producing vast hydrogen quantities whereas group two results are used to compare the most environmentally friendly electrolyser technology between AWE and PEME.

Note. Ten million tonnes of hydrogen are produced under scenarios 2 & 3. Under Scenario 2, AWE produces 70% of the required hydrogen while PEME produces the rest 30%. Similar conditions under Scenario 3, however, this time, PEME produces 60% of the required quantities while AWE produces the remaining 40%.

5.1.1. **Input and output flows of material resources and emissions**

Group 1 results in table 15: Baseline Scenario demonstrated the superiority of AWE in producing desired quantities of hydrogen compared to the PEME system. This is evident with AWE having 30% less electricity consumption, approximately 23% less resource input and 22.5% less emission output than PEME system. The PEME systems has greater contribution to the emissions to freshwater with 2.09 x 10^{17} kgs more emissions output when compared to AWE system.Scenario 1 tested the lucrativines of using 75% electricty from wind energy and 25% from solar energy based on the profile of renewable energy abundance of EU region. The results revealed that using wind energy for these systems led to 13% increase in emission output and a 9% increase in material resource input for both AWE and PEME systems. This can further be attributed to the difference in total plant material use per MW out put scale where wind plant total mass input / mw output is at 506 t/MW which is much bigger than the solar PV plant total material usage which is 186 t/MW. It should be noted that for an average wind plant 75% of the total material input are structural component materials whereas for solar PV plant structural materials constitute to over 96.5% of the total solar PV plant.

Furthermore, the emissions to freshwater from the AWE system were also able to increase by 1.88 x 10^{17}, indicating more than 1000% increase in emission from the whole AWE system.

Group 2 results table 16: The results in scenarios 2 and 3 were conducted on the assumption of producing different quantities that amount to 10million tonnes of green hydrogen.

Scenario 2 revealed the best reductions in electricity consumption, resource input and emission footprint of producing hydrogen compared to all other 3 scenarios. To be more specific, total emission outflows decreased by 17%, electricity consumption decreased by 16%, and material resource inputs were also able to decrease by 19% when compared to the results from the baseline scenario. Scenario 3 was able to reveal reduction however these reductions minimal when compared to Scenario 2.

5.1.2. Hydrogen Production under different renewable energy mix

The baseline Scenario, and Scenario 1 were carried out to establish the most favourable renewable energy technology that has least environmental footprint when producing 10 million tonnes of hydrogen. The results presented in figure{11} revealed that increasing wind energy supply for hydrogen production increases emission footprint for both hydrogen conversion technologies as can be observed under scenario 1 where wind energy was the source for 75% of the electricity needed for hydrogen production.

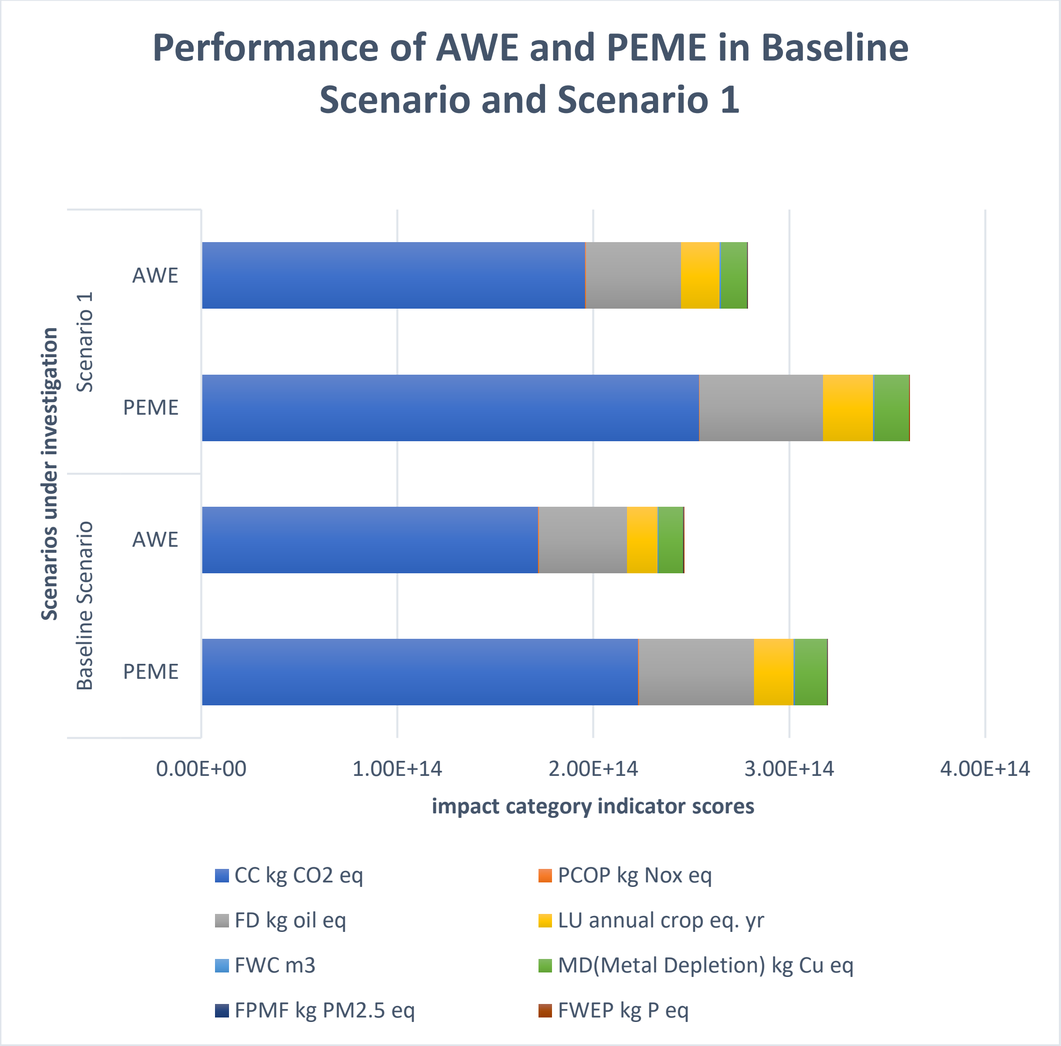


Figure 11: Life cycle result of producing 10 million tonnes of green hydrogen

The emission footprint of hydrogen production from any of these technologies influence strongly impact categories of CC, FD, LU and MD when compared the other four impact categories under study. The reasons for wind electricity having higher emission output can be attributed to the positive correlation between wind plant mass input and electricity production, having higher number of components for technology specific components requirement when compared to solar PV plant much as the efficiency of the wind plant is greater than the efficiency of solar PV in EU region.

The results reveal that the increase in share of electricity from for hydrogen production in scenario 1 results to an increase in emission footprint for both technologies AWE and PEME.

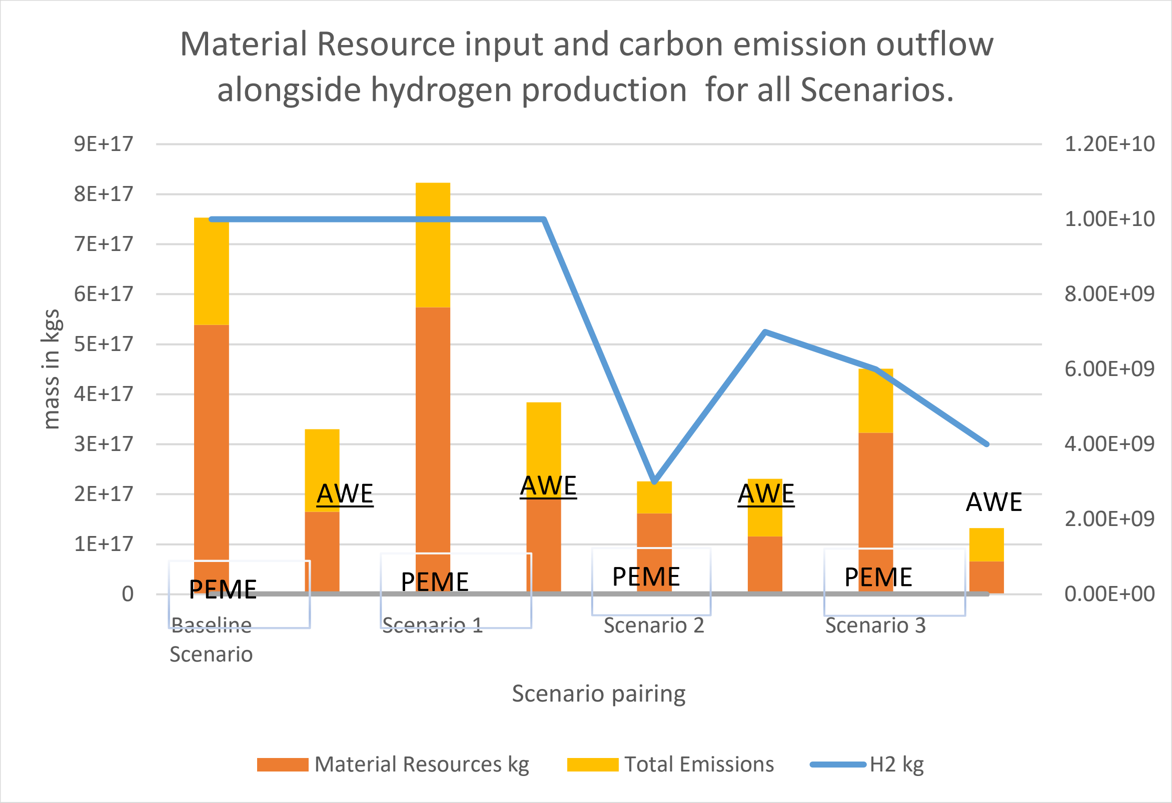


Figure 12: LCI results on input and output flows

5.1.3. **Comparison of hydrogen conversion Technologies.**

It is apparent from figure 12 that AWE under baseline line Scenario has the lower carbon emission footprint in producing the required hydrogen quantities. The superiority of AWE hydrogen production can be observed from the comparisons of Scenario 2 and 3. In Scenario 2, 7 million tonnes of hydrogen are being produced by AWE . In contrast, the rest is produced using PEME using 50/50 renewable electricity from wind and solar PV plants. As a result they are significant reductions in emission footprint of producing the targeted hydrogen quantities as can be observed in figure12. AWE has lower carbon footprint can be attributed to its lower electricity consumption compared to PEME while producing the same quantities of hydrogen. This is evident by material input results under baseline Scenario where to total electricity input for a PEME need to produce 10 million tonnes of hydrogen was 788.9 TWh whereas for producing the same quantities using AWE required 611 TWh of electricity which is approximately 28.9% less than what is needed by the later system.

To understand which scenario has the lowest environmental burdens, the results under baseline and Scenario 1 were aggregated to emissions of producing 10million tonnes. Whereas the results in scenarios 2 and 3 were summed up to get the total emission footprint of producing 10 million tonnes of hydrogen to facilitate investigations in which technological combinations have significantly better results as shown in the figure 13.

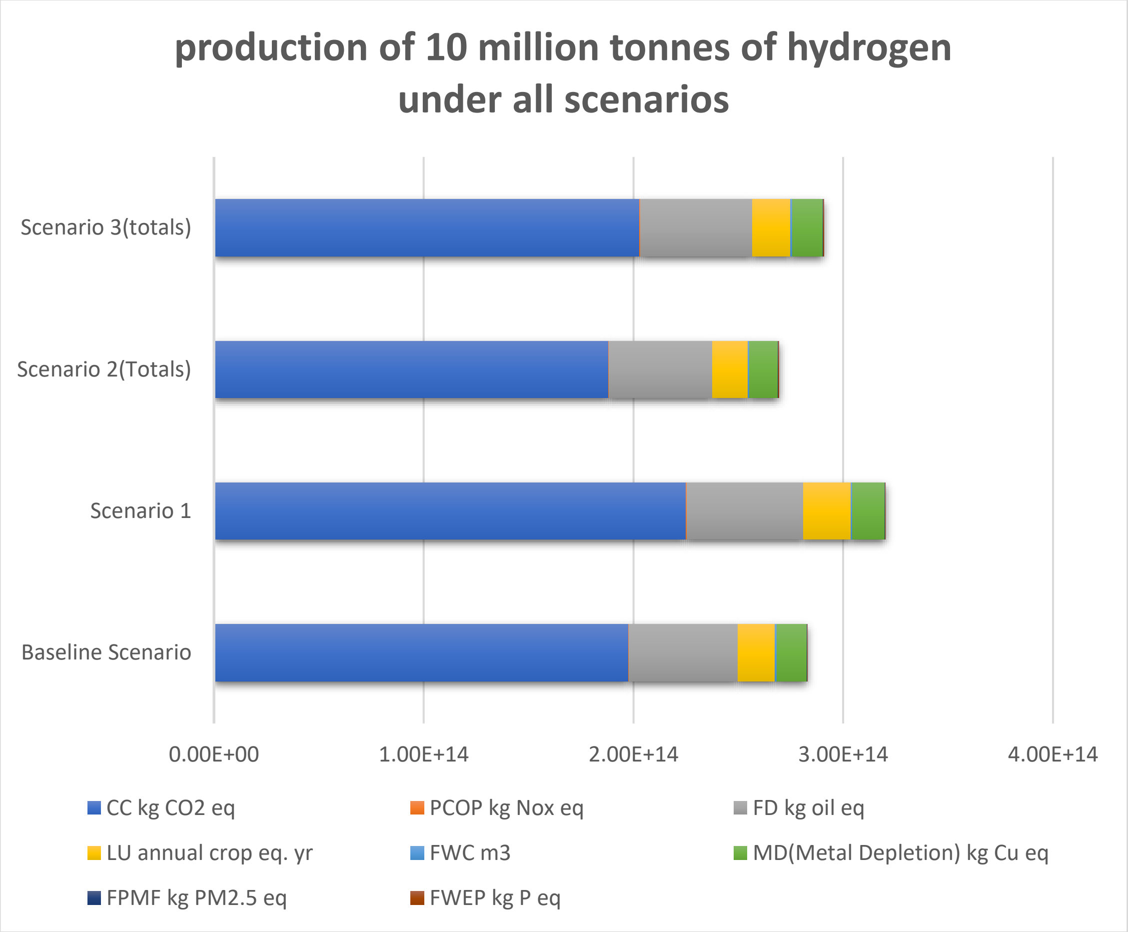


Figure 13: life cycle results of all scenarios

6. Life Cycle Interpretation

The results of producing 10milion tonnes of hydrogen have been presented in the previous chapter and the interpretation will be carried out in-accordance with the goals and objectives of the study. The results reveal the following:

- Production of huge quantities of hydrogen is associated with huge material inputs, especially when produced using Wind Electricity. As seen in figures {13, 12} increase of wind electricity share for hydrogen production resulted in an increase in both input and output flows and emission footprint for both AWE and PEME technologies. This increase can be attributed to the fact that a wind plant's material mass input per MW output is 60% more than the mass input for a solar PV plant.
- AWE has the least environmental burden in producing huge quantities of hydrogen, as observed in all scenarios. The technology combination in Scenario 2 has the least environmental burdens because 70% of the required hydrogen is produced using AWE. Since AWE has a lower electricity input, this results in a reduction in energy needs and emission footprint. Furthermore, baseline scenario has demonstrated that producing 10million tonnes of hydrogen using AWE is not only least burdensome environmentally, but also has the least electricity (lower by 18%) input, least emissions to freshwater and thus more sustainable in this study.
- The results revealed that production of 10miilion tonnes of hydrogen requires much electricity, the effects of that is that many renewable electricity plants will need rapid growth strategy to supply the electricity needs of these hydrogen systems. However, this raises concerns on the environmental impacts of scaling up these renewable technologies since most of them are tired resource depletion especially for critical materials for technology specific components of these renewable technologies. Furthermore, the results revealed emission footprint of producing 10 million tonnes of hydrogen contributes greatly to these damage pathways/impact categories; CC, MD, LU, PCOP.

6.1. Discussion

Several studies have documented the life cycle assessment of hydrogen production, however few of them highlight the impacts of mass producing it on environmental ecosystems. This study set out to determine the life cycle assessment of producing 10milliion tonnes of hydrogen as anticipated by the EU hydrogen roadmap in 2030. The roadmap aims to use mainly renewable electricity sources for this target which means increase renewable energy deployment to meet the future electricity energy needs. This creates uncertainty in the raw material markets for these renewable energy technologies components markets since most of these materials are imported and thus can be exposed to vulnerabilities in the supply chain systems of these markets. These vulnerabilities arise from increased demand for large quantities of components and raw materials (primarily metals) to produce and install wind turbines and PV systems. Bearing in mind the requirements to physically extract the necessary mineral resources used to manufacture these components creates environmental concerns on the associated costs of processing, embodied emissions, and energy use in the manufacturing phases of these components. Furthermore, constraints from locking up many of these resources in wind and solar energy systems structures for the anticipated operational times, may result to shortages in material flows to other sectors of the economy that use the same materials. It should also be noted that there might be a possibility that these materials are finite or assuming they are not, there are associated environmental cost implications of opening new deposits inform of increased energy expenditure to extract lower quality mineral ores, emissions to land/sea and habitat degradation thus necessitating the need for curtailment of these resource.

6.2. Conclusions

The results reveal that the environmental footprint of producing green hydrogen is more sustainable if hydrogen production is carried out using AWE supplied by solar PV electricity. This is because this technology combination has the minimal material input requirement, least energy consumption and least emission footprint compared to available alternative technologies of PEME and wind electricity. However, since the EU has low irradiation levels, choices should be made on having hydrogen production in areas Like North Africa with higher irradiation levels. Furthermore, the current electrolytic technologies still have high energy consumption therefore more improvement is required to improve the energy consumption of these technologies.

This thesis's pragmatism is trying to shed light on why renewable energy systems sometimes do not entirely represent sustainable choices. The sustainability issues of producing these quantities of hydrogen are nested in the challenges of renewable technologies of wind and solar PV power generation systems. The variable nature of these technologies results to low energy densities. Thus , increasing electricity output from these sources means increasing deployment, leading to a rise in material demand and land area requirements (Harjanne and Korhonen, 2019). This can also be seen from the study's results whereby the average electricity needed for producing 10 million tonnes of hydrogen is 697 TWh, which is quite a huge energy quantity. This subsequently creates a need to mine high volumes of potentially scares materials such as: tellurium and indium for solar PV systems, rare earth metals like dysprosium, neodymium, praseodymium and terbium used in permanent magnets for wind plants whereas for hydrogen conversion technologies, critical materials for instance transitional metals needed for electrolysers like platinum, iridium, scandium, titanium and yttrium (Iain Cox, 2017; Kiemel and Smolinka, 2021; Okunlola et al, 2022).

Uncertainties a rise from the bottlenecks of supply chains of these materials. The rise in material demand for these technologies does not correspond to the material supply chains of these materials. The markets for these critical materials will face shortages arising for competition for resources use by other sectors like electronics industry, electric vehicle manufacturers that use the same materials (Iain Cox, 2017). Furthermore, some of these materials are located in limited regions for instance rare earth metals used predominantly in making permanent magnets (neodymium and dysprosium) 95% of deposits and mines are located in China(Dias,2020).

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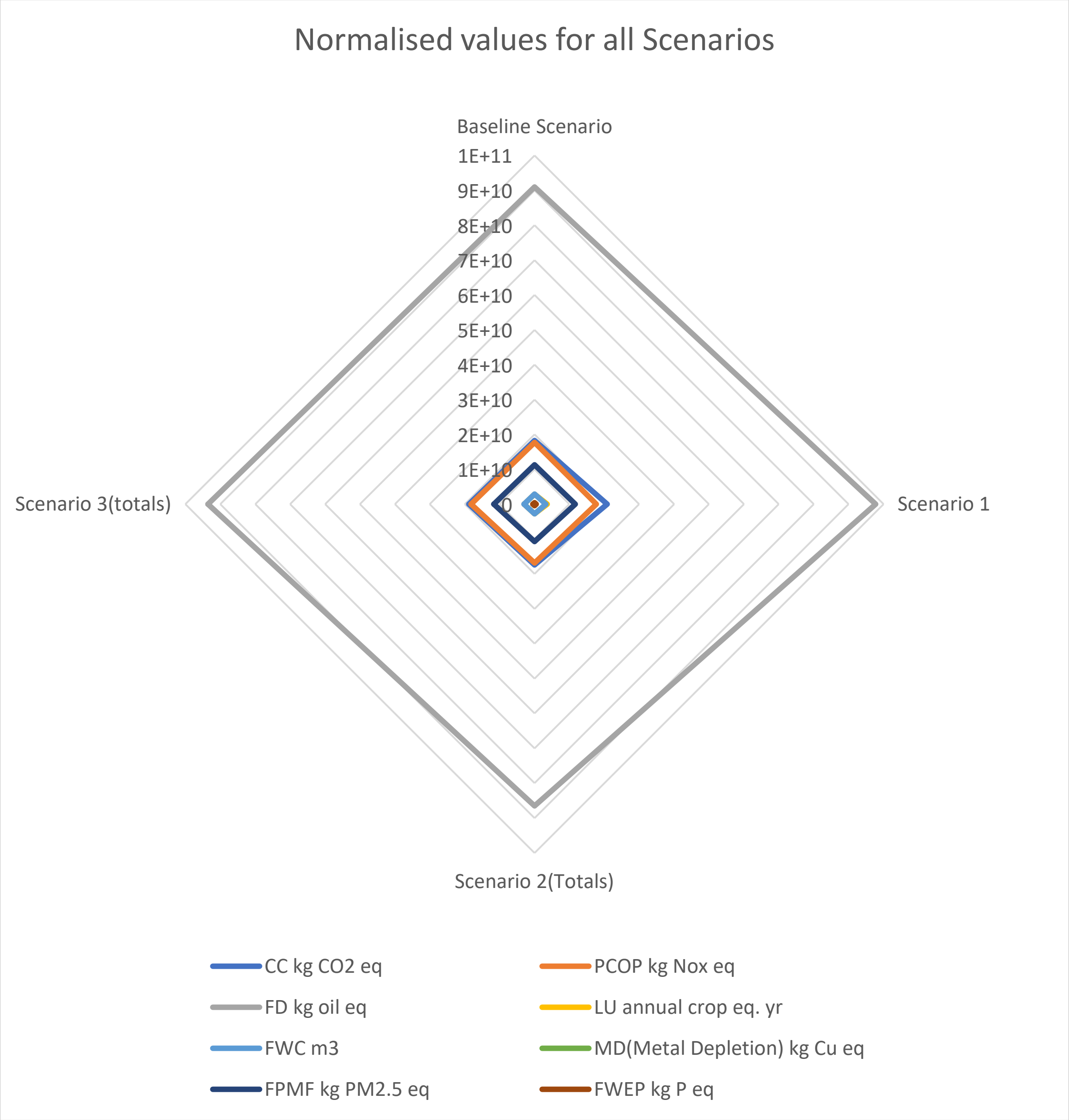
8. Appendix

8.1. Normalized values.



8.2. Table Material usage bye AWE Source: (Mitja M. *et al.*, 2019)

Material Usage by an Alkaline Water Electrolyser including spare parts consumed in 1 year

Material	**Description Of Materials**	**Mass Input, Kg**	**Total Share/Material Type, Kg**	**%Share**
STEEL	carbon steel, stainless steel, cast iron	2698.05	2698.05	27.50
CARBON	Black carbon	3.53	3.53	0.04
NON-FERROUS MATERIALS	Aluminium	267.4	849.32	8.66
	TM	577.99		
	Brass	3.7		
	TM	0.18		
	Bronze	0.05		
PGM PLASTICS TM METALS	copolymer	46.2	340.937	3.47
	Polyester	25.43		
	Thermoplastics	215.05		
	PVC	26.96		
	Polypropylene	24.64		
	EPDM	0.05		
	NBR	0.16		
	Polyurethane	1.12		
	ABS	0.83		
	Polyamide (PA)	0.35		
	PGM	0.147		
OTHERS	Glass	1.06	5920.69	60.34
	Ceramic	31.35		
	Silica	53.8		
	OH steel for container	5627.1		
	Fluorescent lamp	42.32		
	exterior paint	165.06		
TOTAL		9812.527	9812.527	100
Consumables	**Value**	**Unit**	**Value Per Year**	**Unit**
Demi Water	17.88	l tap water/kg H2	3430171.072 demi	kg
Nitrogen - Gaseous	1.5	Nm³/ start-up	1333.431 Nitrogen	kg
Nitrogen - Gaseous	0.18	Nm³/h standby		
Glycol first Fill	222	kg		
KOH Consumption Test Stand + Unit+ First Fill	746.7 (4.7+742)	kg		
Energy Needed for Operation	**1 Year**	**Unit**	**Percentage**	
Electricity Control Standby	5874.456	kWh	100% heat	
Electricity Control Production	4604256	kWh	100 % heat	
Electricity Power Production	18800712	kWh	partly heat	

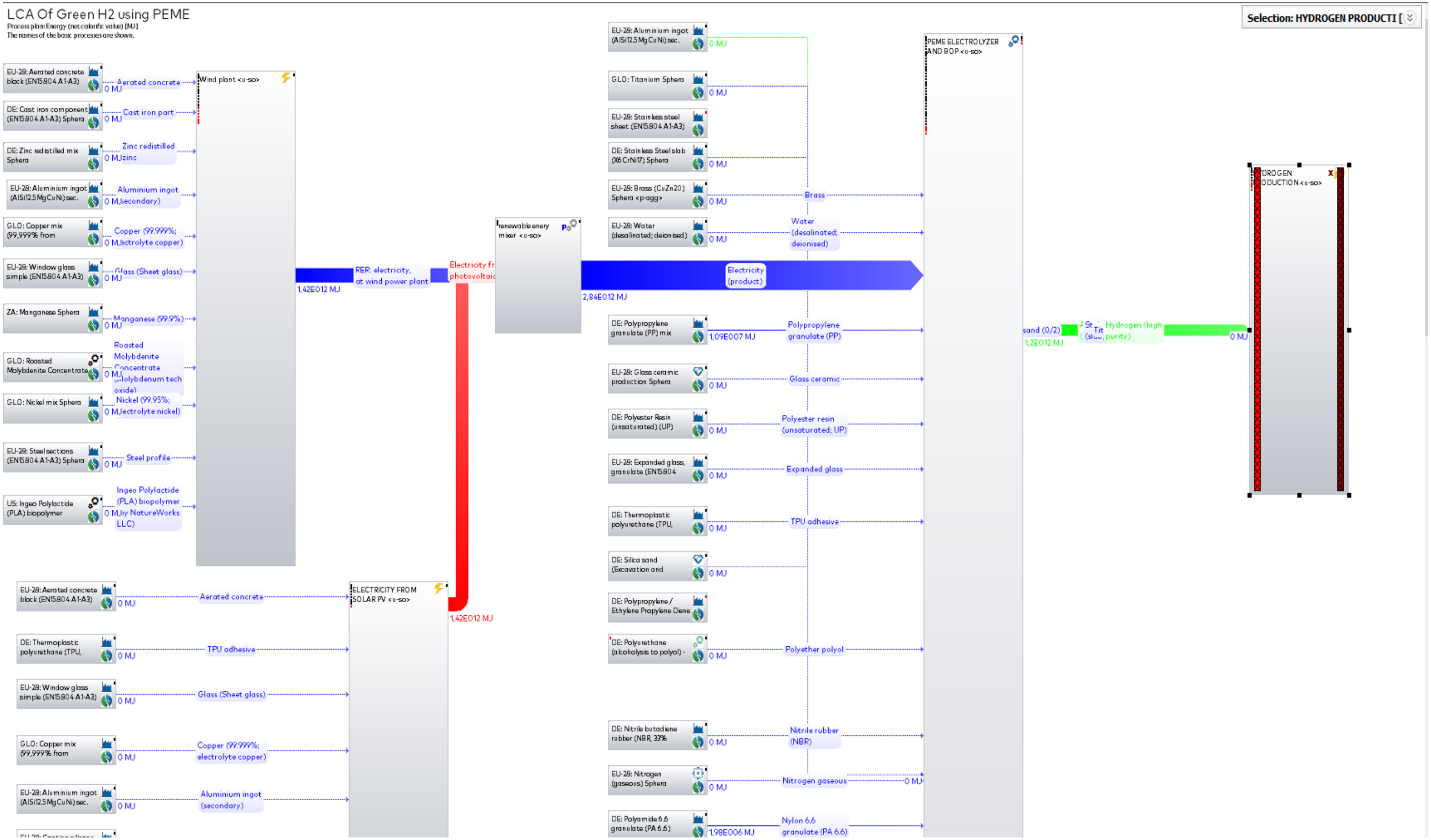
8.3. Table 15: Material usage for PEME Source: (Mitja M. *et al.*, 2019)

***Material Usage by* A *Proton Electrolyte Membrane* Electrolyser Including Spare Parts Consumed In 1 Year**

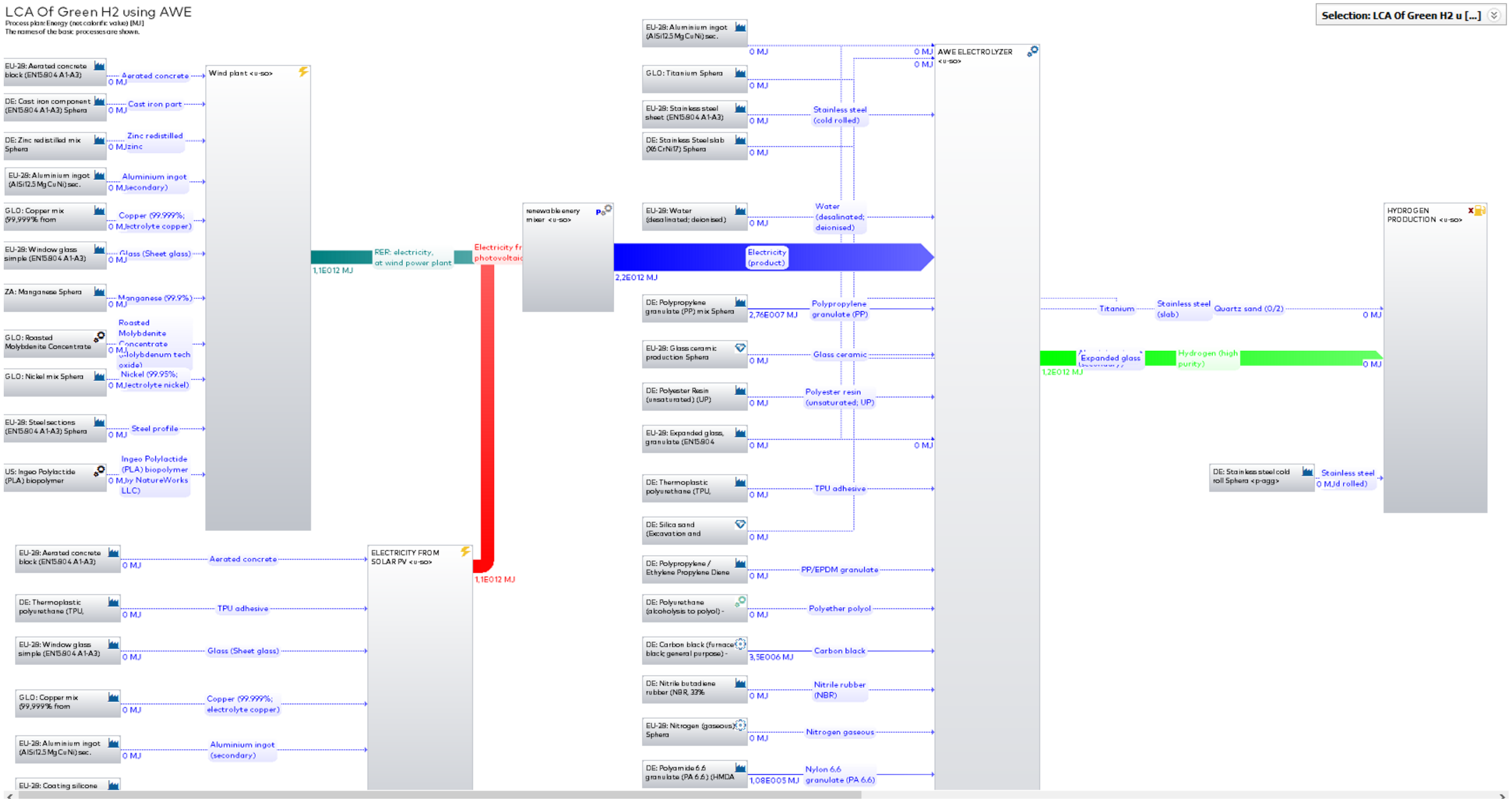
	Description Of Materials	**Mass Input, Kg**	**Total Share/Material Type, Kg**	**%Share**
Steel	Carbon Steel, Stainless Steel, Cast Iron, Sheets, Electro Steel	2167.01	2167.01	24.11
Nonferrous Materials	Aluminium	265.34	850.96	9.47
	TM	567.95		
	Brass	16.14		
	TM	0.18		
	Bronze	1.35		
Plastics	Polypropylene	9.74	140.59	1.56
	Polyester	0.94		
	Polyethylene	0.16		
	Thermoplastics	103.75		
	PVC	10.65		
	PEEK	11.15		
	Polyamide	2.38		
	EPDM	0.18		
	ABS	0.42		
	Polyurethane	1.12		
	NBR	0.11		
PGM	PGM	0.10	0.10	
TM	TM	36.65	36.65	0.41
Others	Silica	32.70	5792.94	64.45
	Ceramics	31.35		
	Glass	0.65		
	PFTE	0.46		
	PVDF	0.30		
	Steel Container	5520.10		
	Paint	165.06		
	Fluorescent Lamp	42.32		
Total		8988.248374	8988.25	100.00
Consumables	**Value**	**Unit**	**Value Per Year**	**Unit2**
Demi Water	11.92	L Tap Water/Kg H2	4573560.96 Demi	Kg
Nitrogen - Gaseous	1.5	Nm³/ Start-Up	1333.431 Nitrogen	Kg

Nitrogen - Gaseous	0.18	Nm^3/H Standby	
Glycol	222	Kg	
Energy Needed* For *Operation	**1 Year**	**Unit**	**Percentage**
Electricity Control Standby	9198	Kwh	100% Heat
Electricity Control Production	10743264	Kwh	100 % Heat
Electricity Power Production	19568088	Kwh	Partly Heat

8.4. PEME hydrogen System Modelling in GaBi



8.5. Alkaline Water Electrolyser Modelling in GaBi



8.6. Global Normalization reference Values

	Midpoint			
	unit	**World**		
Human health		**Individualistic**	**Hierarchic**	**Egalitarian**
Global Warming - Human health	kg CO2 eq. per person in 2010	1.08E+04	7.99E+03	5.80E+03
Stratospheric ozone depletion - Human health	kg CFC11 eq. per person in 2010	6.53E-02	6.00E-02	7.04E-02
Ionzing Radiation - Human health	kBq Co-60 emitted to air eq. per person in 2010	4.70E+02	4.80E+02	6.99E+02
Fine particulate matter formation - Human health	kg PM2.5 eq. per person in 2010	1.60E+01	2.56E+01	2.56E+01
Photochemical ozone formation - Human health	kg NOx eq. per person in 2010	2.06E+01	2.06E+01	2.06E+01
Toxicity - Human health (cancer)	kg 1,4-DCB emitted to urban air eq. per person in 2010	9.90E-01	1.03E+01	2.95E+02
Toxicity - Human health (non-cancer)	kg 1,4-DCB emitted to urban air eq. per person in 2010	5.09E+01	3.13E+04	2.22E+06
Water consumption - human health	m3 consumed per person in 2010	2.67E+02	2.67E+02	2.67E+02
Terrestrial ecosystems				
Global Warming - Terrestrial ecosystems	kg CO2 eq. per person in 2010	1.08E+04	7.99E+03	5.80E+03
Photochemical ozone formation - Terrestrial ecosystems	kg NOx eq. per person in 2010	1.77E+01	1.77E+01	1.77E+01
Acidification - Terrestrial ecosystems	kg SO2 eq. per person in 2010	4.10E+01	4.10E+01	4.10E+01
Toxicity - Terrestrial ecosystems	kg 1,4-DBC emitted to industrial soil eq. per person in 2010	6.73E+03	1.52E+04	1.64E+04
Water consumption - terrestrial ecosystems	m3 consumed per person in 2010	2.67E+02	2.67E+02	2.67E+02
Land use - occupation	m2·annual crop eq per person in 2010	6.17E+03	6.17E+03	6.17E+03
Freshwater ecosystems				

Global Warming - Freshwater ecosystems	kg CO2 eq. per person in 2010	1.08E+04	7.99E+03	5.80E+03
Eutrophication - Freshwater ecosystems	kg P to freshwater eq. per person in 2010	6.50E-01	6.50E-01	6.50E-01
Toxicity - Freshwater ecosystems	kg 1,4-DBC emitted to freshwater eq. per person in 2010	1.26E+01	2.52E+01	2.90E+02
Water consumption -aquatic ecosystems	m3 consumed per person in 2010	2.67E+02	2.67E+02	2.67E+02
Marine ecosystems				
Toxicity - Marine ecosystems	kg 1,4-DBC emitted to sea water eq. per person in 2010	8.80E+00	4.34E+01	2.46E+06
Eutrophication - marine ecosystems	kg N to marine water equivalents per person in 2010	4.62E+00	4.62E+00	4.62E+00
Resources				
Mineral resource scarcity	kg Cu-eq per person in 2010	1.93E+05	1.20E+05	1.20E+05
Fossil resource scarcity				
Crude oil	oil-eq per person in 2010	569.90	569.90	569.90
Natural gas	oil-eq per person in 2010	0.40	0.40	0.40
Hard coal	oil-eq per person in 2010	381.51	381.51	381.51
Brown coal	oil-eq per person in 2010	31.46	31.46	31.46
Peat	oil-eq per person in 2010			
World population				
6895889018				