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MASTER THESIS

Speciality : Economics, Policies, and Infrastructure of Green Hydrogen Technology

Topic :

PROJECT MANAGEMENT STRATEGIES TO ADDRESS ECONOMIC AND ENVIRONMENTAL RISKS AND UNCERTAINTIES OF GREEN HYDROGEN PRODUCTION FROM DIRECT AIR CAPTURE

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ABSTRACT

Green hydrogen is an energy carrier that plays an important role in the energy transition. The production of green hydrogen is hindered by either the availability of renewable energy resources or water. Usually places with high renewable energy potential have limited availability of water as seen in arid or semi-arid regions. Nevertheless, green hydrogen needs to be produced from renewable energy and water. To solve the problem, we introduce the direct-air-capture power to gas (DAC-PtG) technology, which uses a carbon dioxide recovery method, direct-air-capture (DAC) coupled with a polymer-exchange membrane (PEM) electrolyser to produce green hydrogen using renewable energy resource. DAC units are designed to capture carbon dioxide from the atmosphere, they are not point capture systems and can be installed in places different from where the CO_2 is being emitted. The DAC unit co-adsorbs water in the process of capturing CO_2 from the atmosphere, which is then fed into the PEM electrolyser for hydrogen production. The study highlights CO_2 output, electrolyser cost, the weighted average cost of capital, and the efficiency of the electrolyser as economic risk factors. Drivers of environmental impacts are also identified as, source of energy used, type of adsorbent material used for the DAC unit, the DAC plant material used for construction (if recycled plant material is used for construction the environmental footprint of the DAC unit reduces), and the type of electrolyser used. This paper proposes a project management strategy to manage both environmental and economic risks and uncertainties through technology complementarity, electrolyser cost savings methods, green purchasing techniques, identifying a project location with a strong legal framework, and studying the relationship between CO_2 captured, water adsorbed and relative humidity. The findings of this study can be used as a stepping stone to further research especially for the environmental impacts of the DAC-PtG technology. Most importantly, this study can be used as a theoretical reference when setting up DAC-PtG projects.

Keywords: Direct-air-capture power-to-gas (DAC-PtG); Carbon dioxide recovery; Polymer-exchange membrane electrolyser; Environmental impacts; Economic risks; Project management.

RÉSUMÉ

L'hydrogène vert est un vecteur énergétique qui joue un rôle important dans la transition énergétique. La production d'hydrogène vert est entravée par la disponibilité des ressources énergétiques renouvelables ou de l'eau. En général, les régions à fort potentiel en matière d'énergies renouvelables ont une disponibilité limitée en eau, comme c'est le cas dans les régions arides ou semi-arides. Néanmoins, l'hydrogène vert doit être produit à partir d'énergie renouvelable et d'eau. Pour résoudre ce problème, nous présentons la technologie DAC-PtG, qui utilise une méthode de récupération du dioxyde de carbone, la capture directe de l'air (DAC), couplée à un électrolyseur à membrane échangeuse de polymères (PEM) pour produire de l'hydrogène vert à partir d'une ressource énergétique renouvelable. Les unités DAC sont conçues pour capturer le dioxyde de carbone de l'atmosphère, ce ne sont pas des systèmes de capture ponctuelle et ils peuvent être installés dans des endroits différents de ceux où le CO_2 est émis. L'unité DAC co-adsorbe l'eau dans le processus de capture du CO_2 de l'atmosphère, l'eau adsorbée est ensuite introduite dans l'électrolyseur PEM pour la production d'hydrogène. L'étude met en évidence la production de CO_2, le coût de l'électrolyseur, le coût moyen pondéré du capital et l'efficacité de l'électrolyseur comme facteurs de risque économique, tout en identifiant les facteurs d'impact environnemental comme la source d'énergie utilisée, le type de matériau adsorbant utilisé pour l'unité DAC, le matériau végétal DAC utilisé pour la construction (si du matériau végétal recyclé est utilisé pour la construction, l'empreinte environnementale de l'unité DAC est réduite), et le type d'électrolyseur utilisé. Cet article propose une stratégie de gestion de projet pour gérer les risques et incertitudes environnementaux et économiques grâce à la complémentarité des technologies, aux méthodes de réduction des coûts de l'électrolyseur, aux techniques d'achat écologique, à l'identification d'un site de projet doté d'un cadre juridique solide et à l'étude de la relation entre le CO_2 capturé, l'eau adsorbée et l'humidité relative. Les résultats de cette étude peuvent servir de tremplin à d'autres recherches, en particulier sur les impacts environnementaux de la technologie DAC-PtG. Plus important encore, cette étude peut servir de référence théorique lors de la mise en place de projets DAC-PtG.

Mots-clés: Conversion directe de l'air en gaz (DAC-PtG); récupération du dioxyde de carbone; électrolyseur à membrane échangeuse de polymère; impacts environnementaux; risques économiques; gestion de projet.

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ACRONYMS AND ABBREVIATIONS

- BECCS: Bioenergy with carbon capture and sequestrations
- BOS: Balance of System
- CAPEX: Capital Expenditure
- CDR: Carbon Dioxide Recovery
- CO_2: Carbon Dioxide
- DAC: Direct Air Capture
- DAC-PtG: Direct Air Capture-Power to Gas
- H_2: Hydrogen
- IPCC: Intergovernmental Panel on Climate Change
- LCA: Life-Cycle Assessment
- LCI: Life-Cycle Inventory
- LCOD: Levelized Cost of Carbon Dioxide
- LCOE: Levelized Cost of Energy
- LCOH: Levelized Cost of Hydrogen
- LCOW: Levelized Cost of Water
- L-DAC: Liquid-Direct Air Capture
- OPEX: Operational Expenditure
- PEM: Polymer Exchange Membrane Electrolyser
- PMBOK: Project Management Book of Knowledge
- PTFE: Polytetrafluoroethylene
- PV: Photovoltaic
- S-DAC: Solid-Direct Air Capture
- SOEC: Solid Oxide Electrochemical Cell
- WACC: Weighted Average Cost of Capital

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1. INTRODUCTION

Fossil fuels have been the key catalyst of industrialisation in the 19th and 20th centuries. It led to remarkable economic and political growth, and increased technological advancement of many nations. This led to major human development within a short period. However, there is the problem of pollution of greenhouse gas emissions that comes with this development. Greenhouse gases emitted into the atmosphere are major disadvantages to the utilisation of fossil fuels. The increased emissions have reached a breaking point that the Earth cannot withstand without repercussions. The negative effects of greenhouse gas emissions can be seen in many forms but the key notable ones are linked to climate change and global warming, which are the key drivers of the energy transition (Kovač et al. 2021). The Paris Agreement which strengthens the United Nations Sustainable Development Goals was set to create a better world and undertake ambitious efforts to combat climate change. The importance of knowing how to harness renewable energy resources without endangering the lives of future generations cannot be overemphasised to achieve the Paris Agreement goals (Ueckerdt et al. 2021). According to the (International Renewable Energy Agency)to achieve the Paris Agreement targets, the global energy system must go through a rigorous transformation from fossil fuel-based energy systems to efficient low-carbon renewable energy systems.

It should also be noted that it will be impossible to eliminate all CO_2 emissions necessary for the future through emissions reduction from the power sector and energy-intensive industries. Emissions from other industries, including the transport sector would also need substantial CO_2 reductions. This can be achieved by improved energy efficiency and the use of low CO_2 energy carriers like hydrogen and electricity (Davison et al. 2009). The energy-intensive industry and freight transport are the major emission contributors which account for one-third of global-related energy (Figure 1). These economic sectors presently do not have any economic alternative to fossil fuels (IRENA (2018), *Hydrogen from renewable power: Technology outlook for the energy transition*, International Renewable Energy Agency).

Hydrogen produced from the electrolysis of water using renewable energy sources, is the most promising energy carrier to help in decarbonisation (Guo et al. 2022) (Kovač et al. 2021) also states that green hydrogen is the main goal of the hydrogen energy transition. Hydrogen can be used to supply energy for different applications ranging from buildings to the transport sector.

It can also be used for electricity generation when combined with fuel cells. Hydrogen plays an important role in energy storage of excess variable renewable energy. It helps in solving the problem of intermittent energy resources like solar and wind which are dependent on weather conditions and are not always available when needed.

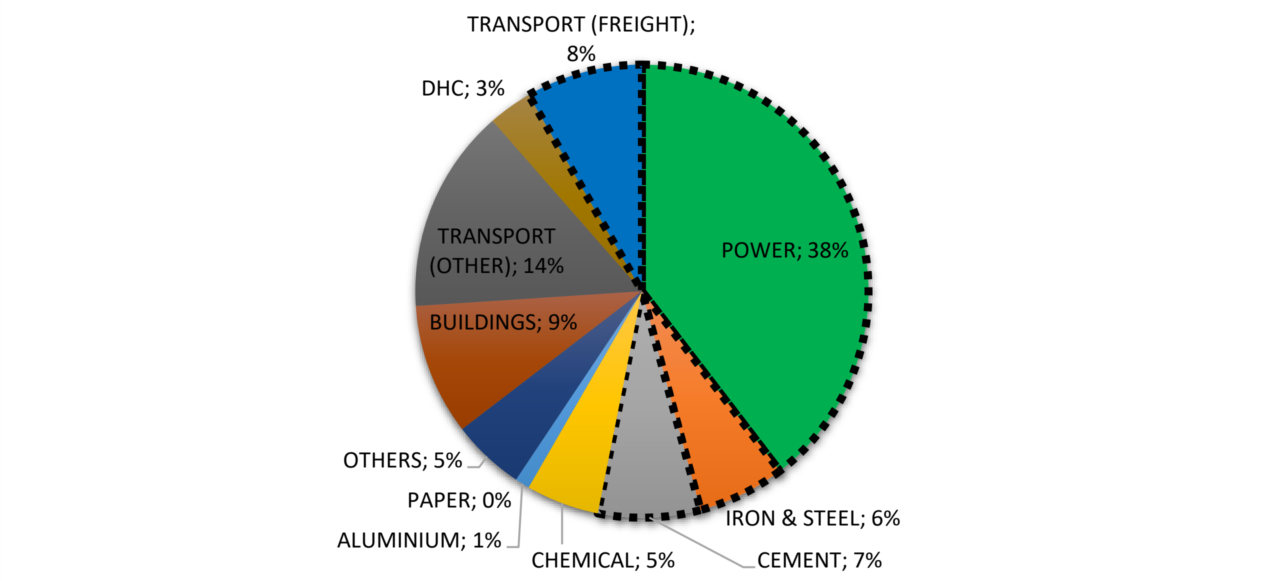


Figure 1 Breakdown of global energy-related CO_2 emissions by sector in 2015.
Source: (International Renewable Energy Agency)

The excess energy from variable renewable energy resources is used to produce hydrogen, which can later be converted back to electrical energy when needed, using fuel cells (Ayodele and Munda 2019).

According to (Kovač et al. 2021) after decades of research and development hydrogen can compete with other technologies in terms of efficiency in most applications and can offer more as a commodity. However, cost parity is yet to be achieved but learning from the development trend of other renewable energy sources technology and the increase in production scale, will drive production costs to be economically profitable.

A major challenge of hydrogen production is the scarcity of fresh water in locations with very high renewable energy potentials. More than one-third of the earth's land surface is arid or semi-arid, this covers approximately 20% of the world's population (Guo et al. 2022). Different studies have been carried out to mitigate the water shortage for electrolysis, but all faced various challenges. Direct saline splitting has the problem of effectively managing the chlorine by-product. The proton/anion exchange membrane which can be fed with high humidity vapor at the anode, produces low-purity hydrogen of less than 2%, and the photocatalytic water splitting also has very low solar to hydrogen efficiency (Guo et al. 2022).

Variable renewable energy sources can be of great use with flexible co-production plants for CO_2 capture and hydrogen storage, providing backup energy supplies and satisfying peak energy demands with low CO_2 emissions (Davison et al. 2009). According to the Intergovernmental Panel on Climate Change (IPCC), 2-20 gigatons of CO_2 should be removed from the atmosphere annually by 2050. Six major technical approaches exist for carbon removal and sequestering, namely: Coastal blue carbon, Terrestrial carbon removal and sequestration, Bioenergy with carbon capture and sequestrations (BECCS), Carbon mineralization, Geological sequestration, and Direct air capture (DAC) (Ozkan et al. 2022).

Out of the six major carbon recovery techniques, Direct Air Capture (DAC) is the most promising technology. Unlike the coastal blue carbon and the BECCS it does not compete for arable land and does not necessarily have to be near a coastal region (Ozkan et al. 2022). DACs can be operated anywhere renewable energy plants can be installed and contribute towards a fossil fuel-independent circular economy (Beuttler et al. 2019). They are also used in net zero emission scenarios to help balance emissions that are difficult to avoid (IEA (2022), *Direct Air Capture: A Key Technology to Net Zero*, International Energy Agency). CO_2 captured from the atmosphere can be used for the production of synthetic fuels for the hard to decarbonise industries. Absorption or adsorption methods are mostly used for CO_2 recovery by the most developed DAC technologies. Absorption by aqueous sorbents is the least expensive and allows for continuous operation but there is huge water loss during the process and it also requires high temperatures. Adsorption can operate in low temperatures (<100°C) and allow for water co-adsorption depending on weather conditions and air humidity (Deutz and Bardow 2021). According to (Guo et al. 2022) there is the existence of inexhaustible and sufficient moisture in the atmosphere; 12.9 trillion tons of water in the air at any moment, which is in equilibrium with the aqua-sphere. This gives rise to a new technology called direct air electrolysis which is the production of hydrogen via the electrolysis of moisture in the air (Guo et al. 2022).

The direct air electrolysis system can be inculcated within the solid sorbent DAC technology to give rise to DAC-Power to Gas (DAC-PtG) systems. The water separated from the CO_2 gas stream can be used as a feedstock for electrolysis (Drechsler and Agar 2020). The average relative humidity from the desert regions is 20-21%, the electrolyser for direct air electrolysis can operate steadily under a wide range of different relative humidity, as low as 4% while producing 95% Faradaic efficient pure hydrogen for 12 consecutive days without the addition of liquid water. (Guo et al. 2022).

This study identifies potential economic and environmental risks and uncertainties of the DAC-PtG technology through quantitative analysis and life-cycle assessment. The study goes further to design a project management strategy to manage the identified risks and uncertainties. The project management strategy can be used as a theoretical reference for future DAC-PtG projects.

1.1.PROBLEM STATEMENT

The scarcity of fresh water in areas with high potential for renewable energy resources hinders the production of green hydrogen, which is essential in the energy transition. The DAC-PtG system is an inclusion of hydrogen production in the value chain of carbon dioxide recovery by DAC systems. The production of hydrogen from the DAC-PtG technology is still in its nascent stages and a clear project management strategy is not defined to address the potential economic and environmental risks and uncertainties. This study aims to answer the following research questions:

1. How would risks and uncertainties of green hydrogen production from DAC technology affect the project's financial sustainability?
2. What are the environmental and economic impacts of hydrogen produced from DAC in arid and semi-arid regions?
3. What is the most suitable project management strategy to address environmental and economic risks and uncertainties?

Answering these questions will help scientists, researchers, and entrepreneurs achieve the goal of hydrogen recovery through DAC systems whilst avoiding economic and environmental risks associated with the processes. This will increase the efficiency of the DAC-PtG systems.

1.2.OBJECTIVES

The main objective of this master thesis is to develop a project management Strategy that will address economic and environmental risks and uncertainties of green hydrogen produced from DAC systems. Other objectives that contribute towards the main objective are; to do a techno-economic assessment to evaluate the financial sustainability of green hydrogen produced from DAC; to identify/quantify economic and environmental uncertainties and risks of DAC systems and to also identify the strengths, weaknesses, opportunities and threats of the DAC technology for green hydrogen production.

A mixed methods research technique is used for this master thesis to obtain the best possible results. The master thesis will be structured to chronologically help the reader better understand the topic in the following format: Abstract, Introduction, Literature Review, Methodology, Results, Conclusion, Recommendations, Limitations, References, and Appendix.

2. LITERATURE REVIEW

2.1. GREEN HYDROGEN PRODUCTION FROM DIRECT AIR CAPTURE

Greenhouse gases play a crucial role in the present climate crisis, which led nations worldwide to adopt the Paris Agreement in 2015. The agreement strengthens the United Nations Sustainable Development Goals to create a better world for future generations (Raman et al. 2022). To achieve the set targets of the Paris Agreement, the world is currently undergoing an energy transition from fossil fuel energy systems to low carbon energy sources or renewable energy systems. Fossil fuels are the primary source of greenhouse gas emissions today.

Hydrogen is the most abundant element in the universe and also an emission-free energy carrier. It has great potential in the electricity generation and transportation sectors. Hydrogen also has a high energy density of about 122 kJ/g which when compared to conventional hydrocarbon fuels is three times greater, which makes it an attractive source of energy (Ayodele and Munda 2019). Hydrogen produced from renewable energy sources with nearly zero carbon emissions plays an important role in the global energy transition (Farias et al.).

The main goal of the hydrogen energy transition is based on green hydrogen (Drechsler and Agar 2020), i.e. hydrogen produced from the electrolysis of water using renewable energy sources. The role of green hydrogen in the energy transition cannot be overemphasised as it brings long-needed solutions to energy systems. It has a high energy density and can be used to store energy in the form of chemicals. An estimated 300TWh excess electricity potential in hydrogen storage for wind and solar energy is expected by 2030 (María Villarreal Vives et al. 2023).

The energy storage characteristics of hydrogen help solve the problem of variable renewable energy systems that are dependent on weather conditions. Excess electricity can be used for water electrolysis to generate hydrogen which can later be converted back to electricity when variable renewable energy is unavailable. According to (María Villarreal Vives et al. 2023) an alternative to using excess renewable energy is to use a power-to-gas approach, by transforming the excess energy into hydrogen for later use. Green hydrogen can also be combined with carbon to produce synthetic fuels which can be used in hard-to-abate industries, freight transport, fertilisers, etc.

Since hydrogen is very crucial in the energy transition, it is needed in huge quantities. However, a problem of green hydrogen production is that either the countries that need it the most do not have sufficient renewable energy resources, or sufficient water to be used for hydrogen production. According to (Kovač et al. 2021) availability of fresh water is a geographical constraint for the deployment of water electrolysers whilst, on the other hand, places with the highest renewable energy potential are usually faced with water scarcity.

Part of the energy transition and net-zero emission scenarios exists a very important phenomenon known as carbon dioxide removal (CDR) from the atmosphere. CDR techniques range from nature-based methods like afforestation and reforestation to technological methods like carbon capture and storage. Direct Air capture (DAC) is a CDR technology that plays a crucial role in meeting net-zero emission targets and provides a balance for difficult-to-avoid emissions from heavy industries, air, and freight transports (IEA (2022), *Direct Air Capture: A Key Technology to Net Zero*, International Energy Agency). There is a high potential for sustainable hydrocarbon production from CO_2 from ambient air and renewable energy (Drechsler and Agar 2020). Basic air capture technologies consist of a contact area, solvent or sorbent, and a regeneration module. The contact area provides a pathway for ambient air to flow through the model, coming in contact with the liquid solvent or solid sorbent, facilitating absorption or adsorption of CO_2 molecules. The solvent or sorbent is very important in the DAC system and hence should be contamination resistant, easy to handle, and should not disappear during the process (Fasihi et al. 2019).

According to (IEA (2022), *Direct Air Capture: A Key Technology to Net Zero*, International Energy Agency) there are currently two technological approaches of DAC being used for CO_2 capture, the solid low-temperature DAC (S-DAC) and liquid higher-temperature DAC (L-DAC). The S-DAC uses solid sorbent filters that adsorb the CO_2 from the atmosphere, the CO_2 is released and captured when the sorbent is heated and can be stored or further processed. The S-DAC technology makes use of a cycle of adsorption and desorption processes of the solid sorbent. The adsorption takes place under ambient temperature and pressure whilst the desorption happens through a temperature-vacuum swing process. The CO_2 is released at low pressure and medium temperature (80-100°C). A single S-DAC system has the capacity to extract water where the conditions are favourable whilst extracting tens of tonnes of CO_2 per year. Earlier S-DAC prototypes extracted 1 tonne of water per tonne of CO_2 captured (IEA (2022), *Direct Air Capture: A Key Technology to Net Zero*, International Energy Agency).

The L-DAC system operates on two closed chemical loops. One loop is called the contactor unit where the ambient air is passed through a chemical solution (e.g., hydroxide solution) where the CO_2 is extracted. The second loop releases the CO_2 in high-temperature (300-900°C) operating units. The L-DAC system can capture 1MtCO_2/year which is more than the S-DAC system. However, water might be required for the operation of the system depending on weather conditions. For example, at 64% relative humidity and 20°C, 4.7 tonnes of water per tonne of CO_2 would be required for the plant (IEA (2022), *Direct Air Capture: A Key Technology to Net Zero*, International Energy Agency).

Table 1: Differences between S-DAC & L- DAC

	S-DAC	L-DAC
CO_2 Separation	Solid-Sorbent	Liquid-Sorbent
Specific energy consumption (GJ/tCO_2)	7.2-9.5	5.5-8.8
Share as heat consumption (%)	75-80%	80-100%
Share as electricity consumption (%)	20-25%	0-20%
Regeneration temperature	80-100°C	Around 900°C
Regeneration pressure	Vacuum	Ambient
Capture Capacity	Modular (e.g., 50 tCO_2/year per unit)	Large-scale (e.g., 0.5-1 MtCO_2/year)
Net water requirement (tH_2O/tCO_2)	-2 to none	0-50
Land requirement (km2/MtCO_2)	1.2-1.7	0.4
Life cycle emissions (tCO_2emitted/tCO_2captured)	0.03-0.91	0.1-0.4
Levelized cost of capture (USD/tCO_2)	Up to 540	Up to 340

Source: (IEA, (2022), Direct Air Capture: A Key Technology to Net Zero, International Energy Agency)

From Table 1, it can be seen that both DAC technologies have distinct features. They both capture CO_2 but depending on the environment of operation, they may offer particular advantages. Direct air capture of carbon dioxide can happen simultaneously with high water co-adsorption as in the case of the S-DAC. Thus, the water separated from the air can be used as a feedstock for electrolysis to produce hydrogen or combined with CO_2 to produce synthetic fuels. The integration of the DAC-power to gas or liquid systems (DAC-PtG/PtL) will lead to high synergies. Thermal integration of the systems can go further to reduce the DAC unit process' external energy demand. This can be achieved by a high-temperature heat recovery strategy to extract the additional heat stored in the water vapour (Drechsler and Agar 2020).

One of the advantages of the S-DAC is the co-adsorption of water. The S-DAC system can therefore be used in arid or semi-arid regions since point source carbon capture is not a necessity for DAC systems. This means they can be deployed anywhere in the world. Even though CO_2 concentration is about 250-300 times less than concentrated sources, the DAC energy demand is only 2-4 times higher (IEA (2022), *Direct Air Capture: A Key Technology to Net Zero*,International Energy Agency).

Table 2 Advantages of S-DAC & L-DAC

ADVANTAGES	
S-DAC	L-DAC
Possible net water production	Less energy-intensive
Less capital-intensive	Large-scale capture
Modular	The operation relies on commercial solvents
The operation can rely on low-carbon energy only	Technology adapted from existing commercial units
Novel and therefore more likely to see cost reduction	

Source: (IEA (2022), Direct Air Capture: A Key Technology to Net Zero, International Energy Agency).

Table 3 Disadvantages of S-DAC & L-DAC

DISADVANTAGES	
S-DAC	L-DAC
More energy-intensive	More capital-intensive
Manual maintenance is required for adsorbent replacement	Relies on natural gas combustion for solvent regeneration (with the potential for full electrification in the future)

Source: (IEA (2022), Direct Air Capture: A Key Technology to Net Zero, International Energy Agency).

From Table 2 and Table 3, it can be deduced that the best technology for DAC-PtG/PtL is the S-DAC system. It can be operated using renewable energy, and even with high energy needs, it is still less capital intensive which means CO_2 and hydrogen can be produced at a lower price.

According to the (IEA (2022), *Direct Air Capture: A key Technology for Net Zero*, International Energy Agency) net zero emission scenarios, around 350Mt of air captured CO_2 will be used for synthetic fuel production in 2050. However, the source of the hydrogen used for the production of the synthetic fuel produced from air-captured CO_2 was not stated. The type of DAC technology used is also not specified. Since water is co-adsorbed in the low-temperature S-DAC system, the amount of hydrogen generated from the DAC system should have been calculated if this system was used. This will help to balance the hydrogen needs and know the amount of hydrogen that would be added after the hydrogen from the DAC technology is used for the production of synthetic fuels for 350Mt of air captured CO_2.

(Drechsler and Agar 2020) states that extracting water from the air comes with a high energy requirement in terms of its heat of desorption which is equal to 1.2 - 3 its heat of evaporation. They went on further to state that one might sacrifice the use of air as a water source in places with sufficient fresh water supply to lower energy requirements. From Table 2, it can be seen that one of the advantages of the S-DAC system is that it is less capital-intensive when compared to the L-DAC system. Even though the energy requirement is higher in the S-DAC system, the levelized cost of CO_2 and hydrogen is expected to be lower. This will increase the demand for CO_2 and hydrogen for the energy transition. Renewable energy sources can be used for the energy requirement and the water from the purification of CO_2 will also not be wasted. (Drechsler and Agar 2020) went further to state the advantage of using salt water to produce fresh water where available using reverse osmosis desalination whilst (Guo et al. 2022) stated the problem of chlorine management in the desalination of water, and promoting the use of direct air electrolysis.

From the literature, the advantage of water co-adsorption of the S-DAC is well highlighted. However, the integration of an electrolyser to the DAC unit for hydrogen production is not critically discussed. It is also not known if the water adsorbed can be used directly for the PEM electrolyser, or if it has to go through a purification process before it can be used for hydrogen production. The amount of water that can be co-adsorbed in different environmental conditions is also not studied in detail. It is mentioned in the literature that point source capture is not a necessity for DAC systems. Even though carbon concentrations are 250-300 times less than concentrated sources, and the DAC energy demand is only 2-4 times higher. The energy requirement is what is only analysed. It would be important to know the amount of water that can be co-adsorbed in carbon concentrated sources and non-concentrated sources. The question of whether the CO_2 output will be equivalent to the water co-adsorbed is an important phenomenon that can open doors for further research.

2.2. ECONOMICS OF GREEN HYDROGEN PRODUCTION

The key driver of hydrogen in the energy transition is climate change. Two-thirds of global greenhouse gas emissions come from energy-related CO_2. According to (IRENA (2019), *Hydrogen: A renewable energy perspective*, International Renewable Energy Agency), the link between economic growth and increased CO_2 emission needs to be broken, and this can only be achieved by an energy transition.

The main challenge of green hydrogen is its production costs compared to other pathways. As per (Henry et al. 2023) a challenge associated with green hydrogen is its high cost when it is not produced as a by-product of processes like steam methane reforming. The entire value chain from electrolysis to transport and fuel cells has a very high cost, coupled with other challenges like lack of existing infrastructure for transport and storage, high energy losses, and the lack of value for the benefit of reduced GHG emissions (IRENA (2020), *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5⁰C Climate Goal*, International Renewable Energy Agency). According to (Kovač et al. 2021), green hydrogen is not cost-competitive when compared to fossil-based hydrogen. (Terlouw et al. 2022) also states that the current costs of green hydrogen are up to 15 Euro per kg of H_2 is still very high when compared to fossil fuel-based hydrogen pathways, the major reason being the high investment cost of electrolysers. Currently, grey hydrogen price amounts to €1.50 per kg, blue hydrogen €2-3 per kg, and green hydrogen €3.50-6 per kg (Kovač et al. 2021).

The price of green hydrogen is expected to drop in the near future as electrolyser cost, which is a major determinant of hydrogen price, is predicted to drop by 50% in 2030 after it dropped by 60% in the last ten years (Kovač et al. 2021). However, (Terlouw et al. 2022) state that there exist large uncertainties with the associated learning curve and future development of electrolysers. They go further to state the need for comprehensive cost assessment to determine the current green hydrogen production costs. The need to assess the time of reaching cost parity with grey hydrogen, which costs 1-2 Euro per kg of H_2 is also highlighted. However, there is a greater possibility to sell hydrogen produced from electrolysis if the by-products of electrolysis: heat and oxygen are utilised. This could lower the cost and increase the efficiency of hydrogen production (Kovač et al. 2021).

In previous studies, hydrogen production costs and environmental risks were usually calculated using static electricity prices or capacity factors applied to renewable resources such as PV and wind electricity generation. In reality, electricity production and price from these resources are location-specific, variable, and intermittent (Terlouw et al. 2022). The design of hydrogen production could be optimised depending on location specific conditions to minimise production costs and environmental risks (Terlouw et al. 2022). Increasing the use of hydrogen in the transport sector will create a market and increase investment potential. Even though the industry has the highest potential from the business perspective, profit margins are also expected in transport.

Around 5,000 km of pipelines of hydrogen are currently present worldwide compared to the 2.91 million km of natural gas (Kovač et al. 2021). For increased possibilities and expansion of hydrogen applications, there is a need for the construction of new hydrogen infrastructure as well as utilisation of existing infrastructure. In the process of rehabilitating existing infrastructure used for other materials to be changed for hydrogen use in the future, it is necessary to perform thorough studies, to avoid environmental impacts when hydrogen is used in these materials.

(Kovač et al. 2021) also provide that in Europe, cumulative investments in green hydrogen could be up to €180-470 billion by 2050 and €3-18 billion for low-carbon fossil-based hydrogen. The EU is supporting the establishment of a global hydrogen market by dedicating finances and providing standards and methodologies. An estimated 24% of the global energy demand is expected to be covered by green hydrogen by 2050, with annual sales in the range of 630 billion Euros (Kovač et al. 2021).

The advantage of having a lower levelized cost of hydrogen when by-products of electrolysis are sold is an important methodological approach, that is highlighted in the literature. This method can be incorporated into the DAC-PtG project by selling the captured CO_2, the oxygen from electrolysis, excess heat, and where possible excess electricity generated from renewable energy resources.

2.3. PROJECT MANAGEMENT

In other to produce environmentally and financially sustainable green hydrogen, it is important to adopt strategies that will mitigate potential risks and uncertainties. A clear project management strategy is crucial in the implementation of green hydrogen projects to meet the project requirements within the stipulated time frame.

According to (Project Management Institute 2017), project management is the application of knowledge, skills, tools, and techniques to project activities to meet the requirements of the project. It is accomplished by applying and integrating the appropriate project management strategy identified for the particular project. A project is a time-bound or temporary endeavour with several related or interdependent tasks to create a unique product or service that adds value. Because projects are new endeavours, there is insufficient experience or understanding regarding project planning and execution (S. Anantatmula). Effective project management can help individuals, groups, or organisations to increase their chances of success, deliver the right products on time, meet business objectives, satisfy stakeholder expectations, respond to risks on time etc, (Project Management Institute 2017).

Project risk management is a process under project management that encompasses the activities involved in risk management planning, identification, analysis, reactions, and project monitoring and control (PThompson 2009). According to (PThompson 2009), the PMBOK (project management book of knowledge) Guide fourth edition also states “ the objectives of project risk management are to increase the probability and impact of positive events, and decrease the probability and impact of negative events in the project". Project risk management is an integral and essential element to successful project management and it is applied throughout the lifecycle of the project. Project risk management identifies uncertainties in project estimates and assumptions. It also considers the element of risks in the output of other processes and adds value by taking risks into account.

Green hydrogen production from direct air capture is an emerging technology still in its nascent stages. It is important to develop a project management strategy to manage the identified economic and environmental risks and uncertainties of the project.

3. METHODOLOGY

The research framework of this paper is based on a mixed methods approach, which combines several research methods to answer the research questions. Desk research is mostly used as the building block of this research. Data on the different systems of the DAC-PtG is collected from the literature. The collected data is further analysed to identify environmental and economic risks and uncertainties of green hydrogen production from DAC. Microsoft Excel is used for quantitative data analysis, to perform a techno-economic assessment using cost structures to calculate the levelized cost of hydrogen. It goes further to determine the overall financial sustainability of the project. A sensitivity analysis on electrolyser cost, CO_2 output, electrolyser efficiency, and the change in WACC is performed on the techno-economic assessment to analyse the impact on the LCOH and the project's overall financial sustainability.

The polymer electrolyte membrane (PEM) electrolyser is used for the DAC-PtG configuration. The PEM electrolyser has a quick start-up time and operating temperatures of 50-80°C, which can be used for the regeneration of the S-DAC unit, as it only needs 80-100°C for regeneration.

According to (Terlouw et al. 2022) PEM electrolysers are known for their fast response time and quick start-up times. They are also known for operational flexibility and therefore most appropriate to be considered in configurations with the integration of intermittent renewable energy generators. (Mehmeti et al. 2018) also states the advantage of high flexibility and better coupling with dynamic and intermittent systems with PEM electrolysers.

Another technology that can be used is the Solid oxide electrolysis cell (SOEC), but it is not as advanced and commercially available compared to the Polymer exchange electrolyser (PEM). It also requires high operating temperatures of >750°C (Henry et al. 2023).

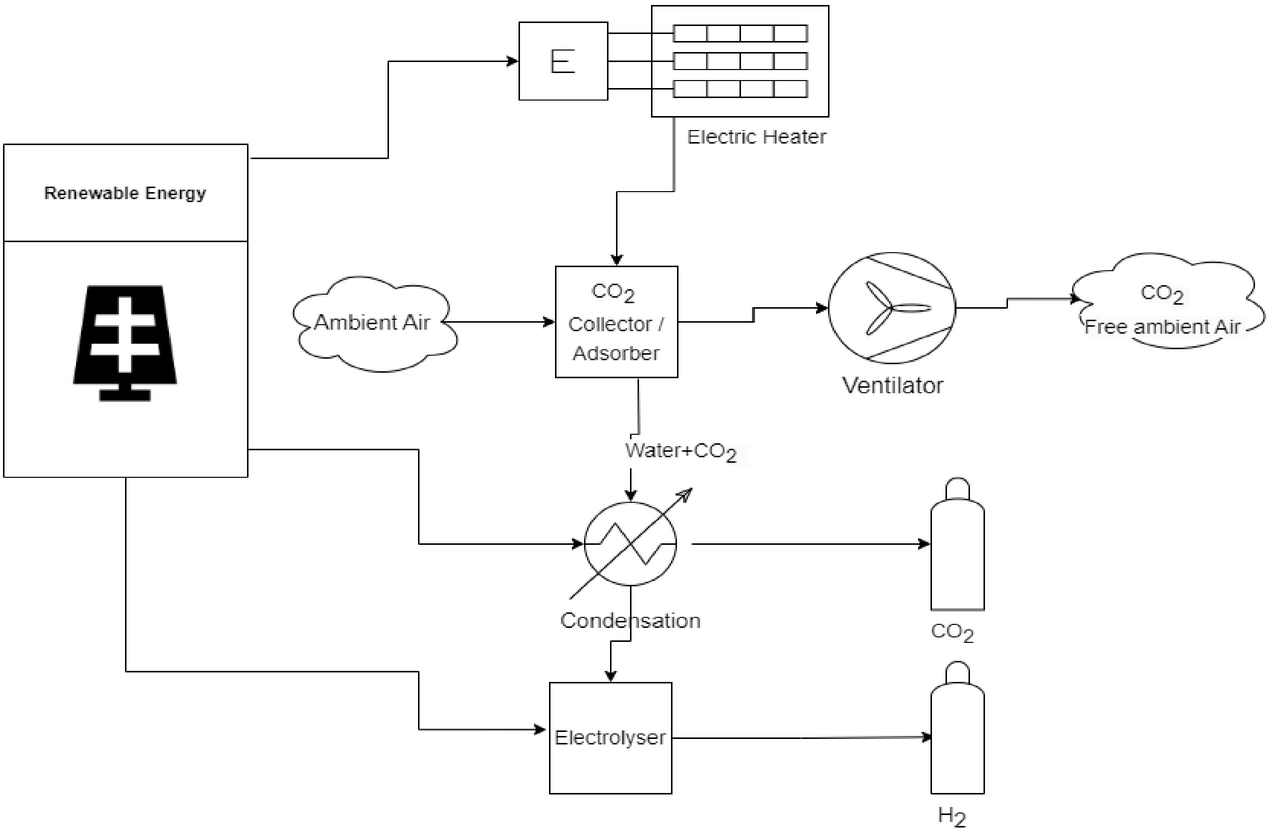
For the environmental risks and uncertainties, a decision-making tool that guides industries toward sustainable resource management called Life Cycle Assessment (LCA) is used. LCA is a standardised methodology that compiles inputs, outputs, and potential environmental impacts of a product throughout its lifetime. It systematically analyses processes and production systems, seeking to incorporate externalities that have major implications for long-term sustainability (Mehmeti et al. 2018). It is essential to perform an LCA for the identification of environmental risks on the DAC-PtG technology as it is a new technology. According to (Mehmeti et al. 2018) there is an increase in LCA application of H_2 production to guide in selection between technology paths and challenging decisions.

The LCA is done by separately assessing the DAC unit and the Electrolyser unit. There is no sufficient data to perform a complete LCA for the DAC unit. thus a literature review on an LCA for a DAC unit is analysed. For the electrolysis process, the LCA is performed using Sphera's Gabi education software.

The selected location for this paper is Ivory Coast located in West Africa. Ivory Coast was chosen because of the high presence of renewable energy and it is also located in an arid region,

Figure 2 shows the flow diagram of the S-DAC system combined with hydrogen production via water electrolysis. The system is powered by solar energy with a battery source to store energy to be used during the night. An electric heating system instead of a heat exchanger is used since low regeneration temperatures of 80-100°C are needed for S-DAC.

After the economic and environmental impact analysis is completed, a project management strategy is developed. The project management strategy is meant to minimise possible impacts where possible and manage the identified risks and uncertainties.



Self-Created 1

Figure 2: S-DAC Flow Diagram including Hydrogen Production (DAC-PtG)

3.1. COLLECTED DATA AND ASSUMPTIONS

The data used for the economic and life cycle assessment are all obtained from the literature. The DAC-PtG system is the integration of different systems to obtain the required output of carbon dioxide and green hydrogen. The electricity source is solar photovoltaic, which supplies electricity to the DAC unit, electrolyser, and hydrogen compressor.

Table 4: DAC Data

DAC			
COST TYPE	UNIT	VALUE	SOURCE
Capex	€/tCO_2.a	730	(Fasihi et al., 2019)
Opex	% Of Capex	4%	(Fasihi et al., 2019)
Lifetime	a	20	(Fasihi et al., 2019)
Electric Energy Required	GJ/tCO_2	0.5-1.11	(Jiang et al., 2023
Thermal Energy Required	GJ/tCO_2	3.4-4.8	(Jiang et al., 2023
Storage	$/$tCO_2$	50000	(Sherwin, 2021)
Electrical Demand	kWhel/tCO_2	250	(Fasihi et al., 2019)
LT-heat Demand	kWhth/tCO_2	1750	(Fasihi et al., 2019)

Table 5: Solar PV Data

PV SYSTEM			
COST TYPE	UNIT	VALUE	SOURCE
PV System CAPEX	€/kWp for system > 1 MW	800	(Bhandari & Shah, 2021)
PV System CAPEX	€/kWp for system <1 MW	1000	
PV OPEX	% of capex/year	1	(Bhandari & Shah, 2021)
Battery capex	€/kWh	560	(Bhandari & Shah, 2021)
Battery OPEX	€/kWh	0.027	(Bhandari & Shah, 2021)
Battery Replacement Cost	€/kWh	200	(Bhandari & Shah, 2021)
Battery DOD	%	50	(Bhandari & Shah, 2021)
Battery System Efficiency	%	80	(Bhandari & Shah, 2021)
Battery Autonomy Days	Days	0.5	
Solar PV Capacity Factor		0.29	(Sherwin, 2021)

Table 6: PEM Electrolyser Data

PEM ELECTROLYSER			
TYPE	UNIT	VALUE	SOURCE
Electrolyser Capacity	KW	1000	(H-TEC Systems)
H_2 Produced	kg/day	450	(H-TEC Systems)
H_2 purity	(Meets ISO 14687:2019)	5	(H-TEC Systems)
System efficiency	%	75	(H-TEC Systems)
H_2 production modulation range	%	20-100	(H-TEC Systems)
H_2 output pressure	bar	20-30	(H-TEC Systems)
Electricity	kWh/kg H_2	53	(H-TEC Systems)
H_2O consumption nominal	kg/h	260	(H-TEC Systems)
Water	kg/kg H_2	13.87	(H-TEC Systems)
PEM Electrolyser CAPEX	€/kW	1000	(Bhandari & Shah, 2021)
PEM Electrolyser OPEX	% Of initial capex per year	2	(Bhandari & Shah, 2021)
Stack Replacement Cost	€/kW	420	(Bhandari & Shah, 2021)
H_2 Storage CAPEX	€/kgH_2	460	(Terlouw et al., 2022)
H_2 Storage OPEX	% Of Storage CAPEX	1	(Terlouw et al., 2022)
H_2 Storage Lifetime	Year	20	(Terlouw et al., 2022)
H_2 Compressor CAPEX	€/kW	2440	(Terlouw et al., 2022)
H_2 Compressor OPEX	% Compressor CAPEX	4	(Terlouw et al., 2022)
H_2 Compressor Lifetime	Year	10	(Terlouw et al., 2022)
Electrolyser Degradation rate	%	1%	(Huang et al., 2023)
Max. delivery rate with two IC 50	Kg/h	18	(The Linde group)
Max. feasible compression pressure	Mpa	50	(The Linde group)
Target fuelling pressure at 15 °C	Mpa	35	(The Linde group)
Weight	t	10	(The Linde group)
Ambient operating temperature	℃	-20 to 45	(The Linde group)
Electricity consumption, inlet 0.8 MPa	kWh/kg H_2	2.9	(The Linde group)
Electricity consumption, inlet 2.5 MPa	kWh/kg H3	2.2	(The Linde group)
Compressor Power requirements, installed	KW	95	(The Linde group)
Footprint	m²	15	(The Linde group)
Operating hours (accumulated), reference value	h	28000	(The Linde group)

Table 7: System Design Data

DAC Capacity	Tonne of CO_2	2277.60	
Water Extracted	Tonne of Water	2277.60	
Hydrogen Produced	Kg of H_2	164250.00	
Weighted Average Cost of Capital	%	15	
Project Lifetime	Year	20	
DAC Energy Requirement	GJ	11160.24	Calculated
DAC Energy Requirement	kWh/day	8494.01	Calculated
Electrolyser Energy Requirement	KWh/day	23850.00	Calculated
Total Energy Requirement	KWh/day	32344.01	Calculated
Chosen Location	09.562182°, -007.447083°	Denguele, Ivory Coast	
Global Horizontal Irradiation (HA)	KWh/m²/day	5.64	https://globalsolaratlas.info/map
Irradiance under standard conditions (ES)	KW/m²/day	1	(Bhandari & Shah, 2021)
PV Capacity	KWp	9559.62	Calculated
Battery Size	KWh	40430.02	Calculated
Exchange Rate	1 USD	€ 0.92	https://www.forbes.com/advisor/money-transfer/currency-converter/usd-eur/
CO_2 Storage Days	Days	0.50	
CO_2 Storage Capacity	Tonnes	6.24	Calculated
H_2 Storage Days	Days	0.50	
H_2 Storage Capacity	Kg of H_2	225.00	Calculated
Conversion	GJ to KWh	277.80	
Annual Multiplier of Power Consumption of Electrolyser		1.21	Calculated
CO_2 Price	€/tCO_2	€ 549.63	(Sherwin, 2021)
H_2 Price	$	3-8 USD/kg	(IEA - International Energy Agency)
H_2 Price	€	€ 4.58	

Table 8: LCI Input flow data for 1PEM Electrolyser

Flow Name	Value	Units	Parameter	Unit	Total	Units per RF
Technosphere Flows/Titanium	1	kg	1.51E+03	kg	1.51E+03	kg
Technosphere Flows/Stainless Steel	1	kg	2.86E+02	kg	2.86E+02	kg
Technosphere Flows/Nafion	1	kg	4.57E+01	kg	4.57E+01	kg
Technosphere Flows/Activated Carbon	1	kg	2.57E+01	kg	2.57E+01	kg
Technosphere Flows/Iridium	1	kg	2.14E+00	kg	2.14E+00	kg
Technosphere Flows/Platinum	1	kg	2.14E-01	kg	2.14E-01	kg
Technosphere Flows/Low Alloyed Steel	1	kg	4.80E+03	kg	4.80E+03	kg
Technosphere Flows/High Alloyed Steel	1	kg	1.90E+03	kg	1.90E+03	kg
Technosphere Flows/Plastic	1	kg	3.00E+02	kg	3.00E+02	kg
Technosphere Flows/Electronic Material	1	kg	1.10E+03	kg	1.10E+03	kg
Technosphere Flows/Adsorbent and Lubricant	1	kg	2.00E+02	kg	2.00E+02	kg
Technosphere Flows/Concrete	1	kg	5.60E+03	kg	5.60E+03	kg
Technosphere Flows/Aluminium	1	kg	1.27E+02	kg	1.27E+02	kg
Technosphere Flows/Copper	1	kg	6.29E+01	kg	6.29E+01	kg

Table 9: Electrolyser Output flow data for 1PEM Electrolyser

Flow Name	Value	Units	Parameter	Unit	Total	Units per RF
PEM, Construction	1	piece	1.00E+00	piece	1.00E+00	piece

Table 10: LCI Input flow data for 1kg of H2

Flow Name	Value	Units	Parameter	Unit	Total	Units per RF
Technosphere Flows/Water, purified	1	kg	8.94E+00	kg/kg	8.94E+00	kg
Elementary Flows/resource/water/Water, fresh	1	kg	1.63E+02	kg/kg	1.63E+02	kg
Technosphere Flows/Electricity, AC, 120 V	1	kWh	5.50E+01	kWh/kg	5.50E+01	kWh
Technosphere Flows/PEM, Construction	1	piece	3.14E-07	piece/kg	3.14E-07	piece

Table 11: LCI Output flow data for 1kg of H2

Flow Name	Value	Units	Parameter	Unit	Total	Units per RF
Hydrogen, >99.999 %, 435 psia, 60°C	1	kg	1.00E+00	kg/kg	1.00E+00	kg
Elementary Flows/emission/air/Oxygen	1	kg	7.94E+00	kg/kg	7.94E+00	kg
Elementary Flows/emission/water/Water, fresh	1	kg	1.60E+02	kg/kg	1.60E+02	kg

The calculated system design data in Table 7 makes use of data from Table 4: DAC Data, Table 5: Solar PV Data, and Table 6: PEM Electrolyser Data. All the data used for section 3.2 DATA ANALYSIS is obtained from Table 4, Table 5, Table 6, and Table 7 for the techno-economic assessment. Data from Table 8, Table 9, Table 10, and Table 11 are retrieved from the National Energy Technology Laboratory unit process library online and are used for the Life-cycle assessment using Gabi software.

To have a comprehensive and accurate environmental footprint, it was necessary to model the PEM electrolyser system as it was not found in the Gabi software database.

3.2. DATA ANALYSIS

3.2.1. TECHNO-ECONOMIC ASSESSMENT DATA ANALYSIS

All costs (investments, operation, maintenance, and replacement costs) during the entire lifetime of the DAC-PtG technology are considered for the techno-economic assessment. A 1MW electrolyser from (H-TEC Systems) is chosen for the system design. The electrolyser has an efficiency of 75% and produces 450kg of H_2 per day, with a water nominal consumption of 260kg per hour. This means that 13.87kg of H_2O will give 1kg of hydrogen and hence 164,250kg of hydrogen will be produced from 2277.60 tonnes of water per annum.

The DAC system is then sized based on the amount of water required by the electrolyser since the ratio of CO_2 to water adsorbed is 1. The DAC unit is sized to have the capacity to capture 2277.60 tonnes of CO_2 per year. The electrical and thermal energy required of the DAC unit is in the range of 0.5 to 4.8 GJ/tCO_2 according to (Jiang et al. 2023). The total energy required of the entire DAC-PtG system is calculated and the result is used to calculate the required solar PV capacity for the system. A battery system is also added to be used for 12 hours when there is no sunlight to power the system. The solar PV capacity and battery size are calculated using Equation 1 and Equation 2. All the data used in the equations in 2.3. DATA ANALYSIS is obtained from 2.1. COLLECTED DATA AND ASSUMPTIONS.

The levelized cost of CO_2, electricity, and hydrogen is then calculated using Equation 3, Equation 4, and Equation 5 respectively. For the calculation of the levelized cost of CO_2 and water, half of the initial investment for the DAC unit is used. This is done to avoid double counting, as the ratio of water to CO_2 in the DAC unit is 1.

$$Ppeak(kW) = \frac{\left[Ed(kWh) \times Istc\left(\frac{kW}{m^2}\right)\right]}{G\left(\frac{kWh}{m^2}\right) \times Q}$$

Equation 1

Ppeak is- the required solar PV capacity in kW

Ed- The total energy demand in kWh per day

Istc- Radiation at standard test condition in kW/m² (value 1 kW/m²)

G- Global solar irradiation in kWh/ m² (value taken from global solar atlas)

Q- Quality factor or performance ratio (value 0.6 for off-grid)

$$Battery\ size(kWh) = \frac{Eavg(kWh) \times DOA}{DOD \times ή system}$$

Equation 2

Eavg- Daily average energy demand

DOA- Days of autonomy

DOD- Depth of discharge of the battery 50%

ήsystem- Battery system efficiency 80%

$$LCOD = \frac{\left\{\frac{Io}{2} + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}\right\}}{\sum_{t=1}^{n} \frac{CO_2 t}{(1+i)^t}}$$

Equation 3

LCOD- Levelized cost of CO_2

Io- Investment expenditure in €

At -Annual total cost in € per year t

$CO_2 t$ – Annual total CO_2 captured in kg per year t

i-Real interest rate in %

n- Economic lifetime in years

t- Year of a lifetime (1, 2, ... n)

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^t}}$$

Equation 4

LCOE- Levelized Cost of Electricity in €/kWh

Io- Investment expenditure in €

At -Annual total cost in € per year t

Mt, el- The produced amount of electricity in kWh per year

i-Real interest rate in %

n- Economic lifetime in years

t- Year of a lifetime (1, 2, ... n)

$$LCOH = \frac{\left\{Io + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}\right\}}{\sum_{t=1}^{n} \frac{H_{2t}}{(1+i)^t}}$$

Equation 5

LCOH- Levelized cost of Hydrogen

Io- Investment expenditure in €

At -Annual total cost in € per year t

H_2- H_2 captured in kg per year

i-Real interest rate in %

n- Economic lifetime in years

t- Year of a lifetime (1, 2, ... n)

$$LCOW = \frac{\left\{\frac{Io}{2} + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}\right\}}{\sum_{t=1}^{n} \frac{H_2Ot}{(1+i)^t}}$$

Equation 6

LCOW- Levelized cost of Water

Io- Investment expenditure in €

At -Annual total cost in € per year t

H_2Ot - Annual total H_2O captured in kg per year

i-Real interest rate in %

n- Economic lifetime in years

t- Year of a lifetime (1, 2, ... n)

$$NPV = \sum_{t=1}^{n} \frac{Cf_t}{(1+WACC)^t}$$

Equation 7

NPV- Net Present Value

Cf- Cash Flows

WACC- Weighted Average Cost of Capital

n- Economic lifetime in years

t- Year of a lifetime (1, 2, ... n)

$$ROI = \sum_{t=1}^{n} \frac{TCf_t}{Io}$$

Equation 8

ROI- Return on Investment

TCf- Total Cash flow

Io- Initial Investment

n- Economic lifetime in years

t- Year of a lifetime (1, 2, ... n)

A sensitivity analysis was performed, to calculate the LCOH under different economic conditions. The sensitivity analysis illustrates the economic risks that can happen when variables such as electrolyser cost, CO_2 output, WACC, and electrolyser efficiency change during the project. The electrolyser cost of €1 million dropped from 5% to 20% and then increased from 5% to 20%. The LCOH is then calculated in each step where the electrolyser cost is altered.

A change in CO_2 output signifies a change in the water that is co-adsorbed and hence a change in the amount of hydrogen produced. The CO_2 output is increased and decreased from 10%, 15%, and 20% of the initial amount of 2277.6 tonnes. The corresponding LCOHs are calculated to measure the economic risks caused by a change in CO_2 output.

The WACC sensitivity analysis is performed by increasing and decreasing 5%, 10% and 15% of the WACC of the project which is 15%. The LCOHs are calculated in each step that the WACC is changed.

For sensitivity analysis of the electrolyser efficiency, the water requirement of the electrolyser is studied. The higher the amount of water required the lower the efficiency and vice versa. The water requirement of 13.87 kg/kgH_2 for the PEM electrolyser used in this project is increased and decreased from 5% to 20% in variables of 5. The LCOHs are then calculated to measure the economic risk associated with electrolyser efficiency.

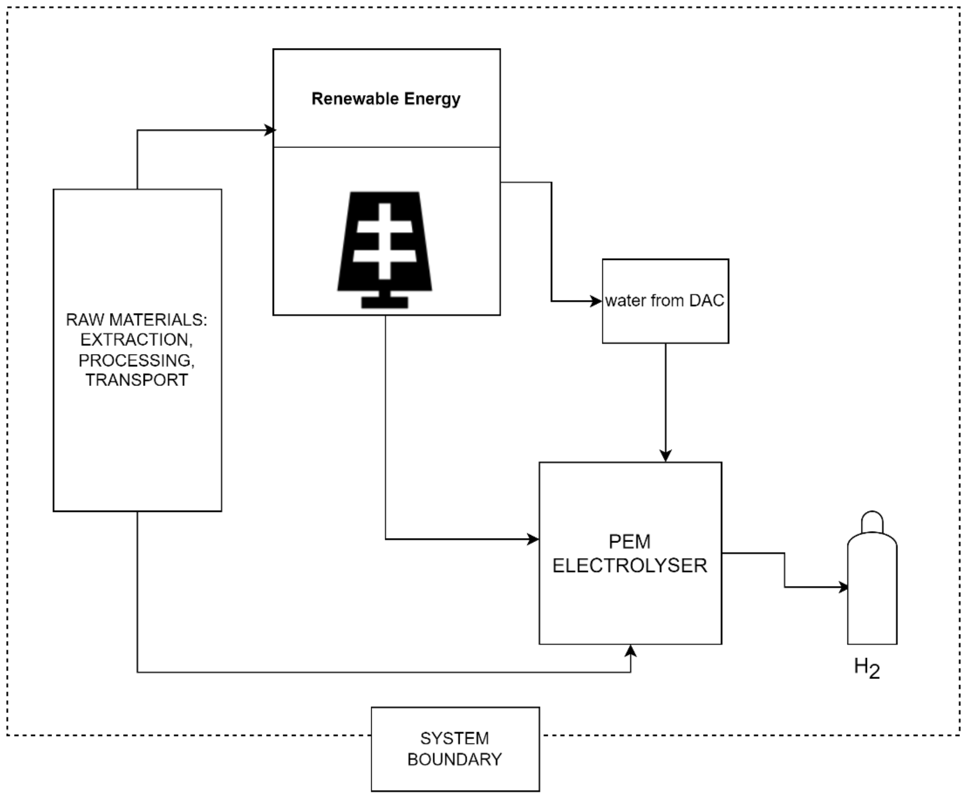
3.2.2. LIFECYCLE ASSESSMENT DATA ANALYSIS

The life-cycle assessment of green hydrogen produced from a PEM electrolyser is performed using the GABI software. The study aims to analyse the environmental impacts associated with the production of 1kg of hydrogen using the DAC-PtG technology. However, sufficient data was not available for the DAC unit, hence the reason why a partial LCA is conducted for the production of hydrogen using a Polymer exchange membrane (PEM) electrolyser.

According to ISO 14040:2026, an LCA should comprise four phases (1) Goal and scope of the study (2) Life cycle inventory (3) Impact assessment, and (4) Interpretation of results. These four phases are outlined for this study in accordance with ISO 14040. The goal and scope, and the life-cycle inventory are discussed under the methodology, whilst the impact assessment and interpretation of results of the LCA are discussed under the result chapter.

I. Goal and scope of the study

The objective of the study is to do a review of major sources and quantitative midpoint environmental impacts associated with the production of green hydrogen from a PEM electrolyser using solar photovoltaics. The functional unit defined is 1kg of green hydrogen with 99.99% purity, and a pressure of 435psia (30 bar) at a temperature of 60°C using a PEM water electrolyser. The analysis is performed from cradle-to-gate and the system boundaries include the extraction of the raw material, their production and transportation processes, and the actual hydrogen production.



The PEM electrolyser for this study should be supplied with water co-adsorbed from the DAC unit, to be used for the electrolysis process. The process for this production of water is not available in the GABI software, thus 'tap-water from surface' process is used as an input instead. A detailed explanation of the electrolysis process for the PEM water electrolyser can be found in the paper of (Bareiß et al. 2019). In most applications, the PEM water electrolyser is integrated into 20ft or 40ft containers. The balance of plant for this study is assumed to be 20 years.

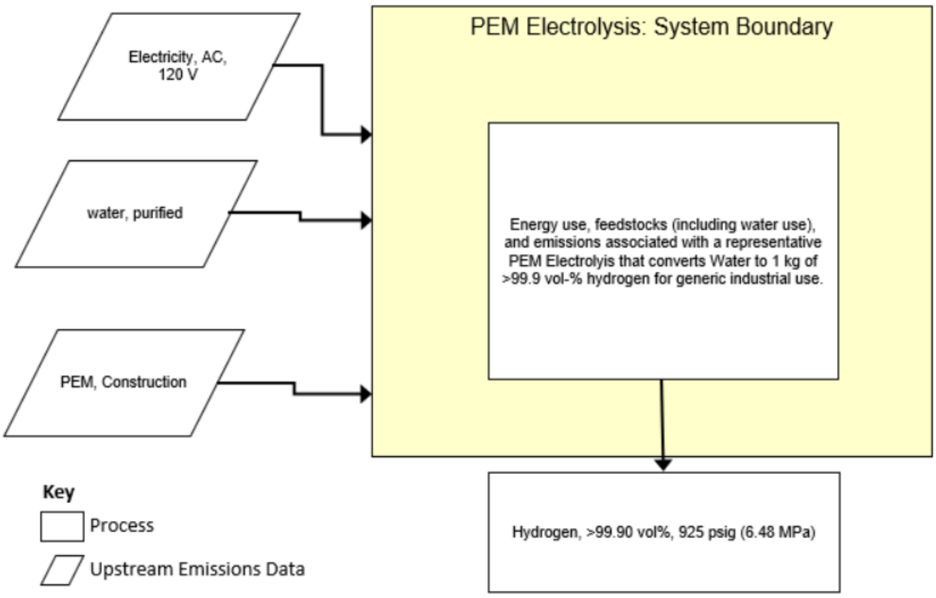


Figure 3: PEM Electrolyser system boundary

II. Lifecycle inventory (LCI)

The life-cycle inventory is all the input and output data used for the life-cycle assessment; it goes further to describe the different processes within the system boundary. The LCI data was retrieved from the (National Energy Technology Laboratory) unit process library online.

Nafion, a relevant data for the PEM construction, was not available in the GABI software. Nafion is a polymer material made by DuPont which is the most commonly used proton exchange membrane. According to (Parker and Shah 2021) Nafion is composed of a polytetrafluoroethylene (PTFE) backbone, with per fluorinated-vinyl-polyether side chains terminating in sulfonic acid groups. Polytetrafluoroethylene (PTFE), which is the main component of the nafion was available in the database, thus it was used to replace nafion as an input parameter in the PEM construction model. From the dataset, the calculated percentage of nafion used as an input material compared to all other input materials is 0.286%. Even though nafion is a very important input material, a small quantity is required for the PEM construction.

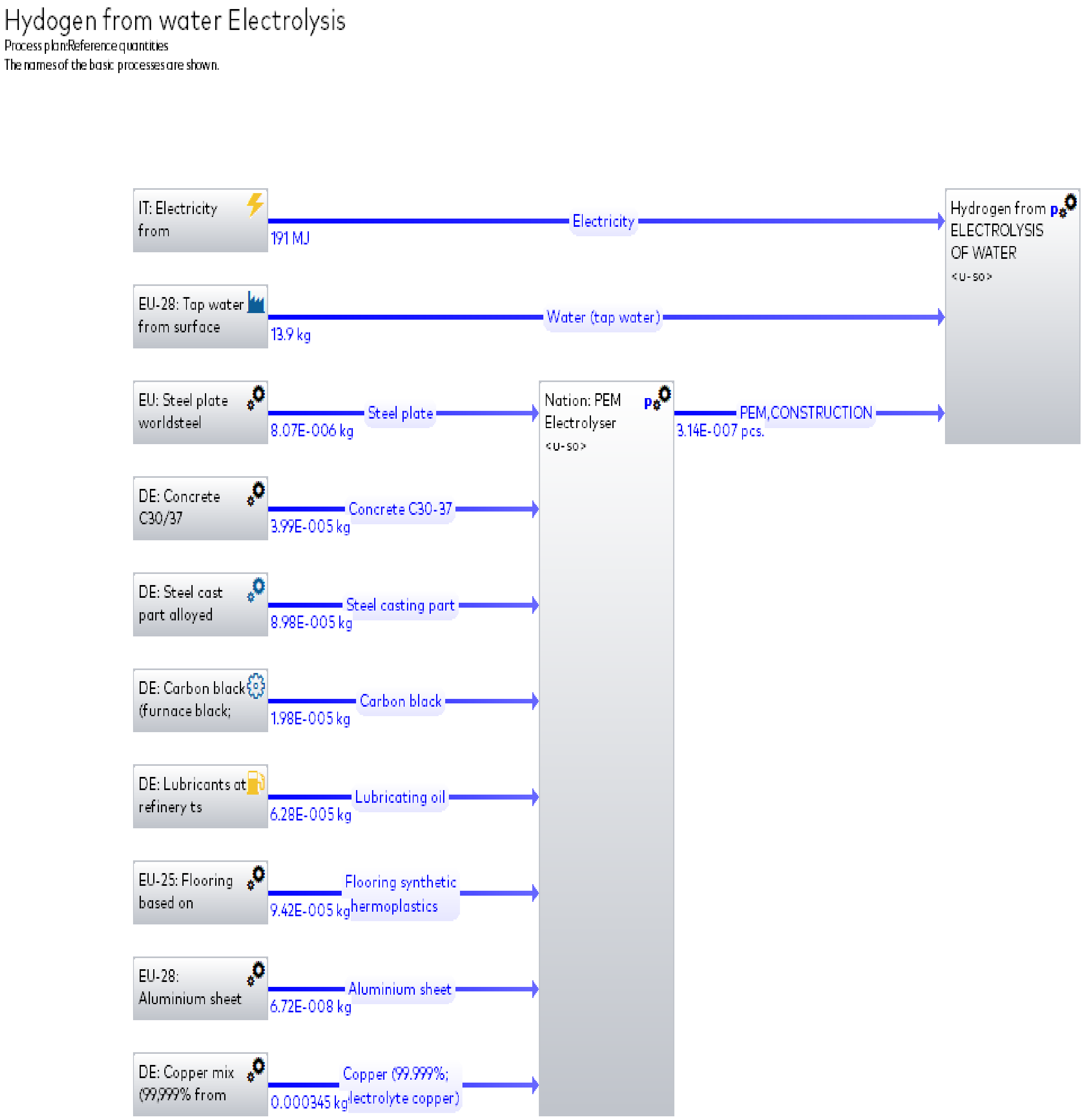


Figure 4: DAC-PtG flow process- Gabi Interface

4. RESULTS

From the results of the economic and environmental analysis, it can be seen that hydrogen can be produced from the DAC-PtG with limited environmental impacts compared to other pathways. Successfully producing hydrogen in arid and semi-arid regions is a positive development toward a hydrogen-sufficient energy transition. Economically, hydrogen from the DAC-PtG can also compete with other green hydrogen production pathways. The findings from this study can also be a building block for further research.

4.1. TECHNO-ECONOMIC ASSESSMENT

The techno-economic assessment analyses the economic impacts of green hydrogen produced from DAC-PtG technology. The levelized costs of all the products from the DAC-PtG system are calculated, except for that of oxygen from the electrolysis process. The LCOE and LCOW are input parameters in the calculation of the LCOH which is a key variable in the analysis of economic risks. The calculated LCOH is €3.30/kg which falls in range with the current price of hydrogen; \$3-8/kgH_2 which is approximately €2.69 to 7.17 /kgH_2 (IEA - International Energy Agency). For this study, the hydrogen is sold for €4.58/kg which is in range with the current hydrogen price but higher than the calculated LCOH.

The CO_2 captured is an important raw material that is also sold to increase the financial sustainability of the project. The levelized cost of carbon dioxide calculated from the study is 0.11€/kg, but it is sold at the current price of €0.55/kg (Sherwin 2021). The study has a positive return on investment (ROI) of 54.01%, meaning the project is financially sustainable. Further analysis shows that if the price of hydrogen is dropped further to €1/kg the return on investment will still be positive at 23.83%, this is as a result of the carbon price which takes up the financial burden of hydrogen production. For €1/kg green hydrogen can compete with hydrogen produced from fossil fuels.

Table 12: DAC-PtG Levelized Costs-Base Case Scenario

LCOE (€/kWh)	0.09
LCOD(€/Kg)	0.11
LCOH(€/Kg)	3.30
LCOW(€/kg)	0.09
Price of CO_2 (€/Kg)	0.55
Price of H_2 (€/Kg)	4.58

From the data used to perform the economic analysis, it is observed that the battery system for the PV has the highest cost in the capital expenditure followed by the PV system.

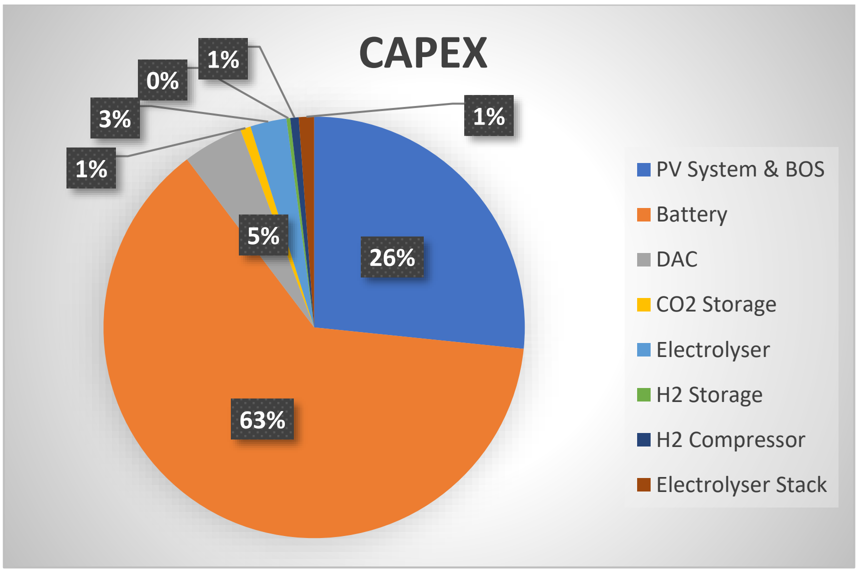


Figure 5: DAC-PtG CAPEX share

For the OPEX, the battery also has the highest percentage share of the cost, this is because the battery is changed once in the lifetime of the system. The second highest percentage share of cost is the Electrolyser operational expenses which takes into account the cost of electricity and water.

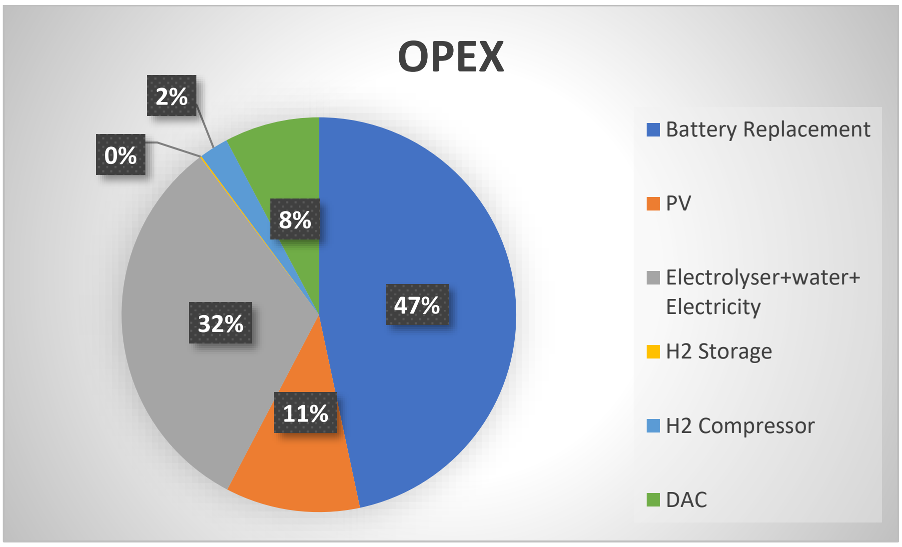


Figure 6: DAC-PtG OPEX Share

For the sensitivity analysis, the battery system was eliminated to carry out further economic analysis of the system. The battery which contributes to 63% of the CAPEX is only used to power the system for 12 hours when there is no sunlight for the PV system. Eliminating the battery will result in the reduction of the CAPEX. The downside of battery elimination will be a reduction of the total amount of hydrogen produced. This is because the system will just be operating for 12hours when there is sunlight, and will be shut down during the night when there is no sunlight to power the solar PV system. The calculated LCOH when the battery is eliminated is €6.57/kg. This is almost double the LCOH when the system is connected to a battery. Nevertheless, the hydrogen is still sold at the same price of €4.58/kg, which is the same price it is sold for when the battery is connected to the system. The system yields an ROI of 70.37%, which is higher than the battery-connected system by 16.36%.

Table 13: DAC-PtG Levelized Cost-Battery Eliminated

LCOE (€/KWh)	0.05
LCOD(€/Kg)	0.23
LCOH(€/Kg)	6.57
LCOW(€/kg)	0.18
Price of CO2	0.55
Price of H2	4.58

Another scenario performed for this study was the elimination of the water cost, the water was treated as a by-product of the CO_2, meaning the cost of water is included in the LCOD. The LCOH then becomes €2.01/kg when the water used for the electrolyser is free, and the LCOD increases from €0.11/kg to €0.18/kg which is still lower than the current price of CO_2. Both the CO_2 and H_2 are sold for the same price used in the base case scenario and the battery eliminated scenario. The ROI for the free water scenario is 64.83% which is 10.82% higher than the base case scenario.

Table 14: DAC-PtG Levelized Cost -Water cost Eliminated

LCOE (€/KWh)	0.09
LCOD(€/Kg)	0.18
LCOH(€/Kg)	2.01
LCOW(€/kg)	0.00
Price of CO2	0.55
Price of H2	4.58

A sensitivity analysis of CO_2 output and electrolyser cost showed that CO_2 output has greater sensitivity on LCOH compared to electrolyser cost. This is because a change in CO_2 output means a change in water produced which is the key element of hydrogen production. The CO_2 output is varied from -20 to 20% in variable of 5. It is observed that a 20% decrease in CO_2 output will cause an increase in LCOH to €3.97/kg whilst a 20% increase will cause a drop in LCOH to €2.82/kg. The cost of electrolyser also varied from -20 to 20%. A 20% decrease in the cost of electrolyser yields an LCOH to €3.10/kg and a 20% increase yields an LCOH of €3.56/kg.

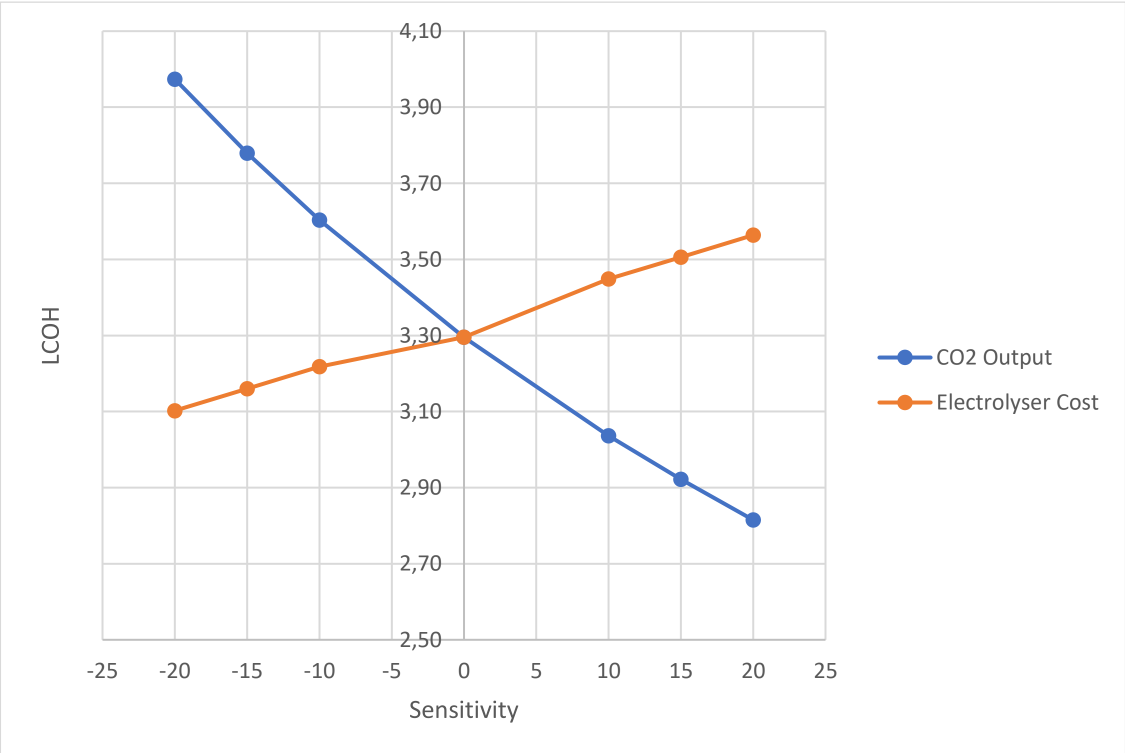


Figure 7: CO2 Output and Electrolyser Cost Sensitivity vs LCOH

For the sensitivity analysis of electrolyser efficiency, the water-to-hydrogen ratio is varied. A positive linear regression is observed in Figure 7, this is because water is a key resource in the production of hydrogen from water electrolysis. The PEM water requirement of 13.87kg was decreased by 20% and also increased by 20% in variables of 5% to analyse the corresponding LCOHs. When the electrolyser water requirement increases compared to the rating of the electrolyser it means that the efficiency of the electrolyser has dropped. When electrolyser efficiency drops hydrogen production is decreased and as a result, the LCOH increases and vice versa.

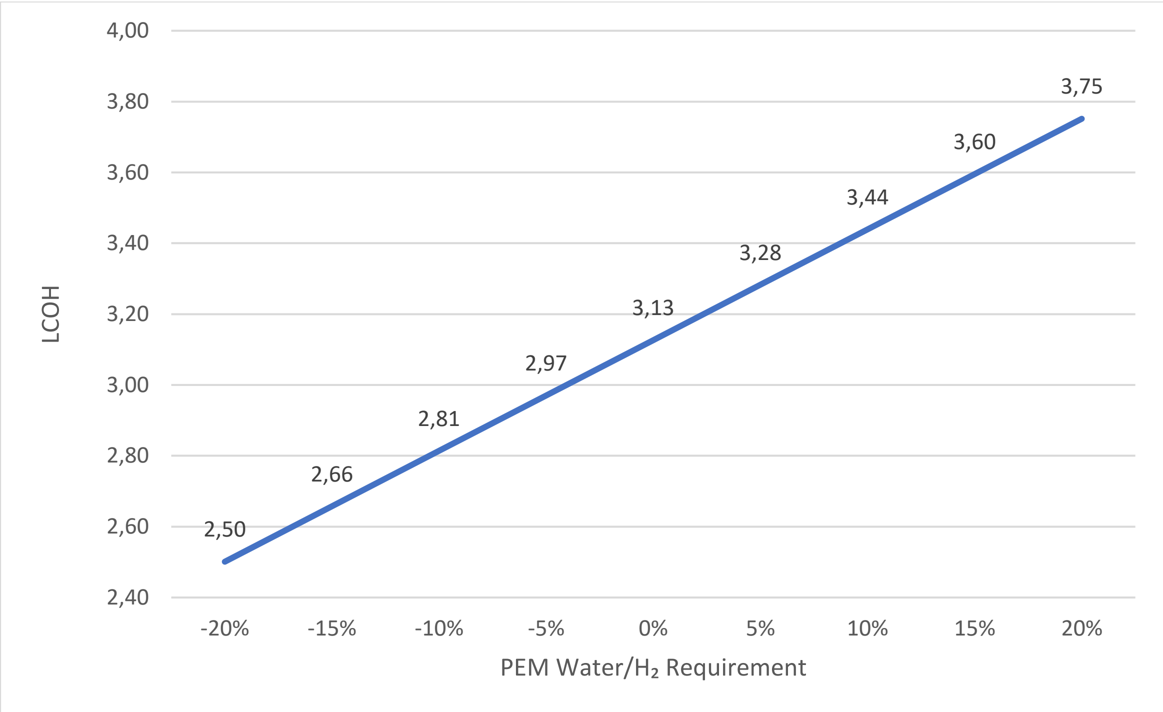


Figure 8: Electrolyser Efficiency Sensitivity Analysis vs LCOH

The WACC is an important parameter in cash flow analysis. In this study the WACC is used as the discount rate factor for future cash flows in discounted cash flow analysis. It is also the discount rate used in the study to estimate the net present value. The sensitivity analysis of the WACC compared to the LCOH as seen in Figure 9 was performed, and the results show a positive linear regression as the output. The WACC of 15% used for the study varied from -15 to 15%, with corresponding LCOHs of 3.15 and €3.44/kg respectively. The results can be interpreted that lower discount rates will increase the financial sustainability of projects.

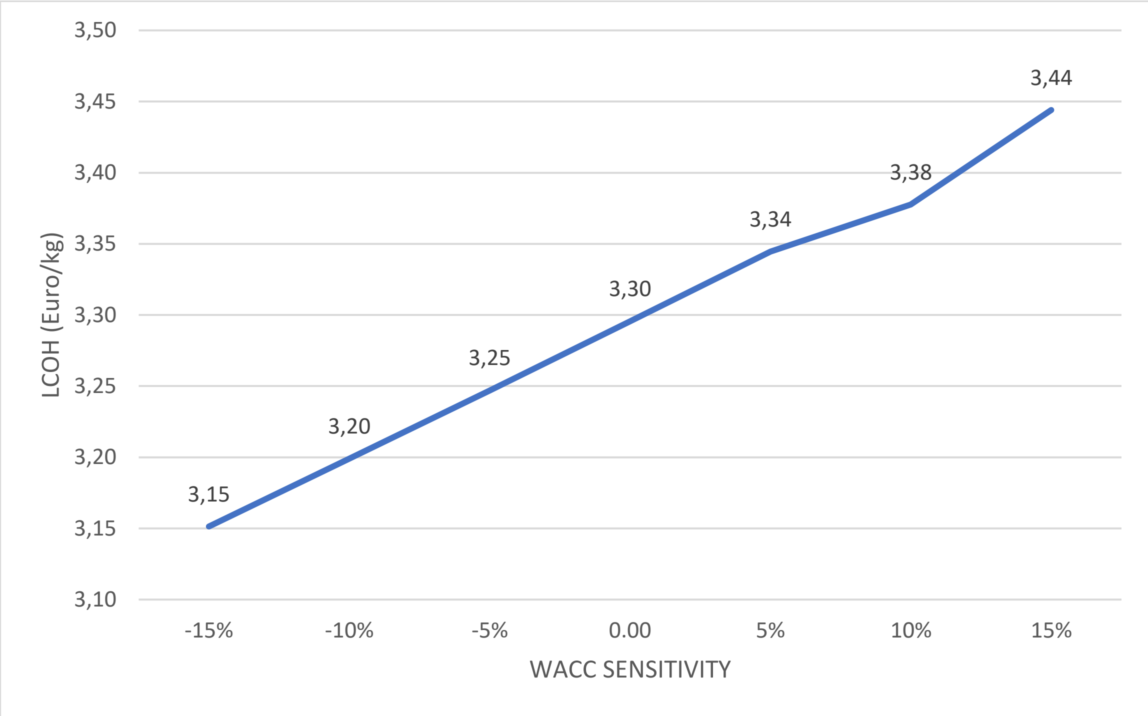


Figure 9: WACC Sensitivity Analysis vs LCOH

4.2. ANALYSIS OF LIFE CYCLE ASSESSMENT OF GREEN HYDROGEN PRODUCTION FROM DAC

To analyse the environmental impacts of green hydrogen production from DAC, an environmental life-cycle impact assessment needs to be conducted. Life-cycle assessment is a decision-making tool that can be used to measure and compare the sustainability of various hydrogen production pathways. According to ISO 14040: 2006, LCA is defined as the compilation of inputs, outputs, and the potential environmental impact of a product system throughout its life cycle. The life-cycle contains all activities from cradle-to-grave; that is from the extraction of raw materials, transportation, production, and product use, to recycling and final disposal of waste.

For this study, there was not enough lifecycle inventory data to perform the entire life-cycle assessment. The GABI Education software that was used does not contain datasets on direct air capture systems. We also could not obtain industrial data from manufacturers of DAC units. Hence the reason for a literature review on the life-cycle assessment of the DAC unit is to complete the environmental analysis. The paper of (Deutz and Bardow 2021) "Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption" is studied in detail.

For the solar photovoltaic system which is the energy source of the DAC-PtG unit, and the polymer exchange electrolyser (PEM), a complete life-cycle assessment is conducted using Sphera's GABI Education software.

4.2.1 LIFE-CYCLE ASSESSMENT OF DIRECT AIR CAPTURE PROCESS BASED ON TEMPERATURE-VACUUM SWING ADSORPTION

The paper of (Deutz and Bardow 2021) which is a life-cycle assessment of an industrial direct air capture process based on temperature-vacuum swing adsorption is studied in detail to analyse the environmental impacts of the S-DAC system. The goal and scope definition of the LCA study is a comprehensive LCA for direct air capture via temperature–vacuum swing adsorption with six adsorbents. The LCA study focuses on four goals:

1. Environmental impacts of captured CO2 from cradle-to-gate and cradle-to-grave.
2. Comparing the environmental impacts of six adsorbents.
3. Environmental impacts of the DAC plant construction.
4. Environmental impacts of capturing 1% of global annual CO2 emissions (This point will not be looked at in detail for this study)

The functional unit is '1 kg CO_2 captured around ambient conditions with a purity above 99%.

I. ENVIRONMENTAL IMPACTS OF CAPTURED CO2 FROM CRADLE-TO-GATE

For this study, we will only be concentrating on the environmental impacts of CO_2 captured from cradle-to-gate, this is because the main interest of this study is the green hydrogen produced from the water that is co-adsorbed with the captured CO_2. The environmental impacts of hydrogen will further be studied in detail.

According to (Deutz and Bardow 2021) the LCA results show that the industrial DAC unit provides CO_2 with a negative carbon footprint today from cradle-to-gate, provided there is availability of waste heat or the electricity source used has a lower carbon footprint than Italy when a heat pump is used. For the future scenario of 2030 with the projected global energy mix, material improvement and change in energy use from today will increase carbon capture efficiency by 25.4% from 43.1% to 66.7% when a heat pump is used. There will be a decrease of 7.4% of the increase in carbon capture efficiency in 2050 for a less carbon-intensive global electricity mix.

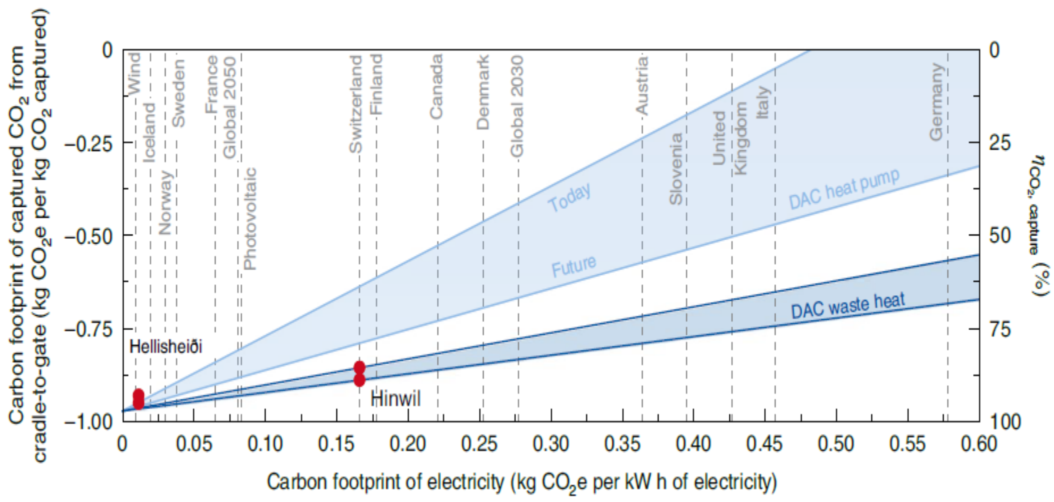


Figure 10: Carbon footprint of captured CO2 depending on the carbon footprint of electricity from cradle-to-gate.

The carbon footprint of the captured CO_2 depends linearly on the carbon footprint of electricity supply as seen in the figure. Although the carbon footprint is dependent on the electricity supply, the carbon capture efficiency does not reach 100% even if surplus power is assumed. Carbon capture efficiency is reduced by 0.6% and 2.4% by the DAC construction and the production of the adsorbent respectively.

II. ADSORBENTS

The LCA compares the environmental impacts of six adsorbents used in the DAC unit, namely: 1) Amine on alumina 2) Amine on Silica 3) Amine on cellulose 4) Carbonate on silica 5) Carbonate on activated carbon, and 6) Anionic resin. From Figure 11 it is seen that the production of the adsorbents has higher carbon footprints per kg of CO_2 captured compared to the end of life. According to (Deutz and Bardow 2021) the production of the adsorbents contributes 60-91% of the total carbon footprint. The study goes further to highlight that the difference between the carbon footprints of the different adsorbents is minimal, considering uncertainties in the life-cycle inventories at their early development stage. It is also observed that no adsorbent has the best score in all sixteen environmental impact categories. This will lead to a compromise depending on which impact is more important to the particular project when selecting an adsorbent for a DAC unit.

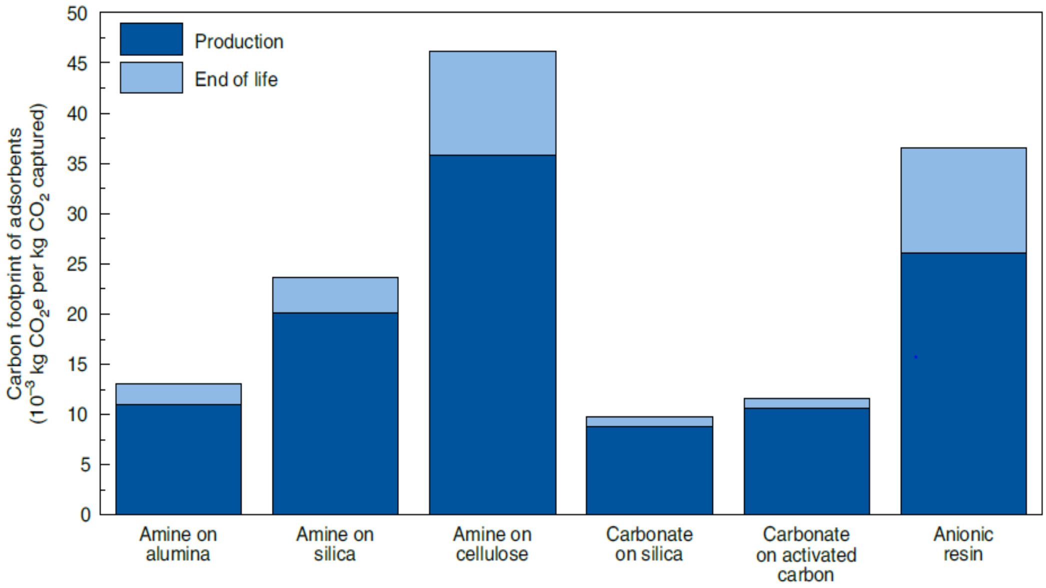


Figure 11: Carbon footprint of the adsorbents considered, over their entire life cycle.

Generally, the Amine on alumina performs better in almost all the impact categories but has a high human toxicity (cancer) impact, this is a result of the production of the alumina support. Whilst Silica production for amine on silica causes the depletion of material and metal resources. High eutrophication of freshwater is observed in the carbonate-based adsorbents caused by the production of potassium carbonate, they are also very similar to amine on alumina. The highest environmental impacts are displayed by amine on cellulose and anionic resin. Cellulose, the only bio-based material, is used in amine on cellulose, which is the reason for the high impact on land use. For anionic resin production, a generic process is used for its modelling. The process however leads to a high impact in ozone depletion as a result of heuristics in the life-cycle inventory. The author believes the heuristic does not give a realistic result in this case, which is why the ozone layer depletion impact of the anionic resin is not reported.

A sensitivity analysis of the adsorbents was performed to explore worst-case scenarios because of the uncertainties of the LCI data. The amine-based sorbents demonstrate that environmental impacts could increase by factors from 1.0 to 2.8, while higher factors between 3.6 to 4.6 were observed for anionic resin compared to the generic process.

Amine on silica is considered by (Deutz and Bardow 2021) as the adsorbent in the DAC for this study as a result of its average performance from an environmental perspective.

Table 15: Environmental impacts for the considered adsorbents and their relative differences compared to amine on silica (%)

Environmental impact	Unit	Amine on silica	Amine on alumina	Amine on cellulose	Carbonate on silica	Carbonate on silica	Anionic resin
Climate change	10^{-02} kg CO_2e	2.4	1.3 (+45.0)	4.6 (−95.3)	1.0 (+58.8)	1.2 (+50.8)	3.7 (−54.4)
Ozone depletion	10^{-10} kg CFC-11 equiv	6.9	3.7 (+47.1)	6.8 (+1.2)	6.0 (+13.9)	5.5 (+20.6)	*
Particulate matter	10^{-10} disease incidences	9.1	5.0 (+45.0)	12.0 (−31.5)	4.4 (+51.5)	4.7 (+49.0)	8.1 (+11.1)
Acidification, terrestrial and freshwater	10^{-04} mole H + equiv.	1.1	0.6 (+46.0)	1.1 (+1.2)	0.5 (+50.8)	0.6 (+44.0)	1.0 (+4.9)
Eutrophication, freshwater	10^{-06} kg P equiv.	2.4	1.3 (+45.0)	1.8 (+25.6)	4.0 (−66.0)	3.7 (−54.2)	5.6 (−133.5)
Eutrophication, marine	10^{-05} kg N equiv.	2.7	5.3 (+48.0)	5.2 (+1.6)	1.5 (+71.1)	2.0 (+62.8)	4.8 (+8.6)
Eutrophication, terrestrial	10^{-04} mole N equiv.	1.9	1.0 (+45.2)	2.8 (−48.9)	1.0 (+44.8)	1.5 (+21.4)	2.2 (−16.9)
Ionizing radiation	10^{-03} kBq ^{235}U equiv.	2.5	1.5 (+40.9)	2.1 (+15.2)	0.8 (+66.6)	1.5 (+39.7)	1.0 (+60.3)
Photochemical ozone formation	10^{-05} kg NMVOC equiv.	5.3	2.9 (+44.7)	7.6 (−43.1)	2.6 (+50.4)	3.8 (+28.2)	6.9 (−28.9)
Human toxicity, cancer	10^{-10} CTUh	1.4	2.0 (−43.8)	1.4 (−1.2)	1.1 (+22.2)	1.0 (+28.7)	3.4 (−144.3)
Human toxicity, non-cancer	10^{-10} CTUh	9.1	7.4 (+18.5)	10.5 (−15.4)	9.6 (−4.9)	9.4 (−3.4)	17.6 (−93.7)
Ecotoxicity, freshwater	10^{-03} CTUe	5.7	4.4 (+22.4)	5.1 (+10.2)	3.6 (+36.0)	3.3 (+41.0)	10.7 (−89.7)
Land use	10^{-01} Pt	1.1	0.6 (+39.1)	24.5 (−2,210.6)**	0.7 (+36.9)	1.0 (+1.5)	0.6 (+44.4)
Water scarcity	10^{-03} m^3 world equiv.	9.9	5.0 (+49.3)	17.7 (−78.7)	4.5 (+54.1)	4.9 (+50.8)	12.2 (−23.2)
Resource depletion, energy	10^{-01} MJ	4.4	2.4 (+46.2)	6.7 (−53.0)	1.4 (+68.2)	1.8 (+59.3)	4.4 (−0.8)
Resource depletion, mineral and metals	10^{-08} kg Sb equiv.	3.9	1.9 (+51.5)	2.0 (+47.8)	6.3 (−60.3)	4.7 (−18.7)	8.1 (−106.8)

III. PLANT CONSTRUCTION

The DAC plant capacity considered for the paper by (Deutz and Bardow 2021) is 4ktCO_2/yr. The plant construction has a carbon footprint of 15gCO_2e per kilogram of CO_2 captured, without metal recycling which is the worst-case scenario. For the best-case scenario with metal recycling of the DAC unit, the plant construction has a carbon footprint of 6gCO_2e per kilogram of CO_2 captured. According to (Deutz and Bardow 2021), the reason for the carbon footprint in the scenario with metal recycling is mainly due to the foundation and hall (the building housing the process unit). It contributes 74% of the total carbon footprint. The container collectors and process unit accounts for 13% and 12% respectively, with spare parts accounting for less than 1%.

Table 16: Other environmental impacts of the DAC unit construction

Impact Category	Process	Percentage
Eutrophication of freshwater	Steel production for foundation	63-94%
Human toxicity (cancer)	Steel production for foundation	63-94%
Ecotoxicity of freshwater	Steel production for foundation	63-94%
Resource depletion of minerals and metals	Copper production	87%
All other impacts	Concrete	32-70%
	Foundation steel	11-39%
	Stainless steel	18%
	Insulation	16%
	Aluminium	12%
	Steel	5%
	Painting (Copper and steel)	4%
	Plastics	2%

4.2.2 LIFE CYCLE ASSESSMENT OF GREEN HYDROGEN USING PEM ELECTROLYSER

The potential environmental impacts associated with the production of 1kg of green hydrogen from the DAC-PtG unit is presented in this section. The Recipe 2016 V1.1 Midpoint (H) method is used for the assessment of the environmental impacts. The following impact categories are included in the analysis:

- Global Warming Potential (Climate Change)
- Terrestrial Acidification
- Human Toxicity (Cancer)
- Eutrophication Freshwater
- Land Use
- Ozone Depletion
- Photochemical Ozone Formation-Human Health
- Ecotoxicity Freshwater
- Fine Particulate Matter Formation
- Freshwater consumption

The impact categories chosen are directly related to environmental risks. The most relevant for this study is the global warming potential (GWP)/climate change impact category. It translates to the potential increase in greenhouse gas emissions leading to an increase in average global surface temperature.

Table 12: Recipe 2016 V1.1 Midpoint (H) Environmental impacts for 1kg of H2 produced from a PEM electrolyser

Environmental Impact Category	**Units**	**Value**
Climate Change	kg CO2 eq.	2.86
Terrestrial Acidification	kg SO2 eq.	0.00808
Human Toxicity (Cancer)	kg 1,4-DB eq.	0.0019
Eutrophication Freshwater	kg P eq.	4.78e-6
Land Use	Annual crop eq. yr.	0.138
Ozone Depletion	kg CFC-11 eq.	7.19e-7
Photochemical Ozone Formation-Human Health	kg NOx eq.	0.00559
Ecotoxicity Freshwater	kg 1,4-DB eq.	0.0006
Fine Particulate Matter Formation	kg PM2.5 eq.	0.00272
Freshwater consumption	m3	0.038

The results obtained in this study are further compared with results obtained from the study of (Mehmeti et al. 2018) and (Bareiß et al. 2019), both studies use the midpoint environmental indicator for the analysis of their results. All three analyses use different energy sources. (Mehmeti et al. 2018) uses wind energy as the primary energy source whilst (Bareiß et al. 2019) use an energy mix of 65% wind energy and 35% solar energy in the future scenario of 2050, which is used in this comparison.

Table 13: Comparison of environmental impacts using the midpoint method

Impact Category	Unit	DAC-PtG	Mehmeti et al. 2018	Bareiß et al. 2019
Climate Change	kg CO2 eq.	2.86	2.21	3.0
Ozone Depletion	kg CFC-11 eq.	0.719e-6	1.40e-6	2.3e-6
Human Toxicity-Cancer	kg 1,4-DB eq.	0.0019	0.43	5.6
Terrestrial Acidification	kg SO2 eq.	0.00808	0.0118	0.021
Particulate Matter Formation	kg PM2.5 eq.	0.00272	0.0041	0.011 (PM10-eq)

From the comparison, it is observed that the study of (Mehmeti et al. 2018) has a lower global warming potential (Climate Change) environmental impact whilst the DAC-PtG has lower environmental footprints in all the other impact categories. It is also expected that the DAC-PtG will have a higher land use environmental impact compared to both the studies of (Mehmeti et al. 2018) and (Bareiß et al. 2019) as solar PV uses more land space compared to wind.

From the environmental impact assessment, it is observed that the energy source used, which is solar photovoltaic, is the highest contributor to the environmental footprint in the DAC-PtG system. This is presumably due to the raw materials used in the manufacturing of PV cells, the amount of energy used in the individual processes, and the total land use. As per (Mehmeti et al. 2018), electrolysis is an energy-intensive method of hydrogen production. Irrespective of the electrolyser used if the environmental impact is limited to the electricity supply chain.

The global warming potential for green hydrogen produced from DAC-PtG is within the same range as hydrogen produced from renewable energy sources using PEM water electrolyser. But slightly higher than green hydrogen produced using wind energy. The comparison with other life-cycle assessments as seen in Table 13, shows that all other environmental impacts are lower in the DAC-PtG hydrogen production pathway compared to the other pathways. The results graphs of the Recipe 2016 V1.1 Midpoint (H) environmental impacts, are presented under the appendix section. They show the individual processes involved in the production of green hydrogen from the PEM water electrolyser and their corresponding environmental impacts.

Table 14: Midpoint impact categories and their relationship with endpoint category indicators.

Human Health	**Ecosystems**	**Resources**
Global Warming Potential / Climate Change	Global Warming Potential / Climate Change	
Human toxicity (Cancer)	Terrestrial Acidification	
Ozone Depletion	Freshwater Eutrophication	
Photochemical Ozone Formation-Human Health	Land Use	
Fine Particulate Matter Formation	Ecotoxicity Freshwater	
Freshwater consumption		

Human health damage, ecosystem quality and resource scarcity were quantified on the end point level, similar to the study of (Mehmeti et al. 2018). The midpoint environmental indicators and their connection with endpoint indicators are presented in Table 14.

The environmental impacts obtained from the LCA should not be regarded as a precise prediction, but rather an indication to shed light on the advantages and disadvantages of hydrogen production from the DAC-PtG compared to other hydrogen production pathways.

4.3. RISKS AND UNCERTAINTIES IN GREEN HYDROGEN PRODUCTION FROM DIRECT AIR CAPTURE

(Terlouw et al. 2022) states that several recent studies have quantified hydrogen production costs or environmental burdens generated via electrolysis. This shows that previous studies have several limitations in their environmental and economic analysis. They were either limited to hydrogen production costs or greenhouse gas emissions, with none addressing the possible conflicting goal of minimising costs and life cycle greenhouse gas emissions from hydrogen production. It can be deduced from this study that production costs can have a direct impact on environmental footprint. The higher the production costs, the higher the environmental footprints, this can be seen in the DAC unit construction. If recycled material is used for the construction, cost is lowered and the environmental footprints is also reduced. Another scenario is the use of solar energy, if the capacity of solar PV is increased, the cost increases and so does the environmental footprint.

Findings from this study identify the following as risks of green hydrogen production from the DAC-PtG technology:

- Amount of CO_2 output from the DAC-Unit
- Electrolyser cost
- Electrolyser Efficiency
- Change in Weighted Average Cost of Capital
- Source of energy used
- Type of electrolyser
- Type of adsorbent used for the DAC unit
- Material used for the DAC plant and foundation

5. PROJECT MANAGEMENT STRATEGY PROPOSED

1. Identify a location with high renewable energy potential: The environmental footprint of green hydrogen from the DAC-PtG technology is strongly dependent on the source of energy used. Low-carbon energy sources will reduce the environmental impacts of the technology. Wind energy should be the first option as an energy source if the potential is available, the second option is a hybrid energy system of wind and solar energy, and the third option is solar photovoltaics.
2. A battery technology should be included in the system as a complimentary technology which will eventually increase the financial sustainability of the project. When a battery system is included, green hydrogen production is increased. The finding of this study shows that the LCOH increases when battery technology is not used and decreases when a battery is introduced, whilst the reverse is correct for the financial sustainability of the project.
3. Polymer exchange membrane (PEM) water electrolysers should be used for hydrogen production instead of Alkaline electrolyser or Solid oxide electrolyser (SOEC). The PEM electrolyser having high power density will result in lower global warming potential compared to the alkaline electrolyser. The paper of (Bareiß et al. 2019) states that alkaline electrolyser have lower power densities and the system is correspondingly larger than the PEM electrolyser. It goes further to state that the alkaline electrolyser in their study weighs 30 tonnes which is twice the weight of the PEM electrolyser. For the SOEC, the paper of (Mehmeti et al. 2018) mentions that hydrogen production from an SOEC has a potential advantage over PEM electrolysis and has less environmental impacts. This is because 28% of the energy requirement is provided in the form of heat, which means that up to 40% of the energy requirement for H_2 production using SOEC can be supplied as heat. However, according to the findings of this study, the SOEC requires a longer start-up time. Whereas the DAC-PtG electrolysis system is dependent on water produced from the DAC unit which undergoes a cyclic process. The electrolyser might have to be shut down within intervals depending on the water availability. If the electrolyser requires a long start-up time, the target amount of hydrogen production might not be achieved. This can render the project financially

unsustainable. (The International Renewable Energy Agency) also highlights some disadvantages of the SOEC such as faster degradation and shorter lifetime caused by thermo-chemical cycling caused by shutdown or ramping.

4. Cost-saving methods should be employed when purchasing equipment. This can be achieved by having contracts with vendors where both parties gain. A continuous contract with one vendor at a reduced market price means that the supplier is sure of selling their product and the project can benefit from cost savings, which again will increase project financial sustainability.
5. Select a project location with a strong legal framework. This will have an impact on the weighted average cost of capital (WACC) which means that discount rates will be set to a certain degree and not fluctuate.
6. Green purchasing methods should be used when purchasing project material, especially for solar PV equipment. Minimise transport distance by purchasing at the nearest supplier to the project site or use low carbon transport options.
7. High-efficiency PEM electrolysers with the lowest water requirement should be the best alternative for the DAC-PtG technology.

6. CONCLUSION AND RECOMMENDATIONS

Climate change is the key driver of hydrogen in the energy transition. Green hydrogen which is hydrogen produced from low carbon-intensive methods can be used in electricity production, chemical industries, the transport sector as e-fuels, and all other sectors that use hydrogen as a resource. Hydrogen was produced before and continues to be produced using carbon-intensive methods, like steam methane reforming which increase CO_2 emissions. The production of green hydrogen is mainly hindered by either the availability of renewable energy resources or water availability. In most cases, places with high renewable energy potential have limited water availability as seen in arid or semi-arid regions.

The DAC-PtG technology which captures CO_2 from the atmosphere through a carbon dioxide recovery (CDR) method called direct air capture (DAC), co-adsorbs water from the atmosphere and uses the co-adsorbed water for hydrogen production using a PEM electrolyser. The DAC-PtG technology is a solution that reduces CO_2 emissions in the atmosphere in two ways. First by removing CO_2 from the atmosphere through CDR. Secondly, by producing green hydrogen which is a low carbon energy carrier with limited environmental footprints and can help limit global warming to below 2°C.

The DAC-PtG is an emerging technology that has certain economic and environmental risks and uncertainties that need to be limited or managed as identified in this study. The highlighted risks are; the amount of CO_2 output; which directly influences the amount of water co-adsorbed for the hydrogen production. A decrease in the amount of CO_2 output translates to decreased hydrogen production and increased LCOH. Change in electrolyser cost will have an impact on the LCOH and financial sustainability. The higher the electrolyser cost, the lower the financial sustainability of the project and vice versa. Reduction of electrolyser efficiency highlights a decrease in hydrogen production which also signifies reduced financial sustainability of the project. Another economic risk that harms financial sustainability is an increase in the weighted average cost of capital (WACC).

For the environmental impacts, the source of energy used is a key factor for environmental footprints. Renewable energy sources should be the only alternative used for the DAC-PtG technology. From the analysis of this study the solar PV energy source used is a key contributor to environmental footprints. The global warming potential for 1kg of hydrogen produced from a PEM electrolyser is 2.86kgCO_2 eq. which was all contributed by the solar PV system. The adsorbent for the DAC unit also contributes to environmental footprints with the highest impact observed in the production stage, approximately 60-91% of the total environmental footprints of the adsorbent are contributed by the production stage. Amine-on-silica is considered for this study as a result of its average environmental footprint. The plant construction of the DAC unit also contributes to environmental footprints mainly due to the building of the foundation and hall which contributes 74% of the total carbon footprint of the DAC unit. This can however be reduced through metal recycling.

Recommendations for this study are; to perform a combined life-cycle assessment of the DAC-PtG technology. This will give a detailed insight into the environmental impacts associated with 1kg of H_2 produced from the DAC-PtG unit. This study is limited by the availability of data, which is the reason for the partial LCA study and literature review. Preliminary studies should be carried out to get accurate data on the factors that can affect the amount of water co-adsorbed with CO_2, and the relationship with relative humidity. Data sets that allow an increase in efficiency in the production phase of renewable energy technologies should be created. This will visualise the actual reduction of global warming potential of products that use renewable energy resources for their production, like green hydrogen. It will also be of great advantage to do a life-cycle assessment of a DAC-PtG technology powered by other forms of renewable energy other than solar PV. This will help in the comparison of environmental impacts to identify the most environmentally sustainable DAC-PtG pathway.

6.1. LIMITATIONS

1. The relationship between relative humidity and the amount of CO_2 and water captured could not be established. It is not known whether there will be an equal production of water to CO_2 if the CO_2 output changes in different relative humidity.
2. Lack of data for administrative and land cost in Ivory Coast which is the location for this study.
3. Data on the project location; Ivory Coast was not available in the database for the LCA study.
4. Identifying project management strategies to avoid certain environmental risks. Some of the environmental risks might come from the manufacturing processes of other

components used in the overall system, like solar panels. The project management strategy can only address such risks at a certain level, by using green purchasing techniques if available. Otherwise those risks cannot be avoided by the project management strategy.

5. Different assumptions of functional units, system boundaries, system sizes, and evaluation methods are used. The DAC unit uses a functional unit of 1kg CO_2 whilst the Electrolysis process for hydrogen production uses 1kg H_2 as a functional unit. This is a result of the lack of sufficient data to perform a complete LCA rather than a partial one.
6. Lack of transparency in most of the LCAs used in the review, andcfull identification of sources of discrepancies is not possible.
7. Some relevant data for the PEM construction was not available in the GABI software, like the Nafion (a polymer material made by DuPont) which is the most commonly used proton exchange membrane.

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APPENDIX

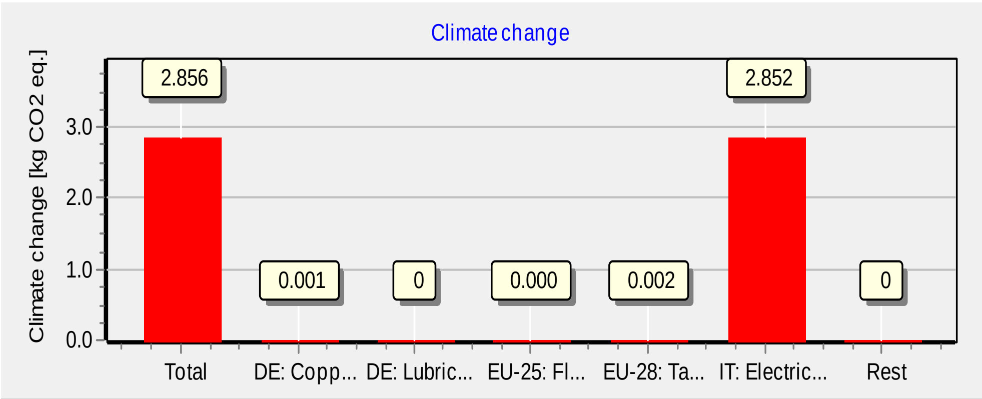

Figure 12 Recipe 2016 v1.1 Midpoint Environmental Impact (Global Warming Potential / Climate Change)

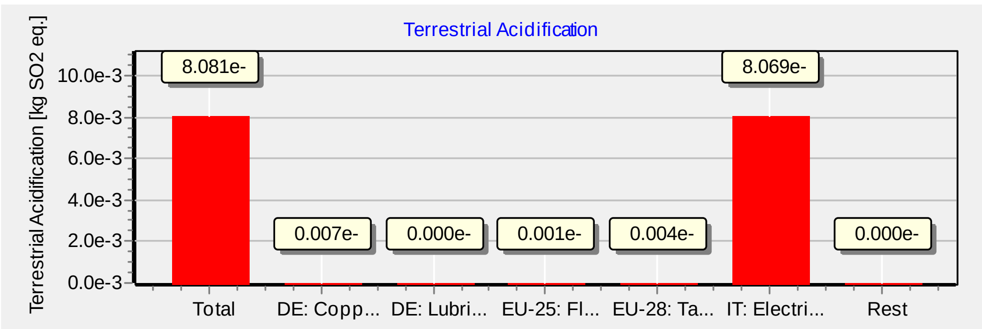

Figure 13 Recipe 2016 v1.1 Midpoint Environmental Impact (Terrestrial Acidification)

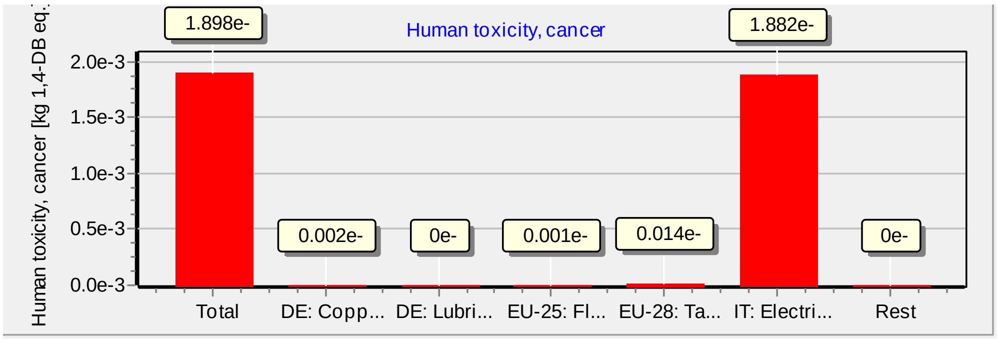

Figure 14 Recipe 2016 v1.1 Midpoint Environmental Impact (Human Toxicity, Cancer)

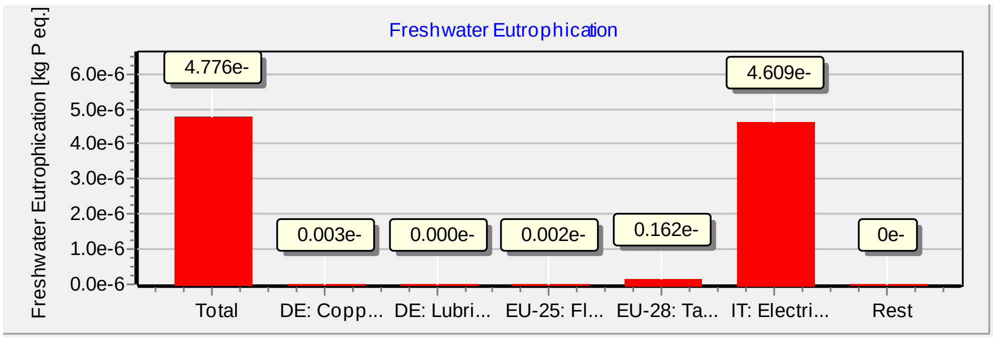

Figure 15 Recipe 2016 v1.1 Midpoint Environmental Impact (Freshwater Eutrophication)

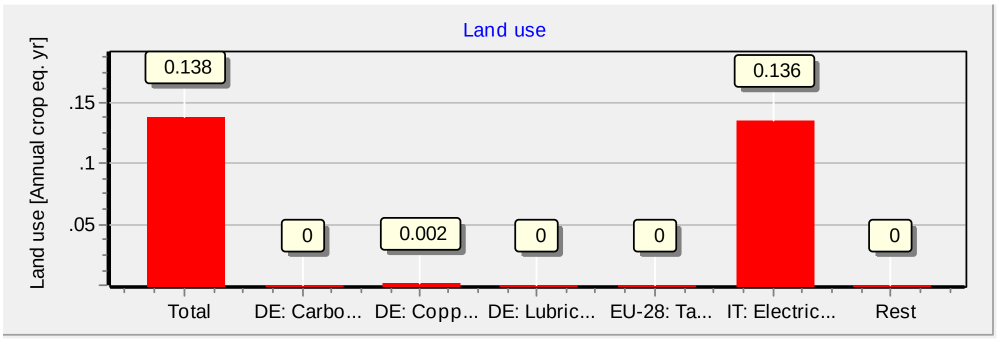

Figure 16 Recipe 2016 v1.1 Midpoint Environmental Impact (Land Use)

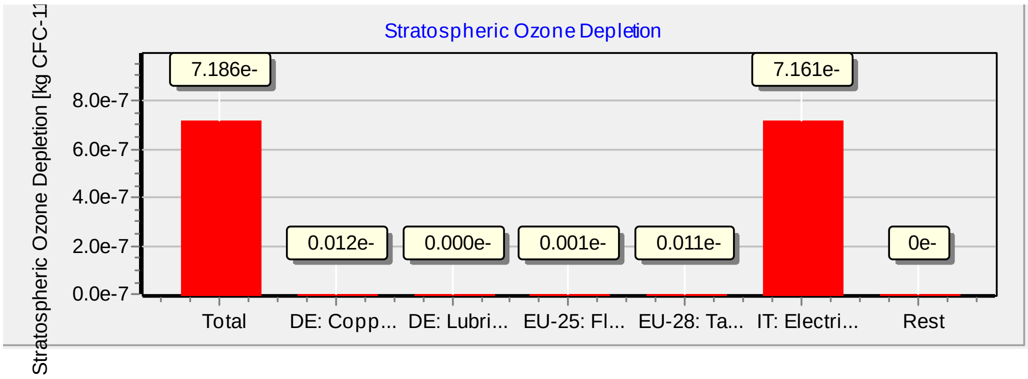

Figure 17 Recipe 2016 v1.1 Midpoint Environmental Impact (Stratospheric Ozone Depletion)

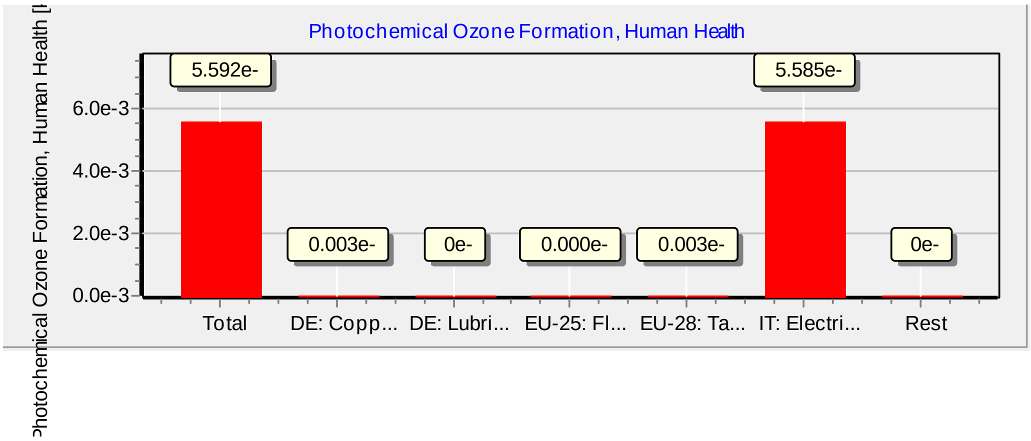

Figure 18 Recipe 2016 v1.1 Midpoint Environmental Impact (Photochemical Ozone Formation, Human Health)

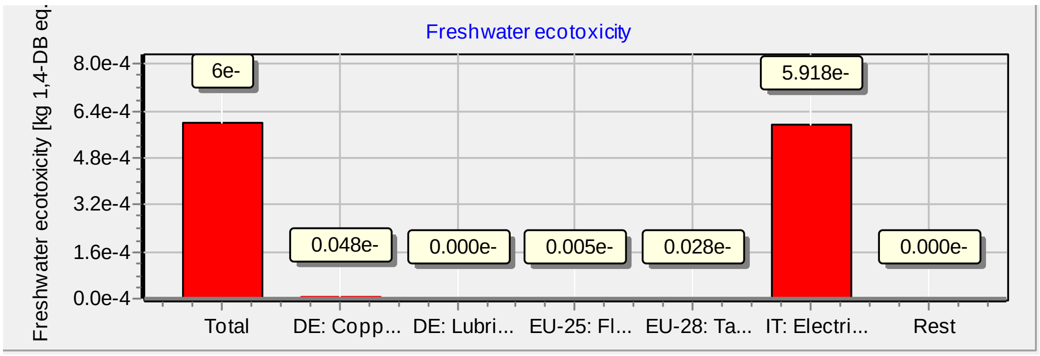

Figure 19 Recipe 2016 v1.1 Midpoint Environmental Impact (Freshwater Ecotoxicity)

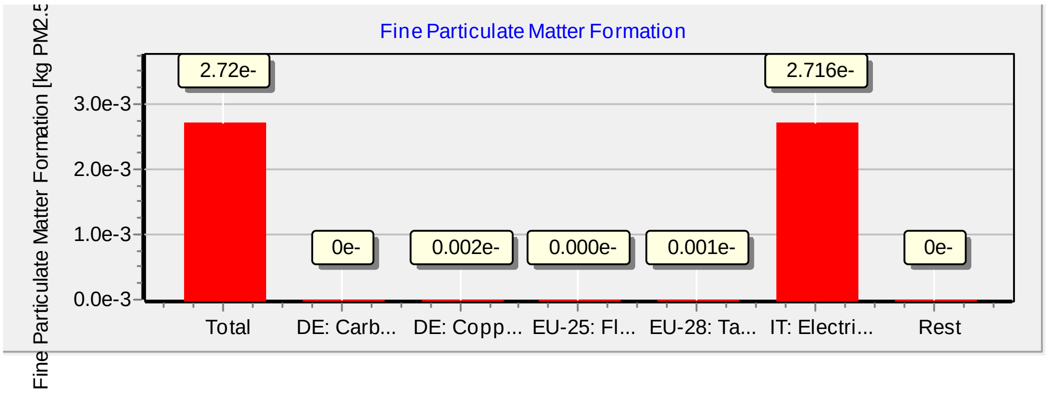

Figure 20 Recipe 2016 v1.1 Midpoint Environmental Impact (Particulate Matter Formation)

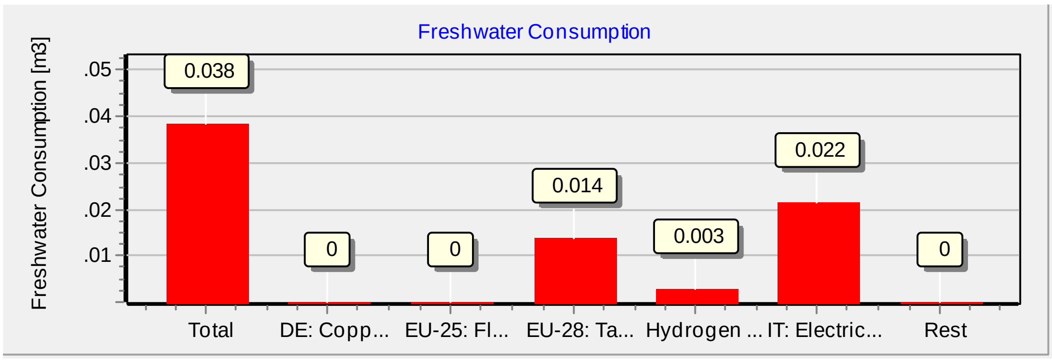

Figure 21 Recipe 2016 v1.1 Midpoint Environmental Impact (Freshwater Consumption)

DECLARATION OF AUTHORSHIP

I, Sohna Huja Jeng declare that this thesis and the work presented in it are my own and have been generated by me as the result of my own original research.

I do solemnly swear that:

1. Where I have consulted the published work of others or myself, this is always clearly attributed;

2. Where I have quoted from the work of others or myself, the source is always given. This thesis is entirely my own work, with the exception of such quotations;

3. I have acknowledged all major sources of assistance;

4. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;

5. None of this work has been published before submission;

6. During the preparation of this work, no tools were used to edit the writing of the thesis. I personally reviewed and edited the content as needed and take full responsibility for the content.

Date: 24th August 2021 Signature: