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Cost modelling of Direct air capture for Water-conscious generation of hydrogen and e-methanol in arid regions

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Dedicace

I dedicate this thesis to my entire family, especially my mother, Fatou SANGARE and my father, for all the sacrifices that have made me the man I am today.

May this work be a comfort to you.

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Abstract

The production of fuels from renewable energy sources and CO2 is a good way to move forward and mitigate climate change, reduce greenhouse gases and achieve a sustainable energy transition. This work presents a cost model for the production of e-methanol using hydrogen and CO2 with a target of 10,000 tonnes of e-methanol per year. The proposed model is an integrated system that includes a solid direct air capture system to produce carbon dioxide and water as feedstocks for the methanol reactor as well as a solid oxide electrolysis cell to produce hydrogen which is combined with CO2 in the reactor to produce e-methanol. The overall system is powered by a PV+batteries system. An economic analysis was conducted to determine the cost implications of the project, considering a 20-year lifetime and a 5% discount rate. Our analysis shows that variable operating costs represent 50% of the total project costs over the life of the project, followed by capital expenditure (29%) and fixed operating costs (21%). The levelized cost method was used to determine the price of the outputs. Therefore, the analysis showed a levelized cost of electricity (LCOE) of 0.11 €/kWh, while the levelized cost for carbon dioxide and water were 335.45 €/t and 238.70 €/t, respectively. Due to the immaturity of solid oxide electrolysis and the cost of electricity, which influences the cost of green hydrogen production, we have a levelized cost of hydrogen (LCOH) of 8459.91€/t. The production of e-methanol is mainly influenced by the cost of green hydrogen and carbon dioxide. The levelized cost of e-methanol is estimated at 2144.35€/t. However, under current market conditions, our methanol is uncompetitive compared to the fossil-based methanol which is priced at 395 €/MT. A sensitivity analysis was conducted to assess the influence of some parameters such as the chemicals replacement, electricity and water on the cost. The results have shown that the cost of electricity and the maturity of technologies using innovative materials significantly affect the cost of green hydrogen and subsequently the cost of e-methanol. Making e-methanol competitive and accessible at a lower price requires more research and development, policies and regulations to accelerate the energy transition to a world without greenhouse gas emissions.

Key words: Cost model; direct air capture; e-methanol

Résumé

La production de carburants ou combustibles à partir de sources d'énergie renouvelable et de CO2 tel que le méthanol offre une bonne voie à suivre et une solution pour atténuer le changement climatique, réduire les gaz à effet de serre et réaliser une transition énergétique durable. Cette étude présente un modèle économique pour la production d'e-méthanol en utilisant de l'hydrogène et du CO2 avec un objectif de 10 000 tonnes d'e-méthanol par an. Le modèle proposé est un système intégré comprenant un système de capture de CO_2 dans l'air appelé capture d'air direct solide ou à basse temperature pour produire du CO2 et de l'eau en tant que matières premières pour le réacteur de methanol. Il comprend egalement un electrolyseur, une cellule d'electrolyse oxide solide, pour produire l'hydrogene qui est ensuite combinée avec le CO_2 dans le réacteur pour produire de l'e-méthanol. L'ensemble du système est alimenté par un système photovoltaïque avec batteries pour le stockage de l'énergie. Une analyse économique a été réalisée afin de déterminer les implications financières du projet, en tenant compte d'une durée de vie de 20 ans et d'un taux de réduction de 5 %. Notre analyse montre que les coûts opérationnels variables représentent 50 % des coûts totaux du projet sur la durée de vie du projet, suivis des dépenses en capital à 29 % et des coûts opérationnels fixes à 21 %. La méthode du coût nivelé a été utilisée pour déterminer le prix des produits. Ainsi, l'analyse a montré un coût nivelé de 0,11 €/kWh, avec un cout respectif de 335,45 €/t pour le dioxyde de carbone et de 238,70 €/t pour l'eau. En raison du caractère encore immaturee de l'électrolyse à oxyde solide et du coût de l'électricité, qui influe sur le coût de production de l'hydrogène vert, nous avons obtenu un coût nivelé de 8459,91€/t. La production d'e-méthanol est principalement influencée par le coût de l'hydrogène vert et du dioxyde de carbone. Le coût nivelé de l'e-méthanol est estimé à 2144,35 €/t. Cependant, dans les conditions actuelles du marché, notre méthanol n'est pas compétitif par rapport au méthanol d'origine fossile vendu à 450 €/t. Dans le but d'évaluer l'influence de certains paramètres sur le cout de production d'un kilogramme, une analyse de sensibilité a été réalisée. Les résultats ont montré que le coût de l'électricité et la maturité des technologies utilisant des matériaux innovants ont un impact significatif sur le coût de l'hydrogène vert et, par conséquent, sur le coût de l'e-méthanol.Rendre l'e-méthanol compétitif et accessible à un prix inférieur à celui du marché actuel nécessite davantage de recherche et développement, ainsi que des politiques et des réglementations pour accélérer la transition énergétique vers un monde sans émissions de gaz à effet de serre.

Mots clés : Modélisations des coûts, direct air capture, e-méthanol

Acronyms and Abbreviations

AC: Alternating current
AEL: Alkaline electrolyser
CAPEX: Capital expenditures
CC: Carbone cost
CCU: Carbon capture and utilization
CCUS: Carbon capture utilization and storage
CH3OH: Methanol chemical formula
CO: Carbon monoxide
CO2: Carbone dioxide
DAC: Direct air capture
DC: Direct current
EC: Electricity cost
EU: European union
GJ: Giga joule
H2C: Hydrogen cost
IEA: International Energy Agency
IFC: International Finance Corporation
IPCC: Intergovernmental Panel on Climate Chage
IRENA: International Renewables Energy Agency
KW: Kilowatt
KWh: Kilowatt hour
L-DAC: Liquid Direct air Capture
LCOC: Levelized cost of carbone dioxide
LCOE : Levelized cost of electricity
LCOH : Levelized cost of hydrogen
LCOM : Levelized cost of methanol
LCOW : Levelized cost of water
LHV: Lower Heating Value

MJ: Mega joule

MT: Metric ton

MtCO2: Million tons of carbone dioxide

MW: Megawatt

NPV: Net present value

OECD : Organisation for Economic Co-operation and Development

OPEX: Operation expenditures

PEM: Polymer electrolyser membrane

PV: Photovoltaic

rSOC: Reversible solid oxide cell

S-DAC: Solid Direct air capture

SiO2: Silicon dioxide

SOEC: Solid Oxide Electrolysis Cell

SOFC: Solid Oxide Fuel Cell

tCO2: Ton of carbone dioxide

tMeOH: Ton of methanol

TRL: Technology readiness level

USD: US dollar

WC: Water cost

YSZ: Yttria-stabilized zirconia

ZnO: Zinc Oxide

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1. Introduction

The burning of fossil fuels is the main source of both air pollution and greenhouse gas emissions that drive climate change. In 2018, fossil fuels and industry were responsible for 89% of global CO_2 emissions(Solomon et al., 2022).

The energy transition is a major issue of our time, as it aims to reconcile access to clean and sustainable energy for all, while reducing greenhouse gas emissions to limit global warming to below 2 degrees Celsius as reported in the Paris Agreement.

One of the major issues facing humanity in the twenty-first century is providing enough energy to the world's population to fulfill desired living standards (International Energy Agency, 2022).

More than 85% of human energy demands are currently satisfied by the combustion of fossil fuels, which can be easily collected from stockpiles of concentrated natural photosynthetic products such as coal, oil, and natural gas.

However, the use of fossil fuels results in the release of greenhouse gases, specifically carbon dioxide, which is the primary cause of climate change. To reduce our dependence on fossil fuels, address their negative effects, and move towards a sustainable and carbon-neutral energy future, innovative methods for producing clean energy are essential. It is crucial to implement significant changes in policies and adopt new, sustainable energy sources on a large-scale.

Negative carbon technologies research is ongoing to find solutions and efficiently face these issues. Direct air capture is prominent among these strategies (Dods et al., 2022).

Direct air capture (DAC) is a new technology that was launched in the late twentieth century to reduce ambient carbon dioxide concentrations.

Direct air capture technologies have the potential to help cut CO2 emissions in the environment while also serving as a climate-neutral feedstock for a variety of products ranging from synthetic aviation fuels to food and drinks (International Energy Agency, 2022).

Some research around the world have been done to assess the feasibility of methanol production. Bos et al.,(2020); Dieterich et al., (2020); Pérez-Fortes et al.,(2016) assessed in their respective work on methanol production using CO2 capture and hydrogen from PEM electrolysers. About the cost, Lee,(2022); Schorn et al., (2021); Sollai et al., (2023) worked on the techno-economic assessment of methanol production and transportation when those researchers like Rafiee, (2020); Van-Dal & Bouallou, (2013) worked on designing and simulation of methanol synthesis.

This research providing one the first literature on the e-methanol production using Solid direct air capture and Solid Oxide Electrolysis cell powered by solar pv system, aims to develop a theoretical framework and analyses a model to assess the feasibility, the cost implication, and economic viability of this integrated system in arid regions.

Methanol is an important chemical building block and a promising new energy source. It is used in a variety of sectors as a solvent, antifreeze, and in the creation of synthetic fuels and building materials. It also has the potential to be used as a vehicle fuel. It is possible to improve engine efficiency and achieve large energy savings by using methanol as a fuel in internal combustion engines (IEA, 2021; Methanol Institute, 2023).

Methanol cost are impacted by a variety of factors, including manufacturing technology and the source of CO2 utilised. Furthermore, the viability of large-scale e-methanol production is dependent on the availability of low-cost green hydrogen and CO2.

The renewable energy potentials especially solar, producing renewable e-methanol utilizing green hydrogen as feedstock in arid locations can be cost effective.

IBERDROLA states that there's a new growth opportunity for the green hydrogen industry in green methanol production for e-methanol generation.

An issue is the water to produce the green hydrogen and Freshwater scarcity is a global issue that threatens human life, particularly in arid places.

The system model proposed in this work in line with the DryHy project is an integrated system including renewable from PV, Solid DAC plant to provide CO_2 and water to feed an SOEC which will provide green hydrogen and a methanol synthetiser feed by the CO_2 and H_2 produced.

Because water is captured from the air, no liquid water is required for operation, making it a "water neutral" process. This may enable the building of free-standing devices in regions where there is no close water supply, such as along roadways or in isolated areas.

Water is now an important resource in all regions of the world, and global water scarcity is now a reality, with countries in the arid and semi-arid zones already experiencing catastrophic water scarcity. This condition necessitates a far more efficient use of water resources in the future. According to the information currently available, Liquid-Direct air Capture (L-DAC) requires water for operation, whereas S-DAC can extract water from the air, around 0.8-2 tons of water per ton of CO2 captured from the atmosphere. The vast ranges are determined by DAC technology, atmospheric temperature and humidity, as well as L-DAC solution concentration (International Energy Agency, 2022).

As reported by Dods et al., (2022)the prospect for removing water alongside CO_2 has been investigated and dependent to the chemisorbent used and the process conditions, we can harvest water with sufficient high purity for industrial, agricultural or potable use.

S-DAC could supply water for its own use in arid regions or supply water to an electrolyser that produces hydrogen, synthetic fuels and captures CO2(International Energy Agency, 2022).

According to Van-Dal & Bouallou, using captured CO2 as a raw material in the manufacturing of a commercial product might become not only economically viable but also profitable.

Lee stated in his 2022 thesis that an economic analysis anticipated a $2 billion capital cost and a $400 million annual operational cost, with the DAC to methanol synthesis unit expected to make $570 million in income yearly.

In a variety of climatic situations across Europe and North America, DAC facilities have been successfully operated. Thus, additional testing would be required in regions with exceptionally dry, humid, or polluted climates (International Energy Agency, 2022).

As a result, numerous investigations are required to evaluate the feasibility, the performance of this technology, environmental issues, risks and management in arid regions.

Scope of the study

This study, titled "Cost Modelling of Direct Air Capture for Water-Conscious Generation of Hydrogen and e-methanol in arid regions," is a part of the DryHy pilot project. The objective of the project is to employ CO2 capture technology to produce e-fuels using renewable energy sources in dry environments.

In this study, we focus on modeling the cost of producing hydrogen and e-methanol by capturing CO2 from the ambient air in arid regions using direct air capture (DAC) technology. We assume a production target of 10 000 tons of methanol per year to analyze the cost implications. The system incorporates a Solid DAC to provide the necessary CO2 and a Solid Oxide Electrolysis Cell for hydrogen production. The entire system is powered by a solar PV system.

Bouake, a region in the center of Cote d'ivoire, is the area selected in our study due to its solar and the energy production potential and its emplacement, also to be in line with the country chosen by the DryHy project which is Cote d'ivoire. The choice of the country is justified also by the political and economic stability, the safe investment atmosphere and others factors linked to the transportation and distribution.

Objectives

The overarching goal of our research is to develop a cost model of Direct Air Capture Technology for hydrogen generation and e-methanol.

In order to reach the overall objective, the specific objectives will be to:

- Define the inputs, outputs, and cost drivers of the overall system;
- Develop the cost model ;
- Analyze the sensitivity to evaluate the cost of 1 kg of hydrogen and e-methanol in relation to some parameters.

Research question:

- **Main research question:**

How can a cost model of direct air capture for Water-conscious generation of hydrogen and e-fuels in arid regions look like?

- **Specific research questions:**

- What are the inputs, outputs and the cost drivers of DAC for Water-conscious generation of hydrogen and e-methanol in arid regions?
- What is the structure of the cost model of DAC for Water-conscious generation of hydrogen and e-methanol in arid regions?
- What is the cost of 1 Kg of hydrogen and e-methanol generated when changing some parameters?

This study is divided into five main sections:

- Introduction
- Literature review
- Empirical data analysis
- Results
- Conclusion and recommendations

As we delve into the existing body of research, it is essential to contextualize our study within the broader scholarly conversation surrounding e-methanol production using direct capture, building upon previous work while also identifying gaps and areas that warrant further exploration.

2. Literature review

This part presents the different works and research done in the field of hydrogen and methanol production using solid oxide electrolysis cell and direct air capture technologies.

Regarding methanol production using air capture technologies, many studies have been done and are ongoing in terms of technical aspects as well as economic feasibility and assessment of the implementation of methanol production project.

2.1. Current state of DAC

From the introduction of direct air technologies to nowadays, the published papers have significantly increased and that can be explained by the importance of the subject and the seek of solutions to reduce greenhouse gases emissions, mitigate climate change and at the same time produce energy.

The call to find solutions to mitigate greenhouse gases emissions and technologies have seen the creation of industries and institutions in order to make use of this captured CO_2.

DAC is technically feasible today, with the latest IPCC report in 2021 clearly stating that urgent climate action is needed to halve emissions by 2030. To do so, we must both drastically reduce emissions and remove legacy CO2 emissions from the air. In order to permanently remove the CO2 emissions, we've captured, we combine our DAC technology with CO2 storage and safely transport them deep underground. Direct air capture and storage, or DAC+S, represents a permanent carbon removal solution(Climeworks, 2022).

The International Energy Agency affirmed in their report in 2022 on DAC that DAC technologies could play an important role to their Net Zero Emissions Scenarios by 2050. The CO_2 capture by the DAC is more than 85Mt in 2030 and 980Mt.

In comparison with CO2 capture from large point sources, DAC displays several intriguing advantages. An outstanding advantage of DAC is that it can address emissions from distributed sources as well as point sources(Yu, 2018).

DAC technology is a promising approach within the larger carbon emissions removal portfolio, and it has benefits compared to other carbon removal approaches, which include few practical limits on scaling, relatively little land area use, and siting flexibility(Ozkan, 2021; Sabatino et al., 2021).

Around the world DAC technologies are been developing by many companies, the three main companies involved in the manufacture and implementation of these plants are:

Climeworks AG, founded in Switzerland in 2009 Gebald and Wurzbacher as a spin-off of the research university ETH Zurich. The company has to date commissioned 15 plants worldwide and has been supported by both public and private investors including the largest private investment to date in DAC. The company focuses on the development of portable-scalable-modular CO2 collectors using their amine-based nanocellulose materials. Their mission is to capture 1% of global CO2 emissions each year by 2025(International Energy Agency, 2022).

Carbon Engineering Ltd, founded in 2009 in Squamish (British Columbia, Canada) from academic work conducted on carbon management technologies at the University of Calgary and Carnegie Mellon University. The company is currently privately owned and is funded by investment or commitments from private investors and government agencies in both Canada and the United States. Carbon Engineering has so far commissioned one pilot plant, and has recently signed a licensing agreement with 1Point5 to finance and deploy the world's largest DAC facility. It has also commenced pre-FEED, with Pale Blue Dot Energy that is a storage company, on the development of a DAC facility in Scotland, United Kingdom. Carbon Engineering has just started engineering on an air-to-fuel plant that is due to become operational in Canada in 2026(International Energy Agency, 2022).

Founded in the United States in 2010 by two academics from Columbia University, Global Thermostat has so far commissioned two DAC pilot plants and is collaborating with ExxonMobil to advance and scale up its capture technology. In April 2021, the company signed an agreement with HIF to supply DAC equipment to the Haru Oni eFuels pilot plant in Chile, which will utilise captured CO2 blended with electrolytic hydrogen to produce synthetic gasoline. The plant is designed to capture up to 250 kg of CO2 per hour, equivalent to around 2 000 tCO2/year(International Energy Agency, 2022).

Many others smaller companies are developing DAC technologies: Hydrocell, Infinitree , Skytree , Soletair Power, CarbonCapture and Heirloom.Kawasaki Heavy Industries is also developing a novel DAC technology based on their existing CCUS technology, originally developed for power generation applications. Carbon Collect Limited is currently commercialising the DAC technology developed at the Center for Negative Carbon Emissions (Arizona State University) called "MechanicalTreesTM"(International Energy Agency, 2022).

The different types of DAC developing around the world are designed and scaled up in order to reach the climate goals. The solid DAC developed by Climeworks and Global Thermostat and the liquid one developed by Carbon Engineering.

The difference between these technologies is the fact that liquid DAC operates at high quality heat at 900°C for regeneration of capture material. In the opposite, the solid DAC requires much lower quality heat (100°C).

The solid DAC is based on sorbent, operating through adsorption and desorption and can capture several tens of tons of CO_2 per year.

One of the particularity of the S-DAC is its capability to be modular and can extract water from the atmosphere from 0.8 to 2 tons of water per ton of CO_2 captured(International Energy Agency, 2022). This potentiality to extract water give to the solid DAC to be implemented in arid regions.

To date, the largest operating Solid DAC plant developed by Climeworks, implemented in captures 4000 tons of CO_2 per year(Climeworks, 2022; International Energy Agency, 2022).

Due to the modularity of Solid DAC technologies, the learning rate is expected to be around 15%(International Energy Agency, 2022).

Yu in 2018 wrote an article focused on CO_2 capture using solid sorbent showed us the use of regenerative sorbent may be attractive and energy efficient than the aqueous solvent due to the lower specific heat as stated in the work of McQueen and IEA.

One of the first papers focused on cost breakdown of air capture from the atmosphere was provided by Keith et al., (2018) in which a process for capturing air from the atmosphere was studied. The scope of their work was to capture 1 Mt CO_2 per year. A levelized cost of \$94 to \$232 per tons of CO_2 been found.

Direct air capture, in the recent years is playing an important role, Beuttler et al., (2019) enhance the fact that the Solid DAC technology could help to achieve the goal around this century due to its modularity and scalability.

A techno-economic assessment of CO_2 direct air capture plant proposed by Fasihi et al.,(2019)in which the scope have been to compare the low temperature DAC and the high temperature DAC. Under two scenarios based on the capacities and financial learning rates from 2020 to 2050. The results of their study showed that low temperature DAC systems are favorable due to the lower heat supply costs. A low temperature DAC powered by a hybrid PV-wind-battery system for Moroccan conditions have been used to assess the costs. The cost of CO_2 capture calculated is 222/133, 105/60, 69/40 and 54/32 tCO_2 in 2020, 2030, 2040 and 2050 respectively.

An article wrote by Sutherland in 2019 on pricing CO_2 from direct air capture. In his analysis, the important participation of sorbent has been showed as critical parameters that have an influence on the cost of direct air capture.

Azarabadi & Lackner, (2019)worked on techno-economic analysis focused on sorbent to see how the sorbent is important and impact the cost of the direct air capture plant.

McQueen et al. in 2020 worked on the roadmap for direct air capture cost reductions through the exploitation of low temperature heat where they focused on Solid direct air capture systems. In their study, three different scenarios have been studied: a base case taking into account the use of steam derived from natural gas, the first scenario emphasizing the use of waste of heat from geothermal based and the last one use 5% slip stream of steam from nuclear-based power plant. Following this work, McQueen et al. in 2021, they made a review of direct air capture where they show the importance of to scale rapidly DAC in order to meet the climates goals.

Sabatino et al., (2021) present a technical comparison of three CO2 removal from air technologies: two aqueous-scrubbing procedures and one solid sorbent technique. On the basis of exergy demand and productivity, three DAC processes were compared. According to their findings, solid sorbent-based methods outperform solvent-based processes. CO2 capture costs are less than \$200/tCO2 for all methods, and all technologies can deliver high-purity CO2; nevertheless, the solid-based approach has the potential to offer the greatest performance, with an exergy demand of 1.4-3.7 MJ:kg-1 CO2 and a productivity of 3.8-10.6 kgCO2:m-3:h-1.

In the same context, Mostafa et al., (2022)presented and analyzed a large scale direct air capture facility. Their focus on this work has been to provide insights on the direct air capture economics. The proposed DAC plant used a sodium hydroxide as chemisorbent. Form their analysis, the cost goes down from 244 \$/t CO_2 to 125 \$/t CO_2 due to the addition of heat exchangers to the network system with a higher operating cost due to the expensive fuel when we consider the renewables scenario.

2.2. Techno-economic assessment of methanol production using DAC

Producing methanol from renewable resources is gaining attention due to its diversified use in industry, transportation and particularly its net zero ability.

IRENA (International Renewable Energy Agency) and Methanol Institute jointly released a report titled "Innovation Outlook: Renewable Methanol" in January 2021. The report provides a comprehensive review of bio-methanol and e-methanol, identifying challenges and offering policy recommendations. The Methanol Institute is tracking over 80 renewable methanol projects worldwide that are expected to produce more than 8 million metric tons per year of e-methanol and bio-methanol by 2027.

The cost of renewable methanol production is currently high. Both methods of producing renewable methanol are notably more expensive than the conventional production for brown and grey using coal and natural gas, respectively as feedstocks. The cost of producing fossil fuel-based methanol is in the range of \$250/mt, in comparison with the cost of bio methanol, estimated at up to \$770/mt(Methanol Institute, 2023). The report by IRENA and Methanol Institute suggests that with the right policies, renewable methanol could become more cost-competitive. The report identifies the following challenges for renewable methanol production: high production costs compared to conventional methanol, limited availability of renewable feedstocks, lack of policy support and incentives, and limited infrastructure for distribution and storage. The report offers policy recommendations to overcome these challenges, including implementing supportive policies and incentives to promote renewable methanol production and use, encouraging research and development to improve production processes and reduce costs, developing infrastructure for distribution and storage of renewable methanol, and promoting international cooperation to share knowledge and best practices.

Research to assess feasibility of e-methanol production from renewables and CO_2 is gaining attention and have been showed different results regarding the scope.

Sollai et al., (2023)present a scope of 500kg/h of e-methanol using a power to fuel and found the levelized cost of methanol around 960Euro/t. Another study done by Bos et al., (2020)with the objective to evaluate a wind power as source of electricity to feed a DAC plant coupled with a water electrolysis plant showed the efficiency of methanol production is around 50% with a cost of methanol to be 300€/t excluding the capital cost of wind turbine and 800€/t when included.

In order to design an optimal reactor for methanol production in efficient way, Rafiee in 2020 worked on different reactor configurations, a one stage, two stages and three stages. According to his results, the two stages configuration offer a profitability of 2.05% with the objectives to maximize the annual profit.

Beside that aspect, having a profitable levelized cost and comply to the sustainable criteria to produce renewable fuels like methanol, Sanchez et al., (2023) in their study affirmed that only PV and Wind are the required sources of energies.

An innovative plant for methanol production from CO_2 sequestered by fossil fuel power plant and hydrogen has been presented by Bellotti et al., (2017) Three different plant capacities have been assessed using W-ECoMP a software developed in Genoa University for thermos-economic assessment. The objective of the study is to analyze the influence of parameters like oxygen selling option, methanol selling price and capital cost of the electrolysis on the profitability of the plant.

Dieterich et al., (2020) in a review study provide an overview of the art synthesis technologies focusing on power to methanol, DME and Fischer-Tropsch. They showed for the power to methanol that the CO_2 hydrogenation offers advantages in terms of by product formations and lower heat development but increase water formation.

Daniel et al., (2022) proposed and designed in their study a novel direct air capture process integrated with a solid oxide electrolysis plant. Their results indicated an unfavorable techno-economics with a NPV and levelized cost of -$4.6 B and $382 tCO_2 respectively.

The article of Marlin et al., (2018) presents the advantages and disadvantages of producing methanol directly from separate sources of CO2 and H2. Overall, the process is advantageous. It is cleaner, less energy-intensive, and more environmentally friendly than conventional processes that use fossil fuel-based syngas. They emphasized that this process offers benefits over the conventional process for producing methanol, both economically and environmentally. They discussed aspects that are unique to the process of converting pure CO2 to methanol. The core advantage of this process is that the impurities in the reaction are essentially limited to only water and dissolved CO2 in crude methanol.

Van-Dal & Bouallou, (2013) designed and simulated using Aspen Plus a process for methanol production from CO_2 captured. In their proposed process, the methanol plant provides heat at

36% that reduce the energy required to capture the CO_2. This heat can be used as affirmed by some researchers can help to reduce the energy requirement for the DAC plant.

Methanol production through CO_2 hydrogenation have also been studied by Bowker in 2019. In his work, he emphasized the importance of shift from fossil fuel by using renewable by taking into account the intermittency of the resources like wind and solar. Storing such energy at peak production times for use in times of low production needed and one way to do this is to convert such energy into chemical energy and the principal way considered at present is the production of hydrogen. This hydrogen can then be stored in an energy dense liquid form such as methanol.

The methanol can be produced from pure CO2 and hydrogen using conventional and novel types of catalysts as stated by Marlin et al., (2018).

Pérez-Fortes et al., (2016) conducted a techno-economic and environmental study of CO2-based methanol synthesis. In their analysis, they assess the potential of this sort of carbon capture and utilization (CCU) plant on net CO2 emissions and production costs when compared to MeOH Europe's traditional synthesis process. In CHEMCAD, a carbon utilization plant that produces methanol is modelled. The overall CO2 demand is 1.46 t/t methanol. When compared to a conventional plant, the CO2 not produced is 0.54 t/t methanol. In Europe, there is a net potential for CO2 emissions reduction of 2.71 MtCO2/year.

Zhang et al., present in 2019 an article on Techno-Economic Optimization of CO2-to-Methanol with Solid-Oxide Electrolyzer. The study explores the potential of using captured CO2 from the air and hydrogen produced by co-electrolysis of CO2 and steam in a solid oxide electrolysis cell to synthesize methanol. The paper focuses on the techno-economic optimization of CO2 hydrogenation to synthesize green methanol integrated with a solid-oxide electrolysis process.

2.3. Current state of Solid Oxide Electrolysis Cell

Water electrolysis to provide hydrogen play an important role in the process of methanol production. Different perspectives in the field of electrolysis development have been and continue to be explored. Solid oxide electrolysis cells (SOECs) have recently attracted increasing research attraction in accordance with the rising demand for non-fossil fuels, energy, and educts for the chemical industry. SOECs are a promising technology for producing hydrogen from water, which can be used as a fuel or feedstock for the chemical industry. However, the high operating temperatures required for SOECs and the impact of bipolar plates on cost structure are challenges that need to be addressed.

Solid oxide electrolysis cell have been developed intensively over the last 15 years according to Nechache et al., (2014). Nechache & Hody, (2021) in their review worked on alternatives and innovatives materials for SOEC. According to their findings, SOEC is the leading technology for green hydrogen due to the fact that it operates at high temperature (750 to 800°C). This ability to operate at this temperature offer to reduce power needed to split water.

SOEC is seen as a possible game-changer technology for several market. To that, the authors added the fact that the SOEC is flexible as it can be decentralized and centralized for mass production in arid regions where the renewable potential is high. A study on bottom up cost evaluation performed by Anghilante et al., 2018 where they assessed the capital cost of SOEC systems from raw materials. In their study, 2 scenarios assuming different capacities and yearly production of SOEC units.

Their results showed an installed capital cost of 309-395 €/kW for SOEC units integrated into power to methane and 380 to 494 €/kW for stand alone. These results showed that the cost of power is less when SOEC is coupled to steam source as confirmed by Nechache & Hody in their work in 2021.

Ni et al., (2008) present technological advancements in hydrogen production using solid oxide electrolyser cell, emphasizing that the SOEC has significant promise for efficient and cheap hydrogen production. Planar SOECs are favoured over tubular cells in terms of cell configuration since they are easier to manufacture and perform better electrochemically. Anode depolarization is a useful technique for lowering the electrical energy consumption of SOEC hydrogen generation.

In the report of IRENA entitled *Green Hydrogen Cost Reduction* published in 2020, it appears that Solid oxide electrolysers can be coupled with heat-producing technologies for a higher system efficiency. Another point highlighted in the report is coupling SOECs with concentrated solar power could supply both electricity and the heat to the SOEC electrolyser. SOEC electrolysers can achieve lifetimes of 20 000 hours, but under constant power and well-defined operating conditions. The main degradation mechanism is the thermal cycling, due to the high operating temperatures and need to cool down in case of dynamic operation. Reversible operation of solid oxide cells (electrolysis + fuel cell) could help increase the hours of operation and thus keep the system at operating temperature. Deploying SOEC at large scale would require larger cells.

In the report, the following activities to improve the performance of solid oxide electrolysers have been proposed : sstabilize the chemical structure and compatibility of the electrodes, control the oxidation state of electrocatalysts on the oxygen side (anode) or nickel agglomeration, increase the electro catalytic activity of electrodes at lower temperatures, ssolve challenges related to lanthanum manganite (LSM) or lanthanum ferrite (LSF) delamination from electrolyte, improve kinetics for hydrogen and oxygen evolution and maintain long-term stability, eliminate or reduce contamination issues related to silicon dioxide (SiO2) dissolution from stack sealants, eliminate thermal instability issues caused by an expansion coefficient mismatch between electrolytes and electrodes , scaling up of stack components towards larger stack MW units.

Frank et al., (2018) in Julich research center developed a reversible solid oxide cell used as electrolyser and fuel cell. Their rSOC presents a storage and reconversion of renewable energy in large capacities, a 100% system fuel utilization in SOFC mode, an eenvironmentally-friendly via pure hydrogen/steam operation and an innovative plant design with off-gas recirculation.

In their article on this technology, they showed that the plant incorporates both a storage via electrolysis mode and the electricity production in the reverse, fuel cell mode. The final plant design showed an efficiency of up to 67.1% in fuel cell- and 76% in electrolysis mode and therefore a round trip efficiency of 51%.

Following the research of Franck et al., a study to maximize the efficiency of the electrolysis mode of the rSOC has been done by Kruse et al. in 2021 using steam generator. The design is based on a pinch analysis showed that the steam generator was estimated to increase electrolysis efficiency from 70% to more than 74%.

The growing interest in finding new alternatives for a sustainable world is evident from the literature reviews presented earlier in this section. However, some of the research is quite limited geographically and does not take into account certain aspects such as the degree of aridity, relative humidity and a strong disparity in the data.

Therefore, in order to assess the economic importance of the value chain for the production of e-fuels, the impact on society and the impact on the environment, it is important to extend the research to other horizons like Africa.

3. Empirical data analysis

3.1. Sizing of the PV system

Designing an efficient energy system is crucial for our project to attain the set objectives and meet a daily energy demand equal to KWh.

As stated in the study scope, our research is focused on the Bouake area, which has geographical coordinates of latitude 7.6513 and longitude -5.1102.

To determine the capacity of our PV system and battery, we obtained solar irradiation data and sized our PV system using the NASA Power data viewer.

Certain parameters, such as the Depth of Discharge (DOD) and battery efficiency, have been assumed based on previous research conducted byBhandari & Shah, 2021.

The Capacity of the PV System is Calculated as Follows:

$$Ppeak\ (KW) = \frac{[E_d(KWh) * I_{stc}(KW/m^2)]}{[G(KWh/m^2) * Q]}$$

Where:

- Ppeak: the required solar PV capacity in KW
- E_d: the energy demand in KWh per day
- I_{stc}: Radiation at standard test condition in kW/m2 equal 1.
- G: the global solar irradiation value for 2021: 4.82 KWh/m^2.
- Q: the performance ratio equal to 75%.

Then, we calculated the energy generation using the following equation:

$$E_{gen}\ (KWh) = \frac{[P_{peak}(KW) * G(KWh/m^2) * Q]}{[I_{stc}(KW/m^2)]}$$

For the sizing of the battery, the following formula was used:

$$Bat\ size\ (KWh) = \frac{E_{req}}{(DOD * \eta_{sys})}$$

Where:

E_{req}: the energy to be supplied from the battery

DOD: the depth of discharge of the battery assumed to be 80%.

η_{sys}: the overall battery system efficiency assumed to be 80%.

3.2. Data collection

In this work, the data are collected from the literature using articles and academics thesis and market prices via platforms such as ScienceDirect, Google Scholar, ResearchGate, official websites of companies and international agencies such as International Renewables Energy Agency (IRENA) and International Energy Agency (IEA).

3.2.1. Data assumptions

The first part of the data collection is to determine the different quantities according to the assumptions made in the work.

The decision to produce 10,000 tons per year of e-methanol is justified by the fact that we are assessing the feasibility of the project and it is important to have a look at the cost implications on a small scale, rather than being faced with huge costs.

According to the report of IRENA and the Methanol Institute published in 2021, producing 250 Mt of e-methanol will require about 350 Mt of CO_2 and 48 Mt of hydrogen. Based on these data, we assess the amounts of feedstock needed to produce our desired methanol amount that is 10 000 t/year.

Let's assume x represents the amount of CO_2 required and y represents the amount of H_2 required.

From the collected data, we have the following ratios:

350,000,000 tons CO_2 / 250,000,000 tons CH_3OH = x / 10,000 tons CH_3OH

48,000,000 tons H_2 / 250,000,000 tons CH_3OH = y / 10,000 tons CH_3OH

Now, we can solve for x and y.

x = (350,000,000 tons CO_2 / 250,000,000 tons CH_3OH) * 10,000 tons CH_3OH

x = 14,000 tons CO_2

y = (48,000,000 tons H_2 / 250,000,000 tons CH_3OH) * 10,000 tons CH_3OH

y = 1,920 tons H_2

To confirm our analysis, we used the data from (Schemme et al., 2020) to perform a calculation according to our assumptions to produce 10 000 tons per year corresponding to 27,7 tons per day.

In the article of Schemme et al., 2020, to produce 1 kg of methanol, the conditions are 0.189 kg of hydrogen and 1.373 kg of carbon dioxide.

For 1 kg of methanol, we need 0.189 kg of hydrogen.

Therefore, for 27,700 kg of methanol, we can calculate:

27,700 kg methanol × (0.189 kg hydrogen / 1 kg methanol) = 5,233.3 kg hydrogen

For 1 kg of methanol, we need 1.373 kg of carbon dioxide.

Therefore, for 27,700 kg of methanol, we get:

27,700 kg methanol × (1.373 kg carbon dioxide / 1 kg methanol) = 38,001.1 kg carbon dioxide

So, to produce 27,700 kg of methanol, you would need approximately 5,233.3 kg of hydrogen and 38,001.1 kg of carbon dioxide

In order to reach the target that is to produce 10000 tons /year, we calculated the amount to be produced per day assuming 360 days/year. The capacity to be produced is shown in the following table.

Table 1: Raw materials need for the production

Technologies	Quantity	
	Tons/day	Tons/year
SOEC	5.25	1920
S-DAC	38	14000
MeOH	27.7	10000

Source: Author

Table 2: Energy requirement

Technologies	Unit	Quantity	Source	This work
SOEC	kWh/kgH2	40 35 42.3	Sunfire, 2021 (Putta et al., 2022) (Gerloff, 2023)	42.3
S-DAC	KWh/t CO2	2943.8	Sanchez et al., 2023	2943.8
MeOH	KWh/kg MeOH	0.154	(Schemme et al., 2020)	0.154

Source: Author

Table 3: Energy requirements per day calculated based on our assumptions

Technologies	Energy required per day in Kwh
SOEC	222075
S-DAC	111864.4
MeOH	4265.8
Total	338205.2

Source: Author

The table above shows the energy required to power each component and the overall system in order to produce the desired amount of output per day. Based on the results, our solar PV system has to provide 338205.2 Kwh per day.

Table 4: Land requirements

Technologies	Quantity	Source	This work	Land required
Solar PV	0.9 – 1.4 ha/Mwh	IFC, 2021	1.15 ha/Mwh	109.25 ha
SOEC		Sunfire, 2021	0.078358 ha	2.79 ha
S-DAC	1.2-1.7 km2/MtCO2	(International Energy Agency, 2022)	0.000145 ha/t	0.000551ha
MeOH		Assumptions		3 ha
Total				115.040551 ha

Source: Author

The methanol land requirement includes the methanol production facilities and other installations on the production site.

3.2.2. Data for cost

The data to be collected in order to build a cost model are: the capital expenditures (CAPEX) including each technology cost, the land acquisition cost, the indirect and administrative cost, the operation expenditures (OPEX) divided in fixed and variables ones. The fixed costs are the labor, the maintenance cost, the energy cost, the chemicals cost.

We assumed in this study the project life time to be 20 years and a discount rate of 5% based on the paper published by (Szabó et al., 2021)in which their study is focused on Sub-Saharan Africa, East and South Asia.

Regarding the costs used for the calculations, we utilized the average value of these costs where we have different options due to range and selected the costs that were exact.

Most of the cost data found on the literature have been converted from USD to Euros using the reference exchange rate of the European Central Bank. The reference exchange rate on May was chosen for our study. The conversion rate was 0.933 € for 1 USD.

A database of relevant data has been created from all the reviewed publications, for further analyses.

Table 5: Capital expenditures

Technologies	Costs	Sources	This work
Solar PV Plant	800 €/kWp	(Bhandari & Shah, 2021)	800
SOEC	2000€/KW; 1400€/kW 1 750 €/kw	(Dieterich et al., 2020;) (Putta et al., 2022) (Gerloff, 2023)	1750
S-DAC	280 to 560 €/t CO2	(International Energy Agency, 2022)	420
MeOH reactor	1 120-2 240€/t	IRENA, 2021	1680
Batteries	200 €/kWh	(Nizami et al., 2022)	560
Hydrogen storage	45 700 €/t	(Huang et al., 2023)	45700
Methanol storage	8000 €/t	(Dias et al., 2020)	8000
CO2 Storage	50 000€/tCO2	(Sherwin, 2021)	50000
Land acquisition	2500€/ha	This work	2500

Source: Author

The cost of land depending on factors like the location, the accessibility and the intended use. Based on the research, we assumed to take the average cost of agricultural land that is in the range of 2300 USD to 3800 USD. Due to location chosen for our project, we assumed to take 2500 € as cost for 1 ha.

Operating expenditures

The operating expenditures is divided in two different parts, the fixed OPEX and the variables ones.

The operating fixed cost include the maintenance cost, the labor cost, and all the different costs that are part of the fixed OPEX determination.

Table 6: Fixed operating expenditures determination

Technologies	% of CAPEX	Sources
PV system	1	(Bhandari & Shah, 2021)
Batteries	7.5	(Nizami et al., 2022)
SOEC	4	(Gerloff, 2023)
S-DAC	4	(Daniel et al., 2022)
MeOH	2	(Nizami et al., 2022)
H2 Storage	1	(Huang et al., 2023)
CO2 Storage	1	Assumptions
MeOH Storage	1	Assumptions

Variables operating expenditures

In the variables cost, we have the replacement costs for each technology.

The batteries serving to store the energies need have a life time of 12 years and need to be changed once during the overall time of the project. For a capacity of 1473 kWh and a cost of 200 €/KWh (Nizami et al., 2022), we have a batteries replacement cost of 294679.2 €.

CO_2 and water production from the DAC require a certain amount of sorbent. According to McQueen et al., 2021, the sorbent replacement take place each year with a quantity between 0.25-38 kg/tCO2 to a price of 11–38 €/tCO2(International Energy Agency, 2022). In our study, the quantity to be changed based on the CO_2 requirement is 722 kg for the average cost of 24.5 €/tCO2. The sorbent replacement cost is 17689 €.

Concerning the stack replacement cost, we based our assumptions on the article of Gerloff, 2023 saying that for a SOEC working at around 8000 hours a year, the replacement cost count for 24% of the SOEC capex and need to be replaced 5 times over a lifetime of 20 years. The stack replacement cost is therefore is 3,730,860.00 €.

For the catalyst replacement cost, we used the data in the article of Sollai et al., 2023 in which their target is to produce 4000 t/year. The catalyst consumption is equal to 73 kg/year with a cost of 95.24 €/kg. Based on our target, the catalyst consumption is equivalent to 182.5 kg/year, therefore the catalyst cost 17381€.

3.3. Methodology

To accomplish this goal, we utilized a methodology that entailed outlining the working process of the system, recognizing expenses, computing levelized expenses, and conducting a sensitivity analysis to evaluate the influence of specific factors on costs.

3.3.1. Process description

In this part, the overall plant system to be implemented to produce methanol in arid regions based on the requirement of the DryHy pilot project, is described taking into consideration each technology process.

By combining Direct Air Capture, Solid Oxide Electrolysis Cell powered by a solar PV plant, and methanol synthesis, the overall process enables the utilization of CO2 from the atmosphere and renewable energy sources to produce methanol, a valuable chemical and fuel.

It's important to note that this specific process description involving DAC, SOEC, and solar PV power is a conceptual integration of technologies. The specific details, system configurations may vary based on the design, scale, and specific implementation of such a system.

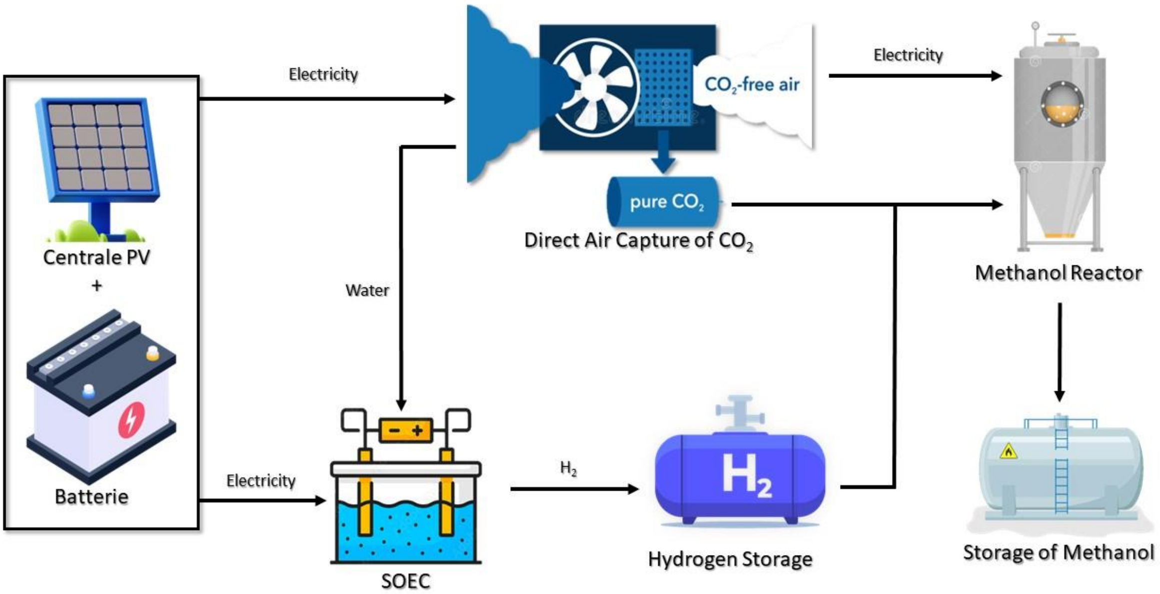


Figure 1: Overall system flowchart
Source: Author

In the Figure 1 above describing the overall system intended to produce methanol from the power source to the methanol output. Taking into consideration the energy requirements of the technologies to be supplied, the Solar PV system is design to power in optimal way to reach the objectives in order to have the necessary output at each technology. The Solid direct air capture plant feeding by the energy coming from the PV system to allow the fans to turn and collect the ambient air. In the DAC plant, we have two processes occurring know as adsorption where the sorbent collects the air and the desorption process to generate the CO2 and the water. This CO2 is stored in order to be used in the next process and the water is then collected to feed the SOEC as showed with blue line in the figure. The SOEC receive as inputs the water from the DAC plant and the electricity from the PV system to produce green hydrogen.

This green hydrogen combined with the CO2 produced from the DAC are used as raw materials where they will be compressed, distillated into the methanol synthetizer to give at the end e-methanol.

Solar PV System

For the implementation of the DryHy project, a stand-alone solar PV system has been chosen to power the overall system due to the huge potential of the solar resource in the arid regions where we can record a solar irradiation around 6 to 7 hours.

Our solar PV system is designed taking into account in order to meet the energy need of the overall system composed by the SOEC, the S-DAC plant and the methanol synthesizer reactor. A field of polycrystalline PV based silicon module assembled in series or parallel according to the capacity to collect the sunlight to produce energy required to power the overall system. We assumed, in order to produce energy over 24hours, batteries are used to store and supply energy during non-irradiance period.

Solar PV cells are basic devices that convert sunlight into voltage or electric current by utilizing the capacities of semi-conducting materials like silicon to absorb light and give a part of energy to electrical current carriers (Guerra et al., 2018).

When these panels are exposed to sunlight, which consists of tiny packets of energy called photons, the semiconductor material releases electrons and generates an electric charge.

This electric charge, known as PV charge, produces a direct current (DC) that is harnessed by the wiring within the solar panels (Sena, 2021). To make the electricity usable for appliances, it is converted from DC to alternating current (AC) by an inverter. AC is the type of electrical current used in standard wall sockets where you plug in your devices.

To summarize the functioning of our system, we can outline the following points:

- Solar panels absorb sunlight and convert it into electrical energy.

When a piece of semiconductor is lit by a light pulse with photon energy greater than the band gap energy, electrons transfer from the valence band to the conduction band, leaving holes in the valence band. To achieve thermal equilibrium in the system, the reverse process must also occur: surplus electrons in the conduction band recombine with holes, releasing energy (Guerra et al., 2018).

- The inverter transforms the captured energy into usable electricity.

AC systems additionally require an inverter, which converts the DC electricity generated by PV modules and stored in batteries into alternating current electricity. The inverters made to different sorts of electricity quality based on the system that we provide energy either high voltage or lower voltage (Yost, 1997).

- The batteries use to store the energy for utilization in period of non-irradiation.

The battery stores electricity for usage at night or during the day when the modules are not producing enough power to meet load needs. PV systems require deep cycle batteries to deliver electricity over lengthy periods of time (Yost, 1997).

Solid Oxide Electrolysis Cell

Producing hydrogen is a fundamental part as it will serve as raw material to the production of methanol. In order to produce hydrogen at large scale and in efficient way using renewables energies and in arid regions, the solid Oxide electrolysis cell has been chosen among the others types of electrolysis.

The assumptions behind the choice of SOEC is due to its high efficiency, its robustness and its ability to operates easily with renewables energy resources especially available in arid regions.

In early commercially stage, Solid Oxide Electrolysis Cell (SOEC) is an electrochemical device that enables the efficient conversion of electrical energy into chemical energy by splitting water molecules into hydrogen (H2) and oxygen (O2) gases. It is a variation of Solid Oxide Fuel Cell (SOFC) technology, operating in reverse(Pandiyan et al., 2019).

The SOEC operates at above 700°C to electrolyze water, facilitate the production of hydrogen on a large scale, this capacity to operate at that temperature decreases the amount of electricity consumed by replacing the electricity used with heat (Lee et al., 2021). The electricity requirement is around 39.4 kWh/kg of H_2 with an efficiency of 100% and 43.8 kWh/kg without heat for an efficiency of 90% (Leo et al., 2022).

Solid Oxide Electrolysis Cells can therefore offer a promising pathway for large-scale hydrogen production with reduced carbon emissions, contributing to the transition towards a more sustainable energy system.

It is a very good candidate technology for securing sustainable development for the future. It allows CO2 to be recycled into usable fuels and has potential for hydrogen economy (Stempien et al., 2013).

Structure:

According to Ni et al., 2008; Nechache & Hody, 2021 in their respective articles that have been used to describe the process of SOEC, an electrolysis cell, typically with a thickness of 200-300 am, consists of an oxygen electrode (anode) and a hydrogen electrode (cathode) separated by a dense ionic conducting electrolyte.

The electrolyte, commonly made of ceramic materials like yttria-stabilized zirconia (YSZ), allows the conduction of oxygen ions (O2-) while blocking the flow of electrons. It serves as a barrier between the cathode and anode, preventing electrical short-circuiting.

The cathode, where oxygen reduction occurs, is typically composed of a porous material such as lanthanum strontium manganite (LSM), which facilitates the reduction of oxygen ions.

On the other hand, the anode, where oxygen evolution takes place, is also a porous material, often made of nickel-YSZ (Ni-YSZ) or nickel cermet. The anode facilitates the oxidation of oxygen ions, resulting in the release of oxygen gas.

During the water splitting process in a Solid Oxide Electrolysis Cell (SOEC), when a voltage is applied, oxygen ions (O2-) migrate from the cathode through the solid oxide electrolyte to the anode, where they combine to form oxygen gas (O2) through the oxygen evolution reaction (OER).

Simultaneously, at the cathode, the reduction of oxygen ions generates electrons that flow through an external circuit to the anode. At the anode, these electrons react with water molecules, causing them to split into hydrogen ions (H+) and oxygen gas (O2). The hydrogen ions then migrate through the solid oxide electrolyte to the cathode.

Overall Reaction: The overall reaction in a Solid Oxide Electrolysis Cell can be represented as follows: 2H2O -> 2H2 + O2

A breakdown of the Solid Oxide Electrolysis Cell (SOEC) process:

Apply a voltage across the SOEC.

Oxygen ions (O2-) migrate from the cathode to the anode through the solid oxide electrolyte.

At the anode:

a. Oxygen ions (O2-) combine to form oxygen gas (O2) through the oxygen evolution reaction (OER).

b. Water molecules (H2O) at the anode are split into hydrogen ions (H+) and oxygen gas (O2).

Hydrogen ions (H+) migrate through the solid oxide electrolyte to the cathode.

At the cathode:

a. Hydrogen ions (H+) combine with electrons and oxygen ions (O2-) to form hydrogen gas (H2).

b. Oxygen gas (O2) produced at the anode is released as a by product.

The overall reaction: 2H2O -> 2H2 + O2.

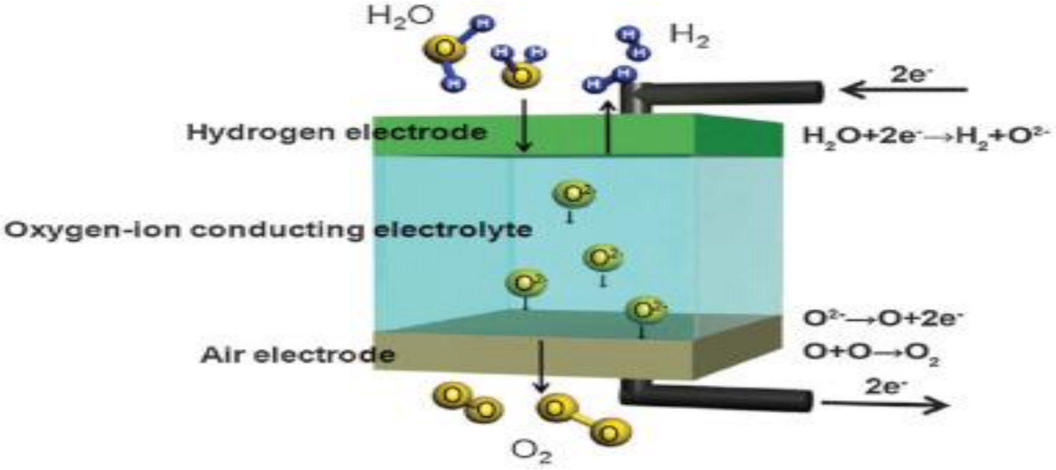


Figure 2: SOEC principle for H2 production

Source: Nechache & Hody, 2021

The advantages of the SOEC are:

- **Steam electrolysis:** Utilization of industrial off-heat as steam reduces electricity demand.
- **Efficiency:** Market-leading efficiency ($84\ \%_{\text{LHV TO AC}}$) yields lowest hydrogen costs.
- **Reliability:** Certified electrolysers with proven long-term operation.
- **Flexibility:** Modular design simplifies scaling to any desired electrolysis capacity.
- **Sustainability:** No use of PGM-based materials in electrolyser productionn.

Direct Air Capture Plant

CO_2 capture in the world is done using different technologies based on factors and conditions such as environments, climactic conditions and capacity of extraction.

Presently, Direct air capture is seen like the hope to decrease the greenhouse gases in the atmosphere. DAC stands for a variety of technology-based solutions that can extract carbon dioxide from the surrounding air, regardless of the location on the planet (Beuttler et al., 2019). Two approaches, namely the Liquid DAC and the Solid DAC, are employed worldwide to capture CO2 from the atmosphere.

In our study, we are focused on Solid Direct Air capture because of the scope of the DryHy project. The justification for chosing the S-DAC is due to its adaptability with arid regions, its low water demand but its capacity to produce water, its scalability as it is a modular technology.

According to the 2022 report from the IEA, the Solid DAC (S-DAC) has the capability to supply water for its own operations and to support a water electrolyzer for hydrogen and synthetic fuel production.

Another reason for selecting the Solid DAC is its capacity to be powered by renewable energy sources throughout the entire process. Arid regions excel in terms of renewable resources such as solar PV and wind, making them ideal for powering the Solid DAC system.

DAC is a promising technology that is currently in the demonstration stage (TRL 6). It has significant potential for enhancing performance and reducing costs.

The Solid DAC (S-DAC) utilizes solid adsorbents and operates through a cyclic process of adsorption and desorption. During adsorption, CO2 is captured from the air at ambient temperature and pressure. The subsequent desorption involves a swing process where CO2 is released at a low pressure and medium temperature (80-100°C). The energy required to feed the DAC plant 166–305 kWh/tCO_2 for electricity and 4.4–7.2 GJ/tCO_2 for heat(Sanchez et al., 2023).

The process of the Solid DAC can be described as follows:

- Fans push air through the contactor unit, and the CO2 adsorbs onto the solid sorbent under ambient conditions.
- Once the solid sorbent becomes saturated with CO2 or reaches the desired CO2 uptake, the system switches from adsorption to desorption mode.
- At this stage, the contactor is isolated from the surrounding environment. A vacuum pump removes residual air from the contactor to prevent dilution of the produced CO2 by residual oxygen and nitrogen, as well as to minimize degradation of the amine sorbent due to air exposure.

- Steam is used to flush the released CO2 from the contactors. The CO2 is then separated from water in the condenser and directed to compression for subsequent transportation, storage, or utilization.

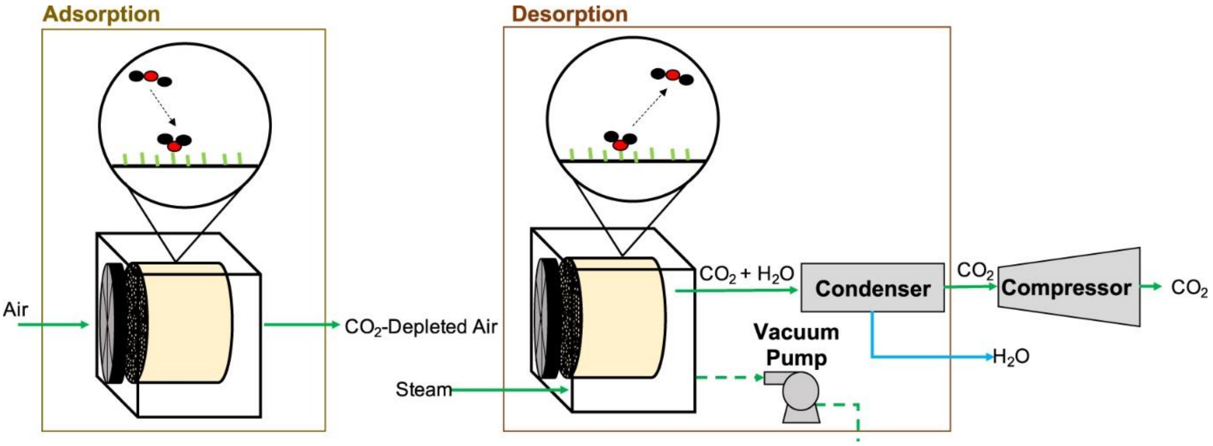


Figure 3:Representative process flow diagram for solid sorbent DAC

Source:(McQueen et al., 2021)

- **Methanol reactor**:

The cost of e-methanol produced by this route is highly dependent on the cost of the raw materials: CO2 and hydrogen. The cost of hydrogen itself is closely linked to the cost of the electrical power needed to produce it

In order to produce the amount of 10 000tonnes per year defined above in the scope of this work, we need to have a reactor with specific working conditions.

Methanol synthesis reactor is fed by CO2 and H2 in gas phase in order to produce methanol through a catalytic reaction over Cu/ZnO/Al2O3 catalyst under the adiabatic condition based on the ICI technology (Bowker, 2019)

A methanol reactor is a chemical reactor used for the production of methanol through the catalytic conversion of synthesis gas, which is a mixture of hydrogen (H2) and carbon monoxide (CO)

The reaction is typically carried out at high pressures and elevated temperatures, along with the presence of a catalyst.

The methanol synthesis reaction can be represented by the following equation:

CO + 2H2 -> CH3OH

The following papers: Dieterich et al., 2020; Tamura, 2016; Van-Dal & Bouallou, 2013 have served as based to describe the methanol synthesis process.

In a typical methanol reactor, the process involves several steps:

Synthesis Gas Preparation: The feedstock for the methanol synthesis reaction is usually a mixture of hydrogen and carbon monoxide gases known as synthesis gas or syngas. The synthesis gas is produced through processes such as steam reforming of natural gas or coal gasification.

Catalyst Bed: The synthesis gas is then directed into a catalyst bed within the methanol reactor. The catalyst used is typically a mixture of metallic compounds, such as copper, zinc, and aluminium oxides, supported on an inert material.

The process of methanol synthesis in a typical reactor can be summarized as follows:

- Synthesis Gas Preparation: The starting point is the preparation of synthesis gas, which is typically derived from natural gas or coal. Steam reforming or partial oxidation processes are employed to convert the feedstock into a mixture of hydrogen and carbon monoxide gases.
- Catalyst Selection: A catalyst is used to facilitate the conversion of synthesis gas into methanol. Copper-based catalysts are widely used in commercial methanol synthesis reactors. They are typically supported on materials like alumina ($Al2O3$) or silica ($SiO2$) to enhance their activity and stability.
- Reaction Conditions: The reaction takes place at elevated temperatures and pressures to favor the methanol synthesis. Common operating conditions include temperatures of around 200-300°C and pressures ranging from 50 to 100 bar. These conditions are chosen to optimize the equilibrium conversion and reaction rate.
- Methanol Synthesis: Inside the reactor, the synthesis gas is brought into contact with the catalyst. The carbon monoxide and hydrogen molecules adsorb onto the catalyst surface, undergo various chemical reactions, and eventually form methanol molecules. The methanol synthesis reaction is an exothermic process, releasing heat in the reactor.

- Heat Management: Efficient heat management is crucial in a methanol reactor to control the reaction temperature and avoid temperature fluctuations. Heat is typically removed from the reactor using cooling systems such as heat exchangers or cooling coils.

- Product Separation: After the reaction, the mixture leaving the reactor contains methanol along with unreacted gases, by-products, and impurities. The product separation stage involves processes like distillation, condensation, and purification to separate and purify the methanol from the remaining components.

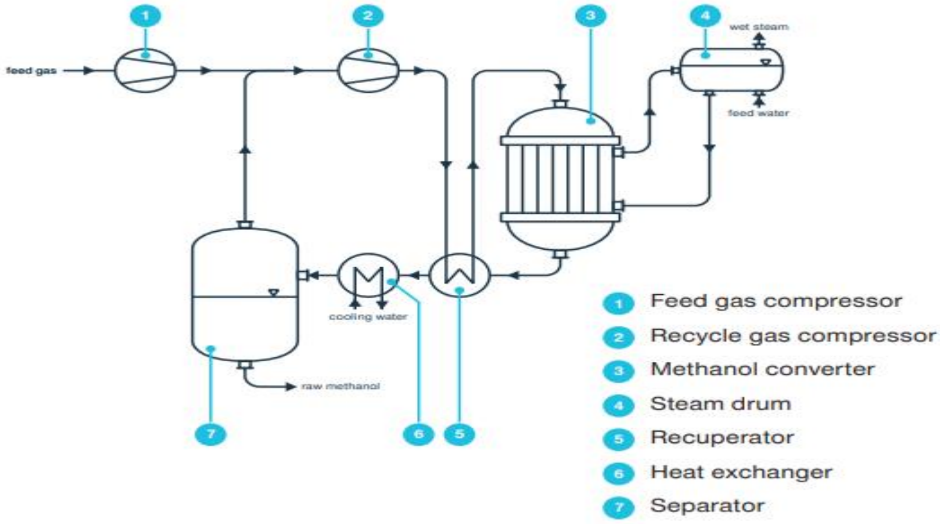


Figure 4: Methanol synthesis diagram process

Source: *Tubular Reactors from MAN Energy Solutions*, 2021

3.3.2. Identification of the costs

The analysis is divided into capital cost of the designed units as well as the operating cost incurred for a year.
Based on the data collected, the production cost has been calculated using:

- **Capital Expenditures:**

The investments done in the project are represented by the capital expenditures. In this work, the CAPEX of each technology presented in Table…. have been defined and summed to get the overall CAPEX.

$$\mathbf{CAPEX_{total} = \Sigma CAPEX_{PV+SOEC+S\text{-}DAC+MeOH+H2storage+CO2storage+MeOHstorage} + Land + Admin\ cost}$$

Where: $\mathrm{CAPEX}_{\mathrm{total}}$: overall amount of investment of the system expressed in €.

- $CAPEX_{PV}$: Capital expenditures of Solar PV system in €/Kw including all the components and the batteries cost.
- $CAPEX_{SOEC}$: Capital expenditures of the electrolysis in €/Kw Cost for the green hydrogen storage expressed in €/t.
- $CAPEX_{S\text{-}DAC}$: Capital expenditures of the air capture plant in €/tCO_2 includes the cost of DAC technology and Cost for the carbon dioxide storage expressed in €/t.;
- $CAPEX_{MeOH}$: Capital expenditures of the methanol synthesis in €/tMeOH including the Cost for the e-methanol storage expressed in €/t.
- Land: Cost for the land acquisition in €/ha.
- Administrative cost: included all the cost for permits, authorizations and soft costs in €.

Operating expenditures

The operating costs are the costs required to maintain a normal running operation from the raw materials to the utilities. In order to define the OPEX, the cost drivers have been identified and divided into fixed and variables operating cost. The labor, the energy, the maintenance, the chemicals cost are the elements included in the operating cost.

The fixed operating cost are the labor, the different maintenance costs of the technologies and the variables one is constituted by the cost of energy, the sorbents replacements, the stack replacements, the catalysts and the batteries replacement.

Using this addition: $\mathbf{OPEX_{total} = OPEX_{variables} + OPEX_{fixed}}$, the total operating cost is defined and expressed in €/year.

Total Cost definition

Using the cost calculated from the data collected, the total cost incurred for the production of e-methanol is defined:

In simple way, the total cost is the sum of the CAPEX and the OPEX expressed in €.

Total cost= Total CAPEX + Total OPEX.

3.3.3. Levelized cost calculation

The determination of the levelized cost is used in order to have the cost of some components such as electricity cost, water cost, CO_2 cost and hydrogen cost.

The levelized cost method is used in this work to smooth out cost variation from one period to another and help also to reduction cost variation. This method offer a better understanding of production cost and give information for decisions makers regarding pricing and production.

In order to avoid double counting in the determination of the levelized cost of the water and CO2 as they are both outputs from the same technology which is the Solid Direct air capture technology. We assumed to take 50% of the CAPEX and the OPEX of DAC for the water cost and the other 50% for the carbon dioxide cost.

- **Levelized cost of electricity (LCOE)**

$$LCOE = \frac{CAPEX\ (pv+bat+land\ )+\sum_{t=1}^{n}\frac{OPEXfix\ (pv+bat\ )+OPEXvar\ (pv+bat\ )}{(1+r\ )^{t}}}{\sum_{t=1}^{n}\frac{Electricity\ generated}{(1+r\ )^{t}}}$$

- **Levelized cost of water (LCOW)**

$$LCOW= \frac{50\%CAPEX\ (\ dac\ )+land+\sum_{t=1}^{n}\frac{OPEXfixdac+OPEXvar\ (dac\ )+EC}{(1+r\ )^{t}}}{\sum_{t=1}^{n}\frac{H2O\ produced}{(1+r\ )^{t}}}$$

- **Levelized cost of Carbone dioxide (LCOC)**

$$LCOC= \frac{50\%CAPEX\ (\ dac\ )+CAPEX(\ CO2stor\ )+land+\sum_{t=1}^{n}\frac{OPEXfixdac+OPEX\ fix\ (\ CO2stor\ )+OPEXvar\ (\ dac\ )+EC}{(1+r\ )^{t}}}{\sum_{t=1}^{n}\frac{CO2\ produced}{(1+r\ )^{t}}}$$

- **Levelized cost of hydrogen (LCOH)**

$$LCOH= \frac{CAPEX\ (soec+H2stor+land)+\sum_{t=1}^{n}\frac{OPEXfix\ (soec+H2stor)+OPEXvar\ (soec+H2stor)+EC+WC}{(1+r\ )^{t}}}{\sum_{t=1}^{n}\frac{H2\ produced}{(1+r\ )^{t}}}$$

- **Levelized cost of methanol (LCOM)**

$$LCOM= \frac{CAPEX\ (\ MeOHrea+stor+land\ )+\sum_{t=1}^{n}\frac{OPEXfix\ (\ MeOHrea+stor\ )+OPEXvar\ (\ MeOHrea+stor\ )+EC+H2C+CC}{(1+r\ )^{t}}}{\sum_{t=1}^{n}\frac{MeOH\ produced}{(1+r\ )^{t}}}$$

Where:

- LCOE is expressed in €/kWh
- LCOH is expressed in €/ t H_2
- LCOW is expressed in €/ t H_2O

- LCOC is expressed in €/ t CO_2
- LCOM is expressed in €/ t MeOH
- r: is the discount rate
- n: is the project lifetime
- EC: electricity cost
- WC: water cost
- H2C: hydrogen cost
- CC: carbon cost

3.3.4. Structure of the cost model

After determining the different costs identified, the cost model will be developed based on the analysis and the result of the previous section. Using Microsoft Excel, we built a spreadsheet in which we did different calculations in order to have a cost model. The spreadsheet has effectively organized, interpreted, and illustrated our data, from the requirements of the PV system to sensitivity analysis, using graphs.

3.3.5. Sensitivity analyses

The purpose of the sensitivity analysis in our work is to assess the cost of electricity, hydrogen and e-methanol by taking into account the degree of aridity of the regions.

After the determination of the cost model, we defined the elements that are major in the costs in order to see how they influence the overall cost and the levelized cost of electricity, hydrogen and e- methanol of the project.

The sensitivity analysis of this study consists of presenting different cases where we did assumptions in order to see the influence of changing some parameters on the levelized cost of hydrogen and methanol.

In order to assess the sensitivity, we assumed a ±20% of the defined major cost. The major cost of the model is:

- DAC sorbent replacement rates (0.25-38 kg/tCO2) affect operating costs, which could increase even further if more frequent replacement is needed due to site-specific conditions such as air humidity or pollutions(International Energy Agency, 2022).

- The stack replacements account for 24% of the CAPEX and has to take place 5 times over the life time of the project.
- The catalysts replacement in the methanol synthesis;
- The CAPEX of the technology especially for the DAC plant and SOEC due to the uncertainties about their costs and the fact that they are in demonstration phase.

The reference model computed from the collected data has selected as baseline.

The method of LCOE for electricity, LCOH for hydrogen and LCOM for methanol is used for the analysis.

The costs initially calculated for the project will be used as a baseline in the average case in order to make a comparison.

We applied an increase and decrease of 10 and 20% on the variables opex of the DAC, the SOEC and the methanol reactor in the first scenario.

The second scenario has taken into account the decrease of the PV cost by 20% in order to see the impact of energy on the output cost.

The last scenario considered that the water is free as it comes from the DAC plant.

4. Results and discussions

This section summarizes and discusses the main findings of the work. Based on the data collected and the assumptions formulated. In order to produce 10 000 tons of e-methanol per year, the total cost of production has been assessed by determining the capital cost, the fixed and variables costs. Then, using the results from the cost determination, we presented the levelized cost and the sensitivity analysis.

4.1. Cost determination

The production of synthetic fuels such as e-methanol requires significant investment in equipment and infrastructure.

The capital cost of the project, which represents the acquisition costs of the technologies, is estimated at 118,465,715.25 € which is mainly due to the high cost of the PV system including the batteries. As shown in Figure 5, the PV system and the batteries account for 99,841,870.50€ with 74,844,857.54 € for the PV and 24,997,012.97€ making it the most expensive component of the overall system due to the large amount of energy required to operate the facilities. The solid oxide electrolysis and the direct air capture facility follow at cost of 16,439,748.75€ and 1,915,960 €, respectively. The importance of their cost (SOEC, DAC) can be explained by the fact that these technologies are are still in the early stage of development and considerable research and development (R&D) investments are required to improve efficiency, scalability, and cost-effectiveness. These R&D costs increase the project's capital expenditure. Even though the importance of the PV+batteries, it helps to reduce the CAPEX for e-methanol production. The work of Nizami et al., (2022) showed that employing PV-based electrolysis for hydrogen production in methanol synthesis could lower the capital costs by as much as 50% when compared to traditional techniques.

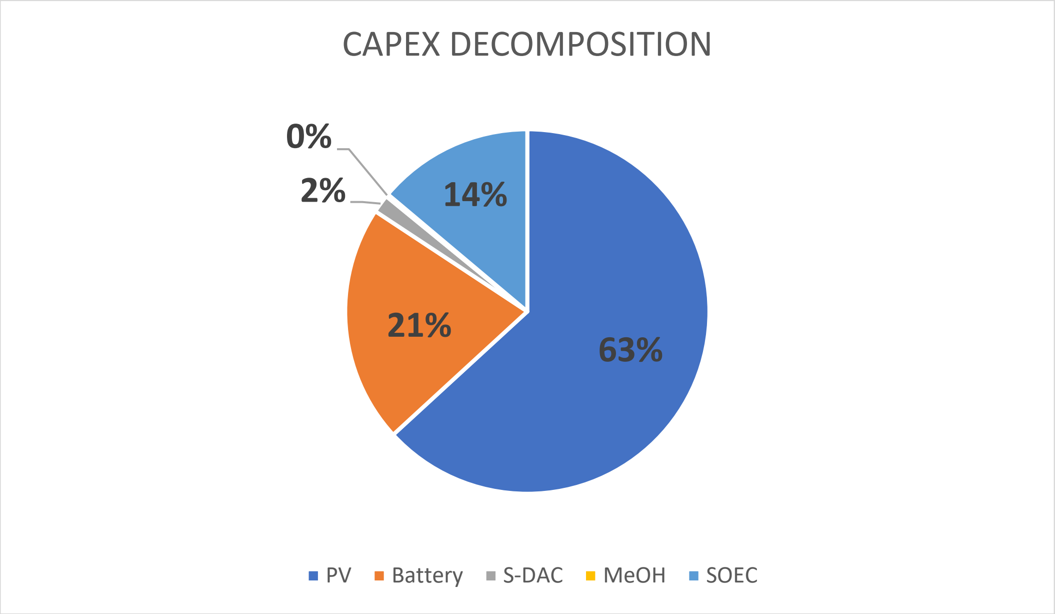


Figure 5: Capital expenditures decomposition

Source: Author

The methanol reactor is the least expensive technologyy with a cost of € 268,136.00 due to the maturity of the technology. Methanol production is a well-known process and is already at a high technology readiness level (TRL9)(Schorn et al., 2021).

The total operational expenditure over the lifetime of the project is estimated at 295,530,307.24 €. This includes the fixed cost of 89,674,587.68 € which covers the operating and maintenance cost of the system, the labor cost and the administrative cost. Additionally, there is 205,855,719.56 € for variables costs.

A decomposition of the operational expenditures including the cost of land for each technology is presented in the following figures.

The Figure 6 illustrating the opex decomposition of the PV system shows that an important cost of land due to the huge surface to be exploit produce the energy required which is 338205 kWh per day. The variable cost is flowed by the fix opex that is 1% of the PV CAPEX taking into account the operation and maintenance cost, the labor and the admirative one. Due to its lifetime of 12 years, the energy storage system is the least costly component of the PV system.

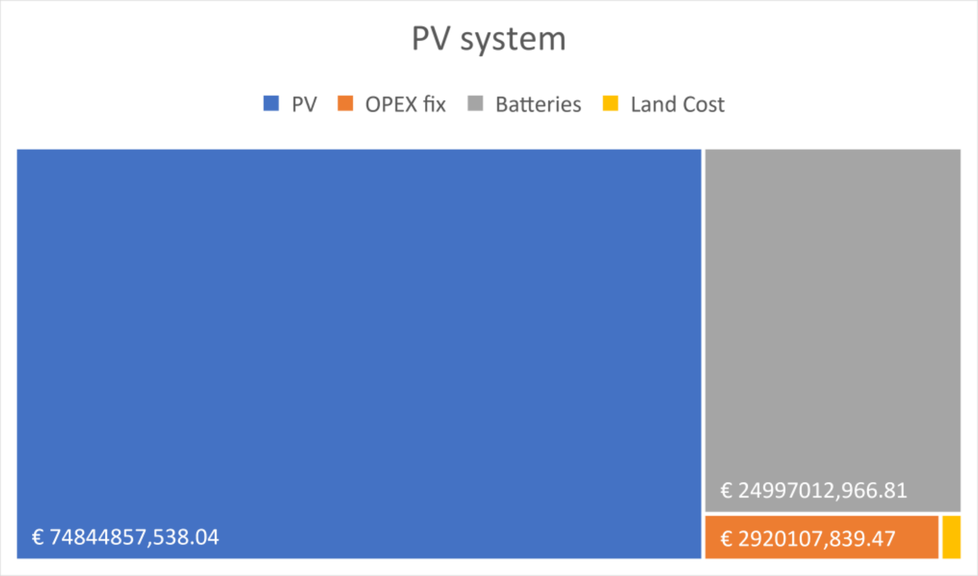


Figure 6: Operating cost decomposition for PV including land

Source: Author

The cost of energy in hydrogen generation using electrolysers is influenced by several factors, including the source of the required electricity, the capital costs of the electrolyser, its utilization, and the average electricity cost. After electrolysers, electricity cost is the biggest cost in hydrogen generation as depicted in Figure 7.

At the laboratory stage, SOEC has a high electricity requirement, similar to other electrolysers, 1 kg of hydrogen requires 42.3 kWh, hence the high cost of electricity at 106,047,394.27 €, followed by the cost of water at 51974536.34 € which is driven by the cost of the direct air capture technology. The stack is to be replaced 5 times over the life of the project, at a cost of 16,152,671.33€.

The costs for maintenance and salaries are less significant compared to the other costs.

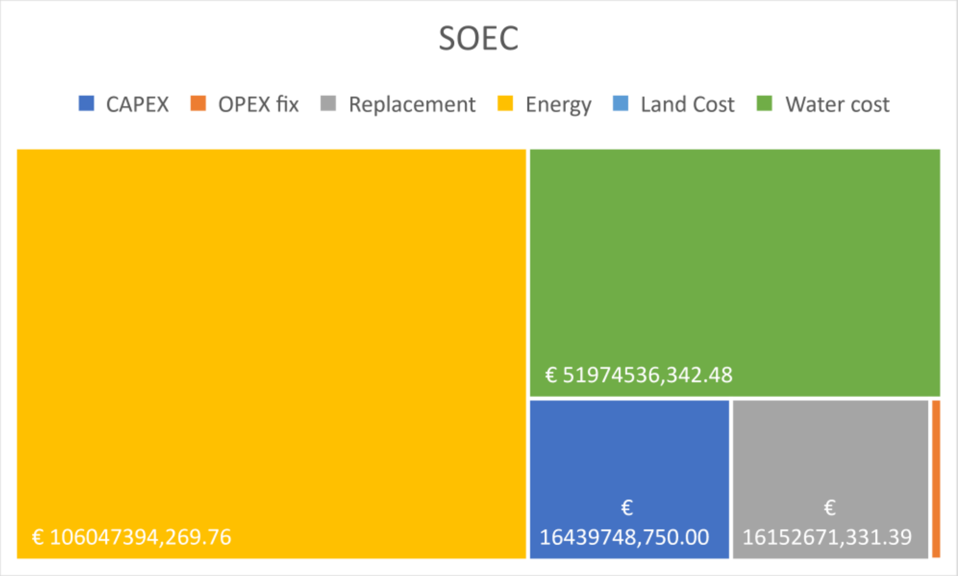


Figure 7: Operating cost decomposition of SOEC

Source: Author

In the case of the direct air capture plant intended to produce the carbon dioxide and water, we have considered in our case study the energy in terms of electricity required to produce the quantity needed in the following process. The total cost to produce 14,000 tonnes of CO2 and 19,600 tonnes of water is55,871,485.96 € mainly lead by the electricity cost counting for 91% with an energy requirement of 2943.8 kWh per tonnes of CO2 produced.

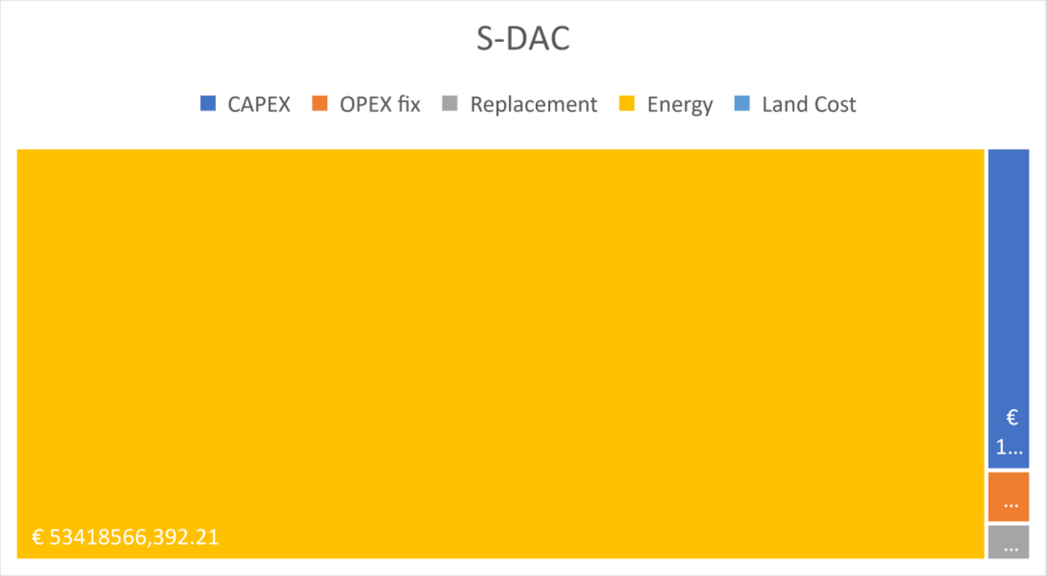


Figure 8: Operating cost of DAC

Source: Author

The technology for producing methanol is already at the mature stage and requires less energy than the other technologies presented above. Figure 8 shows that the inputs, namely hydrogen and CO2, represent the most significant costs in methanol production, which is driven by the cost of hydrogen, which accounts for 79.35 %, followed by the cost of CO2, which represents 19.5% with a cost of 260965461€ for both.

The cost of energy is 2037045.928€ followed by the cost of catalyst replacement and the cost of maintenance and salaries at 216605.678€ and 300,022.47 € respectively.

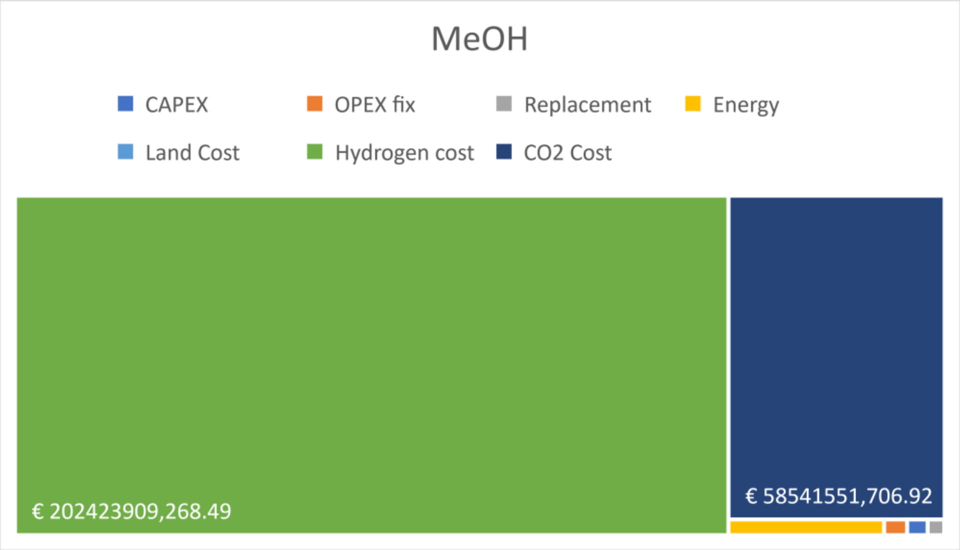


Figure 9: Operating cost decomposition methanol production

Source: Author

Over the lifetime of the project, the total cost is assumed to be 414,283,623.87 €. Based on the calculation and figures presented above, it can be affirmed that the variables cost is leading the total cost for about 50% due to the electricity and replacement cost in each technology. The PV system and the immaturity of some of the technologies like the SOEC and the DAC contribute significantly and representing around 29% of the cost, and the fixed one is about 21%.

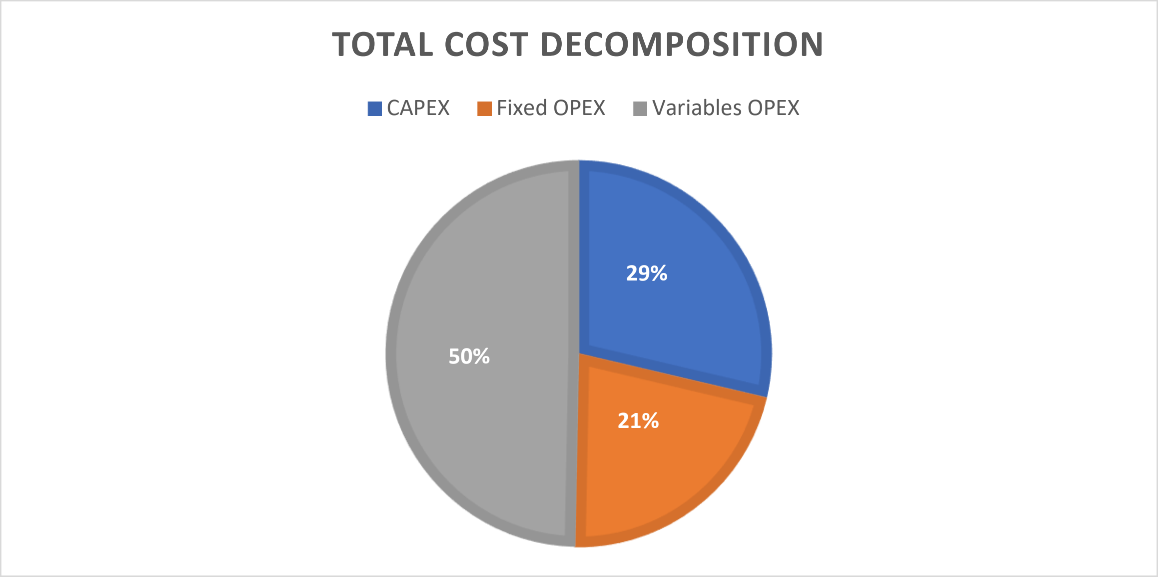


Figure 10: Share of costs in the total cost

Source: Author

4.2. Levelized cost calculation

This section presents the result of the different levelized cost calculated based on the collected data presented in the data collection section.

In our analysis, we presented the levelized cost of electricity (LCOE), the levelized cost of water (LCOW), the levelized cost of carbon dioxide (LCOC), the levelized cost of hydrogen (LCOH) and the one for methanol (LCOM).

Serving as base for calculating the electricity cost of the system, the levelized cost of electricity (LCOE) giving the cost of one unit of electricity of our project is evaluated at 0.11 €/kWh. This is determined based on the calculated CAPEX of the PV and the batteries which amounts to 99,841,870.50 €. The OPEX counting for 1% of the CAPEX for the PV and 7.5% for the batteries is evaluated at 2,623,224.55 € for the fixed one and 24,997,012.97 € for the batteries replacement cost that will take place once.

Compared to the literature and studies assessing levelized cost, our LCOE is between the range 0.05 to 0.19 €/kWh for PV using batteries presented by IRENA in 2020. (Nizami et al., 2022). In our investigation, it is confirmed that batteries play a significant role in electricity production. The price of a battery is 0.05 euros per kWh, while the total cost per kWh is 0.11 euros. Thus, batteries make up a significant proportion of the overall cost of electricity generation. This finding is in line with the work of Nizami et al., (2022) where it is stated that in 2020, the electricity production costs with PV and PV–battery was 5.30 and 12.56 cents/kWh, respectively.

In order to define the levelized cost of hydrogen, we have defined the cost of water from direct air capture. In this case, direct air capture produces both carbon dioxide and water. We have therefore assumed 50% of the CAPEX in order to achieve our calculations. The other elements taken into account in determining the cost of water are the fixed costs, including salaries and maintenance cost and the cost of replacing the sorbent.

The levelized cost of water from direct air capture is 238.70 € per ton per year.

The levelized of carbon dioxide (LCOC) has been calculated using the same process as the LCOW determination but with the inclusion of a storage tank for CO_2. The cost of CO_2 is useful for the determination of the levelized cost of methanol presented below. The levelized cost of carbon dioxide is 335.54 € per ton. From literature and depending on the source of emissions and technologies, the carbon dioxide price varies from 100 to 800 €/tCO2(Fasihi et al., 2019) and range between 125 to 335 €/tCO2(International Energy Agency, 2022). According to IRENA, (2021) , it is estimated that the cost will range from €800-€1,600 per metric ton, assuming that CO2 is sourced from Bioenergy with Carbon Capture and Storage (BECCS) at a cost of €10-€50 per metric ton.

The LCOW and LCOC is mostly driven by the cost of electricity as depicted in Figure 8 that play a crucial role in the capture and absorption and desorption process.

The levelized cost of hydrogen assessing the price of one unit of the hydrogen produced by our system took into account the CAPEX of the SOEC corresponding to € 16,439,748.75. The electricity as presented in Figure 7 count for around 46% in the determination of LCOH followed by the water cost which is around 23%. The stack replacement cost and the fixed cost are €   16,152,671.33 and 947,062.30 € respectively. The calculated LCOH is 8,459.91 € per ton. The electricity playing an important role like for the CO_2 and water generation is the most important cost in the hydrogen generation confirmed by the work of (Bui et al., 2023).

The SOEC even in early commercial stage proved a good LCOH when compared to the literature in which we found different LCOH such as 4-6 € per kg (IRENA, 2019). Gerloff, 2023 in his comparison study presented a LCOH range between 6.46–9.86 USD per kg using SOEC powered by solar. Another study performed by Bhandari & Shah, 2021 shows a value of 57.61 € per kg using PEM and 45.41 € per kg using AEL and both powered by PV+batteries. Bui et al., (2023) in his work find a LCOH ranges from 2.78 to 11.67 $/kg H2 using SOEC. In our study, the use of heat can make the system more efficient and reduce the price of hydrogen. As stated by Johnson Matthey group in their article on green methanol, SOEC systems are less developed and tend to be smaller in terms of size compared to the PEM and the Alkaline but offer an advantage if there is integration of heat in the system.

The levelized cost of methanol is calculated taking into account the cost of the technology which is at mature stage and evaluated at 275,636 € including the storage and land cost. The methanol cost is dependent production costs on hydrogen in particular, and also the carbon dioxide price that are 202423909.3 € and 58541551.71 € respectively; the cost of electricity is 2037045.928 € and the catalyst replacement calculated is 216605.678 €.

A levelized cost of e-methanol from our analysis is 2,144.35 € per ton which is lower compared to values found in some literature. For instance, Nizami et al. (2022) reported a cost of $1,669.56 per ton using PV and batteries and PEM. Additionally, IRENA and the Methanol Institute found a range of $1,200 to $2,400 per ton when the CO_2 is coming from DAC. However, under current market conditions, our methanol is uncompetitive compared to the fossil-based methanol found at 395 €/MT in Europe (Methanex, 2023). According to a report published by the World Economic Forum in 2021, lowering the cost of renewable electricity and hydrogen in desert economies could lead to PtL production costs as low as $1600 per ton using direct air capture by 2030. Incentives like the Inflation Reduction Act in US are the kind of initiatives that should be taken to reduce cost of green hydrogen and CO_2 that have significant role in e-methanol production

4.3. Sensitivity analysis

In this sensitivity analysis section, we analyzed 3 scenarios and compare them with the base scenario presented in the previous section. The sensitivity analysis results are presented in €/kg.

Scenario 1:

In this scenario, we maintain the electricity price fixed and assumed that the technology improvement can affect the costs. The ongoing Research &Development around the world to find alternatives and solutions to decrease the cost of components like sorbent, catalyst and stack can have an influence on the levelized cost. To observe the cost variation compared to the base cost, we have applied a decrease of 10% and 20% on the replacement cost of the mentioned elements. On the other hand, the crisis and others factors like the operating hours and the degradation rate can have an impact on the replacement cost. In order to see that impact, we applied a 10 and 20% increase on the cost.

The finding of this scenario is presented in the following table and depicted in Figure 11 for the LCOH and Figure 12 for the LCOM.

Table 7: Levelized cost variation under scenario 1

Scenario	LCOE(€/kWh)	LCOD(€/kg)	LCOW(€/m3)	LCOH(€/kg)	LCOM(€/kg)
BC	€ 0.11	€ 0.34	€ 0.24	€ 8.46	€ 2.14
-10%	€ 0.11	€ 0.32	€ 0.23	€ 8.22	€ 2.06
10%	€ 0.11	€ 0.33	€ 0.23	€ 8.43	€ 2.12
-20%	€ 0.11	€ 0.33	€ 0.23	€ 8.23	€ 2.08
20%	€ 0.11	€ 0.33	€ 0.23	€ 8.50	€ 2.14

Source: Author

As mentioned above, the electricity price remains constant in our analysis. We observe that if we applied change on the replacement cost, the variation on the water and CO_2 cost is effective in the 10% decrease case with 0.23 €/kg and 0.32 €/kg respectively compared to the other cases that remains quiet constant around 0.33 for the CO_2. We can observe a reduction of the hydrogen cost in the 10% increase and decrease. This reduction can be explained by the fact that the quantity has an impact on the cost and due to the maximum technique for the opposite case. However, the 10% decrease offers a better price of 8.22 €/kg for hydrogen and 2.06 €/kg methanol compared to the 10% increase. This is followed by the 20% decrease for a hydrogen price of 8.23 €/kg driving the methanol price to 2.08 €/kg as illustrated in Figure 11and Figure 12. Even though we have a better cost of hydrogen in the 10% increase, the 20% decrease offer a better cost for the e-methanol due to the least cost of CO_2 in that particular case.

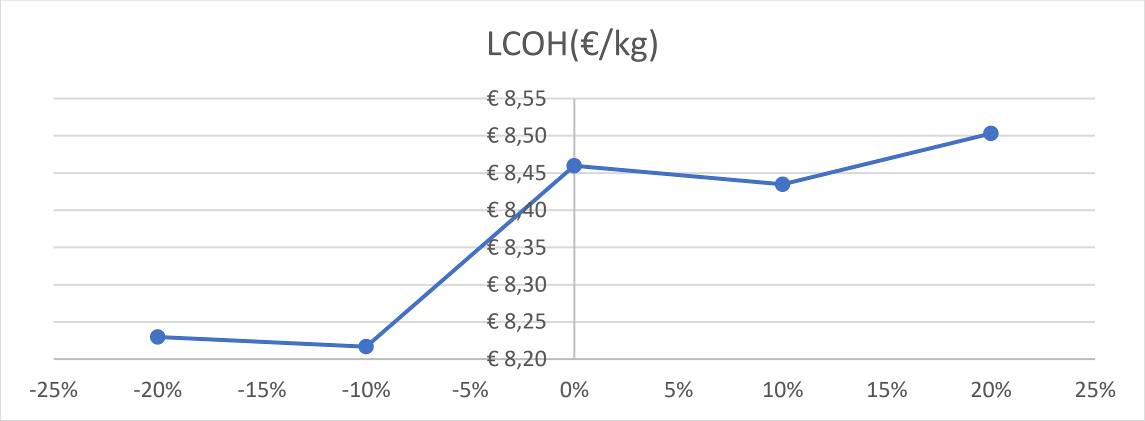


Figure 11: LCOH variation under Scenario 1

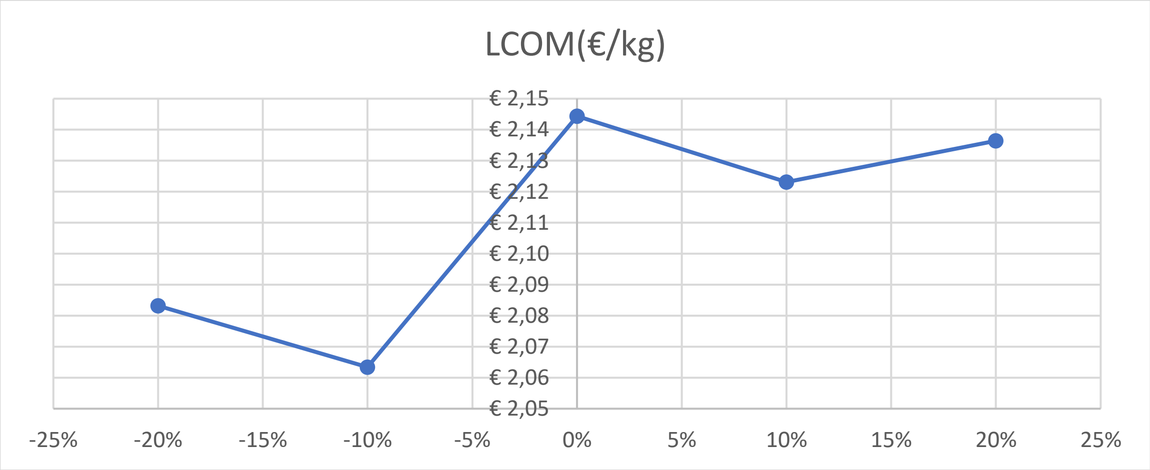


Figure 12: LCOM variation under scenario 1

Source: Author

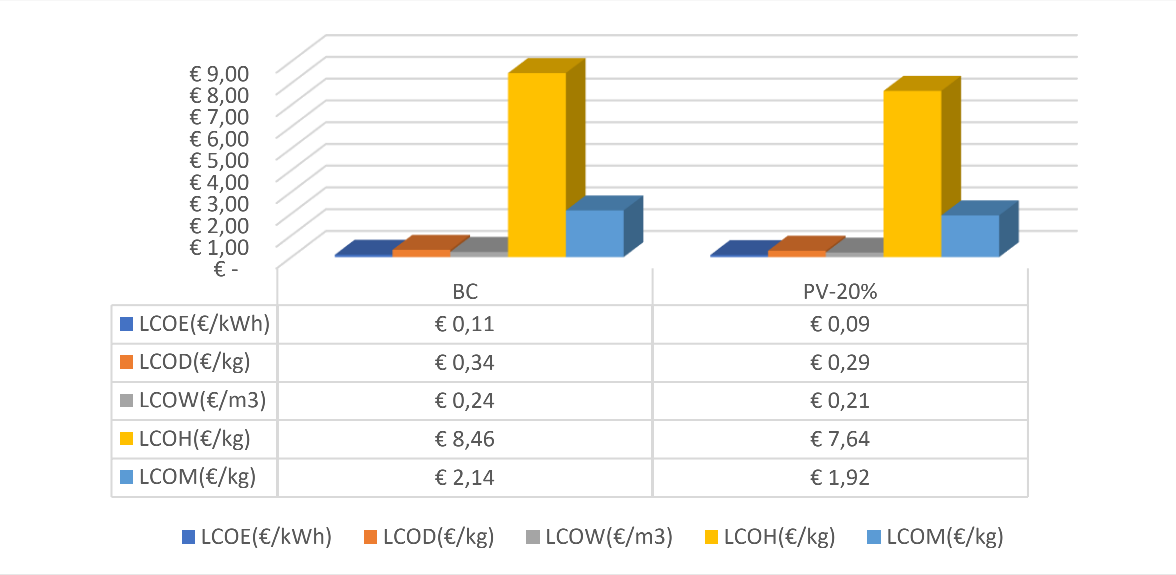
These graphs above shows that that the replacement cost plays a crucial role in determining the overall costs of water and CO2 in the direct air capture process. The base case scenario is represented with 0%.

Scenario 2:

In this section, we evaluate the impact that the cost of electricity can have in determining the different levelized costs. To do this, we applied a 20% reduction to the cost of the PV system.

One of the reasons for this choice is based on the fact that ongoing research into the solar system to reduce the cost of electricity may have an impact on the production of synthetic fuel from renewable energy sources.

After our analysis, we found that electricity variation affects consequently the levelized cost of the technologies.



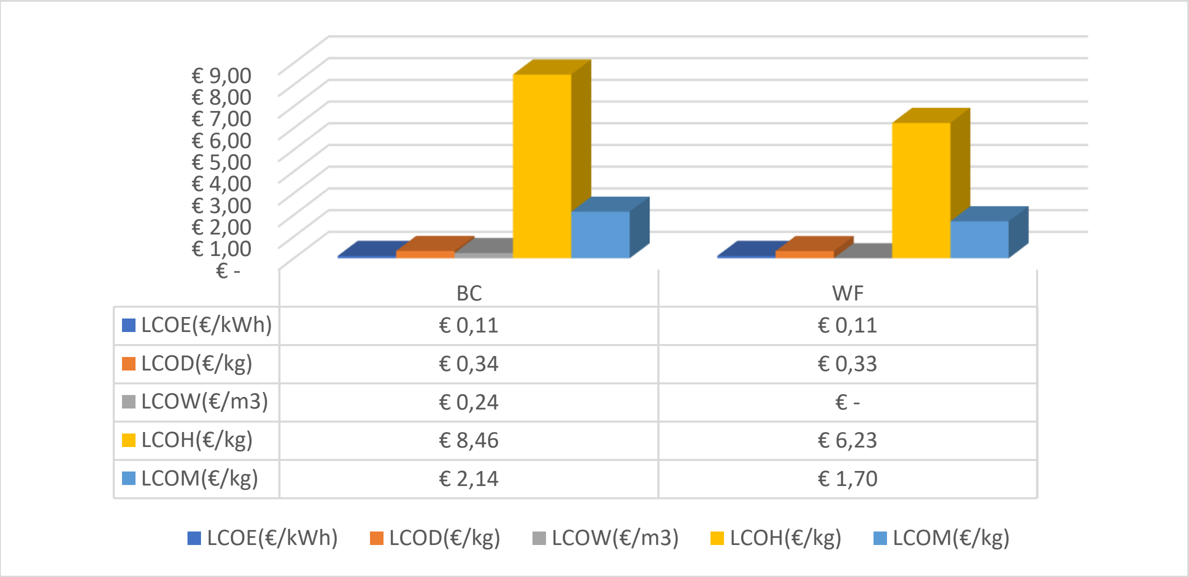
	BC	PV-20%
🟦 LCOE(€/kWh)	€ 0,11	€ 0,09
🟧 LCOD(€/kg)	€ 0,34	€ 0,29
⬜ LCOW(€/m3)	€ 0,24	€ 0,21
🟨 LCOH(€/kg)	€ 8,46	€ 7,64
🟦 LCOM(€/kg)	€ 2,14	€ 1,92

Figure 13: Levelized cost variation under scenario 2
Source: Author

Electricity as explained in previous section plays a significant role. Through technological advancements and improved management of power plants using heat, we can reduce electricity costs. By reducing capex, we can subsequently lower the cost of and all other output costs. Figure 13 shows the impacts of electricity cost on the levelized cost. Compared to the base case, the price drops from 8.46 €/kg to 7.64 €/kg for the LCOH resulting in a decrease in methanol price from 2.14 €/kg to 1.92 €/kg for the base case. This analysis highlights the strong dependence of the levelized cost on the cost of electricity, which can have significant implications for the financial viability and competitiveness of the technologies

Scenario 3:

Contrary to the previous scenario, we assessed the impact of water cost on the output cost by maintaining the cost of electricity constant from the base case. Since the water is sourced from direct air plant primarily used for CO_2 capture, we also considered the scenario where the water is treated as being provided at no cost.



	BC	WF
LCOE(€/kWh)	€ 0,11	€ 0,11
LCOD(€/kg)	€ 0,34	€ 0,33
LCOW(€/m3)	€ 0,24	€ -
LCOH(€/kg)	€ 8,46	€ 6,23
LCOM(€/kg)	€ 2,14	€ 1,70

Figure 14: Levelized cost variation under water free scenario

Source: Author

The results of scenario 3 show that if we consider water from direct air capture as a free by-product, the cost of producing hydrogen falls considerably compared to the base scenario, from 8.46 €/kg to 6.23 €/kg as illustrated in Figure 14.

Consequently, this affects the price of methanol, which rises from 2.14 €/kg to 1.70 €/kg. This is because the cost of hydrogen accounts for more than 50% of methanol production. Thus, our previous analysis is confirmed, showing the impact of the water cost in the generation of green hydrogen.

Today, e-methanol is gaining widespread attention and drawing interest from various quarters, including international institutions, policymakers, researchers, and businesses. This surge in interest is primarily driven by the significant impact e-methanol is beginning to have on the energy landscape. It serves as a catalyst and an opportunity for the development of green hydrogen and the establishment of an economy in alignment with principles outlined in existing literature.

The analyses conducted in this study, when compared to previous research, underscore the economic and environmental significance of producing e-methanol using direct air capture technology. However, it is worth noting that its high production cost renders it less attractive when compared to the prevailing market price of traditional methanol.

In our case study, we employed technologies that are still in their early stages of development for solid oxide electrolysis cells (SOEC) and direct air capture (DAC). This resulted in notably elevated costs for green hydrogen and CO2 capture, which, when combined with electricity expenses, exert a substantial influence on the overall methanol price.

Our sensitivity analysis highlights how certain factors, such as water availability, electricity costs, CO2 capture efficiency, and hydrogen production costs, can significantly impact the feasibility of e-methanol production. Numerous prior studies and ongoing research projects have underscored the importance of employing efficient and cost-effective technologies to make e-methanol more competitive in the market.

Furthermore, reducing production costs necessitates the implementation of policies and regulations conducive to the adoption of these emerging technologies. These measures are crucial in incentivizing companies to invest in DAC and SOEC innovation and encouraging researchers to explore alternative solutions.

5. Conclusion

The need to find solutions to fight climate change and achieve an energy transition for a more sustainable world has encouraged scientific research and development, particularly in the search for alternatives to fossil fuels.

The production of synthetic fuels using renewable energies and carbon dioxide from the air is proving to be a sustainable solution, especially in a context where water is a very important resource.

In our study, the objective is to develop a cost model for the production of e-methanol using a solid oxide electrolysis cell and a solid DAC for capturing CO2 from the air powered by a solar PV system.

From a technical point of view, our system is designed to produce 10,000 tons of e-methanol per year using 14,000 tonnes of CO2 and 1,920 tonnes of green hydrogen. In terms of investment, the overall cost of the system being 118,465,715.25 € without land cost, the PV system (PV+batteries) represents more than 84% for a cost of 99,841,870.50 €.

From the point of view of the operating costs of the system to produce the 10,000 tons of energy, the cost of electricity is the most significant for the production of CO2 and water at the DAC level and green hydrogen at the SOEC level. Due to the immaturity of the SOEC and the cost of electricity, the cost of hydrogen has an impact on the e-methanol price. Over the life time of the project, the electricity count for around 55% in the green hydrogen generation, 96% in the CO2 capture and water production.

The e-methanol price is driven by the cost of hydrogen and carbon dioxide that are sold at 8,459.91 €/t and 335.54 €/t respectively. The levelized cost of methanol is 2,144.35 €/t. Compared to the market conditions where the methanol is produced using fossil fuels, our e-methanol is not competitive.

In order to make our e-methanol attractive financially, we performed a sensitivity analysis to see the effect of some parameters on the economic performance.

Three scenarios have been assessed considering the impact of replacement cost, electricity cost and the water cost.

The analysis shows that the scenario where a decrease of PV CAPEX by 20% affect considerably all the process because electricity cost is an important driver in the production.

From 0.11 €/kWh, the electricity price dropped at 0.09 €/kWh entraining the reduction of the price to 7.64 €/kg for green hydrogen and 1.92 €/kg for e-methanol compared to the base case. Considering the other scenario where the replacement of component like sorbent, stack and catalyst by R&D can occur a reduction of the cost and make the e-fuel attractive.

The scenario considering water free of cost showed a better result from 8.46 €/kg to 6.23 €/kg for green hydrogen and 2.14 €/kg to 1.70 €/kg for e-methanol as the water is coming from the direct air capture plant.

As this study is a theoretical assessment of a cost model for the generation of e-methanol using solid direct air capture and solid oxide electrolysis powered by solar PV system in arid regions, more patterns and pathways using primary data and research on the ground need to be done in order to give suitable economic indicators and business models for a water-conscious generation of e-fuels in arid regions.

Making the e-fuels like e-methanol competitive and accessible at lower price require more research and development, policies and regulations to accelerate the adoption of such kind of initiative and projects because it guarantees a promising and sustainable future through an effective energy transition while solving the greenhouse gas and water scarcity issue especially in arid regions.

6. Recommendations

In this section, some recommendations and solutions have been proposed in order to improve the efficiency and reduce the costs of the project.

At the project scale, the recommendations are made to improve the productivity and efficiency of the system while reducing production costs.

- Optimize an efficient and cost competitive energy system by combining PV and wind;
- Use of heat recovery system to reduce losses and also electricity cost;
- Use of modular technology for DAC and electrolyser in order to master the production and improve the economy of scale;
- Sell the oxygen from electrolyser to cover some production of cost

Add to the recommendations made at the project level, in order to accelerate the adoption of this kind of initiative, there is a need to:

- Set more policies and regulatory framework to encourage more initiatives of this kind;
- Invest in R&D in order to reduce the cost of technologies;
- Develop scientific research to find innovative materials to improve the productivity and efficiency of technologies.

6. Limitations

The data used in this study is derived from the literature, some of which is based on assumptions, hence subject to uncertainties. To cover these uncertainties, a sensitivity analysis has been conducted.

SOEC has not yet achieved commercial maturity, and chemicals such as sorbent, stack, and catalysts are still being developed. Therefore, it is important to collect primary data from industries and adjust the information accordingly.

This study's analyses do not consider the area's relative humidity and degree of aridity, which can significantly influence CO2 and water production.

DECLARATION OF AUTHORSHIP

I, *Benogo Mohamed TRAORE,*

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, I used *QuillBot and DeepL* in order to edit the writing of the thesis. After using this tool, I reviewed and edited the content as needed and take full responsibility for the content.

Date: August 24th, 2023 Signature: **Benogo Mohamed TRAORE**

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