Université Cheikh Anta Diop de Dakar

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MASTER THESIS

Speciality: Economics/Policies/Infrastructures and Green Hydrogen Technology

Topic:

Cost Efficiency Losses Assessment and Economies of Scale Impact in Green Hydrogen and e-Methanol Production from Direct Air Capture Electrolysis

Presented the 18/09/2023 by :

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Determination of Cost Efficiency Losses and Economy of Scale Impacts in the Production of Green Hydrogen and Methanol from Direct Air Capture-Electrolysis

Abstract

Green hydrogen and e-Methanol production have the potential to contribute to decarbonization and a greener economy whilst managing concerns of sustainability in the energy transition. The use of Direct Air capture technology to suck Carbon dioxide and water to yield methanol in combination with a solid Oxide Electrolyzer and a Methanol Synthesis system process is a promising alternative to fossil fuels. while it encounters issues related to cost-efficiency losses. The aim of this study is to investigate alternatives to reduce cost efficiency losses and economies of scale impact in the production process using solar energy. Data were collected from online platforms and databases. This study carried out a techno-economic assessment to evaluate the production costs as well as the economic performance of the model. A sensitivity analysis is also carried out based on input parameters such as electricity cost, direct air capture, solid oxide electrolyzer cell, and e-Methanol synthesis capital expenditure to determine cost efficiency losses. Additionally, the impact of economies of scale was evaluated in regard to an alteration of different capacities of the model system component. The same as, technological advancement simulation based on the learning curve to predict future costs in 2050. This scenario is developed to explore pathways to reduce the Levelized Cost of capture, Hydrogen, and Methanol. The findings showed that the cost of capture, Hydrogen, and e-Methanol were respectively found equal to 0.053 €/kWh, 0.52 €/kg (CO_2/H_2O), 0.36 €/kg, 0.063 €/kg. Meanwhile, the electricity, direct air capture, and solid oxide electrolyzer cell capital investment are the most sensitive parameters affecting the Levelized costs of this study.

The economies of scale assessment results through the simulation of the models' capacity showed that as the component capacity increases, the production cost decreases. In addition to the scenario 2050 which has shown the project profitability based on technological advancement with a positive Net Present Value of 6.84 million €.

Keywords: Direct Air Capture, Solid Oxide Electrolyzer, Methanol synthesis, Techno-Economic assessment, Economies of Scale, Hydrogen-Methanol, Levelized Cost

Executive summary

This work objective is to evaluate cost efficiency losses and the impact of Economies of Scale in the production of Hydrogen and e-Methanol from direct air capture electrolysis powered by a solar Photovoltaic system. With the alternative pathway to transition towards green and sustainable energy, H_2 and e-MeOH are found promising alternative energy sources. Resulting in a need to optimize the production process cost especially when Direct Air Capture Electrolysis is used. This study used comprehensive quantitative methods like a techno-economic assessment to analyze the economic performance by evaluating the levelized costs and economic viability of the project. Additionally, a sensitivity analysis is done by varying the electricity cost as well as the different capital costs of the direct air capture, solid oxide electrolyzer cell, and Methanol Synthesis systems by ±5,10, and 15%.

Besides that, a scenario is simulated upon the change in the model capacity to evaluate the impact of economies of scale in the production of Hydrogen and e-Methanol from DACE.

Moreover, a scenario in 2050 based on the technological advancement of the direct air capture technology is reproduced based on the learning rate of the direct air capture, solid oxide electrolyzer cell, and Methanol synthesis system cost prediction. Consequently, the key findings showed that the different levelized costs of carbon dioxide and water captured, Hydrogen, and e-Methanol found are respectively equal to 0.528,0.36,0.063 €/kg.

The sensitivity analysis result showed that the electricity cost, direct air capture, and solid oxide electrolyzer cell capital Cost are the most sensitive parameters affecting the different levelized costs of the power plant.

In addition to this, the economies of scale impact assessment have shown that the upscaling of the model capacity lowers the levelized cost of electricity, the capture of Carbon Dioxide and water, Hydrogen, and e-Methanol. In addition, the scenario 2050 results in more cost-competitive levelized costs in the same order as 0.038€/kWh, and 0.365, 0.203, 0,002 €/kg.

This study is crucial for more understanding of cost efficiency losses and potential advantages of economies of scale. This study provides guidance on potential cost-reduction opportunities and strategies for future investment.

Résumé

L’objectif de cette recherche est d'évaluer les pertes de rentabilité et l'impact de l’économie d’échelle dans la production d’Hydrogène et electro Méthanol à partir de technologie de capture d’air combiner avec un électrolyseur à oxyde solide, alimenté par un système solaire photovoltaïque.

Considérant la voie alternative de la transition vers une énergie verte et durable, l’hydrogène et l'e-Méthanol sont des sources d'énergie alternatives prometteuses. Il en résulte un besoin d'optimiser le coût du processus de production, afin d’éviter les pertes liées au cout de production, en particulier lorsque les technologies de capture d’air combiner avec un électrolyseur à oxyde solide est utilisé.

Dans cette étude, une méthode quantitative est utilisée, telle qu'une évaluation technico-économique pour analyser la performance des coûts actualisés et la viabilité économique du projet. De plus, une analyse de sensibilité est effectuée en faisant varier le coût de l'électricité ainsi que les différents coûts d'investissement des systèmes de capture d’air, électrolyseur à oxyde solide, et du réacteur de Méthanol de ±5,10 et 15 %. En plus de cela, un scénario sur le changement de capacité du modèle est simulé pour évaluer l'impact de l'économie d’échelle dans la production d’Hydrogène et d'e-Méthanol à partir de technologie de capture d’aire. De surcroit, un scénario 2050 basé sur l'avancement technologique des diffèrent component de notre modèle est reproduit sur la base du taux d'apprentissage des systèmes de capture d’air, électrolyseur à oxyde solide, et du réacteur de Méthanol pour la prévision des coûts. Par conséquent, les principales conclusions ont montré que les différents coûts actualisés de capture du dioxyde de Carbone et de l’eau, d’Hydrogène, ainsi que du e-Méthanol trouvés sont respectivement égaux à 0,528, 0,36, 0,063 €/kg.

Le résultat de l'analyse de sensibilité a montré que la variation du coût de l'électricité, capital d’investissement du système de capture d’air et d’électrolyseur *à oxyde solide* sont les paramètres les plus sensibles affectant les différents coûts actualisés. De plus, la mesure de l'impact de l’économie d’échelle a montré que l’augmentation de la capacité du modèle abaisse le coût de la production actualisée pour les diffèrent produits. Le scénario 2050 se traduit par des coûts actualisés plus compétitifs. Par ailleurs, cette étude fournit une compréhensible analyse et des recommandations sur les pertes de rentabilité et les avantages potentiels de l'économie d’échelle pour les chercheurs, les industries et les gouvernements pour la planification de futures stratégies d'investissement.

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1 Introduction

The (UN HABITAT, 2011) reported that the impacts of climate change will become more significant and make populations more vulnerable to its consequences. These issues are mostly an increase in the world's average temperature, the melting of mountain glaciers, an increase in sea levels, floods, drought, high-temperature increases and much more (Raazia, 2023). Consequently, The Intergovernmental Panel on Climate Change (IPCC) 6th assessment report showcased that anthropogenic emissions due to the overuse of conventional energy sources lead to an increase in the world average temperature, owing to large concentrations of greenhouse gases like Carbon dioxide (CO_2) emissions (Physical & Basis, 2020). The Paris Agreement acknowledged the critical situation about climate change and the necessity to take mitigation measures in fighting against it (Falkner, 2016). This includes an urgent need to rapidly transition the energy, transportation, and industry sectors from fossil fuels to renewable energy sources to decarbonize these sectors (Breyer et al., 2018). The pressing issue of climate change has prompted a global shift towards sustainable energy sources and the reduction of greenhouse gas (Sahoo et al., 2023).

Among the most promising alternatives are green hydrogen (H_2) and e-Methanol (MeOH), which have gained significant attention due to their potential to abate the current climate crisis (Shi et al., 2023). H_2 as a chemical compound, is the most abundant element in the universe (Jena, 2011). On one hand, H_2 has received tremendous interest as a carbon-free energy carrier (Towanou et al., 2023). On the other hand, H_2 produced from Renewable Energy (RE) sources such as wind and solar using water electrolysis technology is considered the most sustainable energy source among others (Kumar & Lim, 2022). H_2 production by electrolysis is an electrochemical process in which electrical energy produced from renewable energy sources is the driving force of chemical reactions to split water (H_2O) into H_2 and oxygen (O_2) (Kwasi-Effah C et al., 2015). While, MeOH is one of the most important industrial feedstocks used in H_2 synthesis, as a solvent, or in the energy and transportation field (Basile & Dalena, 2017). MeOH is commonly produced from a chemical reaction between the reaction of H_2, CO_2, and Carbon monoxide (CO). MeOH is represented by the chemical formula CH_3OH (Hafeez et al., 2022).

However, producing H_2 through electrolysis requires access to a clean water supply, while around 733 million people worldwide do not have access to fresh water (Olabi et al., 2022);

(United Nation, 2021). Consequently, researchers at the University of Melbourne developed a new alternative to H_2 production with a technique called Direct Air Electrolysis (DACE) which drain water from the air. Combined with a non-conventional energy source, it can generate pure H_2 even below a relative humidity (RH) of 4 percent (%) and under permanent operation, requiring low maintenance (Guo et al., 2022).

In the last few years, researchers showcased huge interest in the potentiality of DAC technology with a significant investigation on feasibility assessment (Realmonte et al., 2019). The International Energy Agency (IEA) developed a concept that DAC is a key to Net Zero. They considered DAC to play a crucial role in net zero achievement by 2050 to mitigate climate change with the ability to capture tons of CO_2/H_2O. The IEA also stated that implementation of DAC technologies at EOS could also enhance their potential to cost efficiency opportunities (International Energy Agency, 2022). Therefore, Direct Air Capture (DAC) technology could play a crucial role in climate change mitigation, the CO_2 captured can be availed for synthetic gas production like CO, H_2 and e-MeOH (Mac Dowell et al., 2017). Synthetic fuels are Electro-fuels (e-fuels) that replace a drop-in fuel like H_2 using electricity from RE known as power to X (Pt-X) transformation (Malins, 2017).

DAC has an outstanding opportunity to be installed anywhere to operate, besides many disadvantages like being energy intensive and presenting a high operating cost (Erans et al., 2022). At large scale, the widespread implementation of Direct Air Capture and Storage (DACCS) is expected to be constrained more by cost efficiency and technology readiness rather than the capacity for carbon storage and the availability of low-carbon energy source (Haberl et al., 2010). Combining the captured CO_2 to generate valuable products subsequently can assist in decreasing the overall expense of the DAC production process (Chauvy & Dubois, 2022).

In this study, we considered that the CO_2/H_2O captured from the DAC technology is further utilized by an electrolyzer that further supplies a Methanol Synthesis (MS) system for e-MeOH production (Ahmed, 2021). Among the technology for H_2O electrolysis, the Solid Oxide Electrolyzer cell (SOEC) is considered in this research to co-generate H_2/CO from CO_2 and H_2O supplied by the DAC system (Alenazey et al., 2015). The co-electrolysis ability of the SOEC lowers the energy consumption and contributes to cost efficiency (Jalili et al., 2023). It functions at high temperatures to co-electrolyze H_2O and CO_2 and offers an interesting opportunity to transform CO_2 and H_2O into H_2 and CO respectively through an electrochemical reaction in a single process (Hong et al., 2023). Although DACCS provides a cost-effective alternative, it is too expensive to direct mitigation measures in various sectors, including industry, heavy-duty vehicles, marine transport, and aviation (Ababneh & Hameed, 2022) .The comparison between several methanol synthesis systems from conventional and non-conventional energy sources found that DAC is one of the potential options for capturing CO_2 for MS (Arnaiz del Pozo et al., 2022). In this study, the Sunfire Synlink SOEC electrolyzer is used to generate 750 Normal cubic meter per hour (Nm^3/h) of H_2/CO. It is supplied with 560 Kilogram per hour (kg/h) of steam (H_2O) and 730 kg/h of CO_2 from the DAC unit (Sunfire GmbH, 2020).

1.1 Problem statement

Researchers have proposed the consideration of investigation, innovation, and adapted technology of RE to tackle climate change (Pengue et al., 2022). The adoption of these measures can ensure a safe and responsible transformation of captured carbon, mitigating the negative impacts associated with oil enhanced recovery and preventing the release of captured carbon into the atmosphere. This proactive approach promotes a more sustainable future and safeguards the environment and communities from potential harm (IPCC, 2022).

However, the technology readiness of DAC is at the demonstration level (stage 6) which present high energy need in terms of electricity and heat which is currently limiting the performance of the technology (Matter, 2023). As well as, hurdles in relation to cost efficiency losses and sustainable usage of the CO_2/H_2O captured from the air remains a gap in the existing literature (Ozkan et al., 2022). These challenges need to be scaled up for more cost benefit opportunities, while most researchers showed high interest in optimizing the process on sorbent of Solid-DAC (S-DAC) (IEA, Direct Air Capture, 2022). The team from the Debye Institute for Nanomaterial Science investigated on cost competitiveness showed that non-conventional carbon derivative fuel has huge potential to achieve a reduction of more than 50 % in emissions from the shipping industry alone (Mukherjee et al., 2023). Some of their results support previous researchers' work that building an e-fuel economy requires cost competitiveness which is crucial for their implementation (Bui et al., 2018). On the contrary, many studies investigated the optimization of the e-MeOH synthesis chain to get more efficient catalysts copper/zinc for a more efficient CO_2 While the impact of Economies of Scale (EOS) has also caught a lot of interest in the production of H2 e-MeOH (Kim et al., 2022).

Given these challenges and gaps in the literature, this study will contribute to the field of research with a comprehensive assessment on cost efficiency losses associated with H_2 and e-

MeOH from DAC, whilst analyzing the cost competitiveness opportunities through a TEA and EOS approach.

1.2 Research questions

The described problems about H_2 and e-MeOH from DAC lead us to this research about the determination of cost efficiency losses and EOS impacts in the production of H_2 and e-MeOH from DAC. Then the 3 following questions about the issues introduced previously are stated as follow:

1. What are the key parameters affecting the Levelized Cost of Capture CO_2/H_2O (LCOD), Levelized Cost of Hydrogen (LCOH), and Levelized Cost of e-Methanol (LCOM)?
2. How could EOS impact the production of green hydrogen and e-MeOH from DAC?
3. How could efficiency losses in the production process of H_2 and e-MeOH from DAC be reduced?

The answers to these questions will provide evidence about the environmental potential, economic and social benefits of scaling up the production of H_2 to motivate policymakers to the development of policies and strategies to support the transition to a low-carbon economy.

1.3 Objectives

Determination of cost efficiency losses and EOS impact in the production of H_2 and e-MeOH from DAC is the main objective of this study. The specific objectives of the research include:

1. Evaluation of the key parameters that affect the LCOH, LCOD and LCOM,
2. Investigation on EOS effects of the production unit cost,
3. Contributing to the research fields of DACE technology with more cost benefits opportunities,
4. Assessing the economic viability of producing H_2 and e-MeOH from DACE,

1.4 Thesis Outline

First of all, in Chapter 1, a review of the existing literature is done to identify the existing research about H_2 and e-MeOH production processes, economy, and Cost efficiency losses methods. Then, in Chapter 2 Materials and methods are presented followed by the description and discussion of the study outcome in Chapter 3 result and discussion. Finally, the conclusion and recommendation Chapter is introduced .

2 Chapter 1: Literature Review

H_2 and e-MeOH production from DACE has the potential to offer both decarbonization and sustainable transformation of the energy sector to a cleaner energy landscape (Satterfield et al., 2023). Meanwhile, investigation on cost efficiency losses and economic feasibility of the production is paramount to determine its viability (S. Lackner & Azarabadi, 2021). Although the literature on hydrogen and e-MeOH production economy is wide with various thematic, an overview of the current state of art on H_2 and e-MeOH production processes, economy, and the existing methods of cost efficiency assessment methods are discussed.

2.1 Green Hydrogen and e-Methanol production processes

H_2 production by Water Electrolysis (WE) is an electrochemical process in which electrical energy produced from RE sources is the driving force of chemical reactions to split water into H2 and O2 as per (Zoulias et al., 2004) see Figure 1.

From this research outcomes, electrolysis is considered as the cleanest way to produce H_2 when the required electricity is derived from renewable energy sources which align with our research objectives.

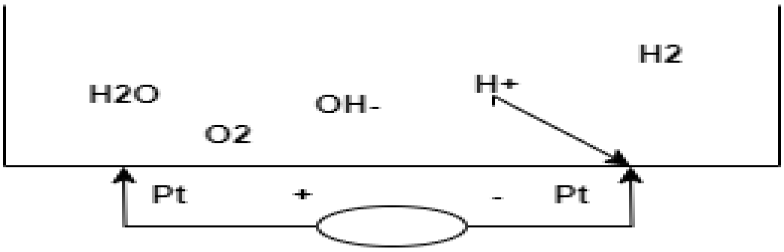

Figure 1: sketch of an electrochemical cell, OH- (hydroxide ion, Pt (platinum)

During the first industrial revolution in 1800, water decomposition was discovered (Praveen & Sethumad havan, 2017). hen by 1902, over 400 industrial water electrolysis units were already in operation. In 1939, the first large-scale water electrolysis plant with a capacity of 10,000 Nm3/h of H2 was implemented followed by important improvements and advancements in technologies (Vasudevan, 2013). The remarkable point about its history remains the establishment of proton exchange membranes suitable for WE units and fuel cell, the technological advancements in high-temperature solid oxide technology, and the optimization and reconstruction of Alkaline Electrolyzers (AEC) (Kwasi-Effah C et al., 2015). This investigation provided us more insight about SOEC ability to optimize e-fuel production (Lux et al., 2021).

On the other hand, the process of WE is an environmentally friendly method for H2 generation (Djinović & Schüth, 2015). This supports our investigation to drain H2O from air as the production of H2 and e-MeOH needs huge amount of H2O. Therefore, these electrolyzers has been deemed to be the most feasible and commercial method for H2 production and energy storage when coupled with RE source such as AEC, Polymer Electrolyte Membrane Electrolyzer (PEMEC), Alkaline Anion Exchange Membrane (AEM), and SOEC (Nasser et al., 2022). While, SOEC is more optimal to our research compared to the listed electrolyzer because of its characteristics to operate at high temperature that lower electricity need compared to other WE technologies and also its promising future to have the ability to be deployed at large scale in a near future (Gmbh, 2021).

The technology of WE electrolysis is based on the following facts that the most common electrolyzers have two electrodes connected to form an electrochemical cell (see Figure 2) powered by an external source (de Fátima Palhares et al., 2018). Aligning with our objective to produce e-fuels through low carbon economy, solar photovoltaic (PV) system was chosen as the external source of power. The electrochemical process of green Hydrogen (H_2) and oxygen (O_2) is driven by electricity coming from renewable energy sources as shown in Equation 1 below.

$$H2O\ (l) \leftrightarrow\ H+\ (aq) +\ OH-\ (aq)$$

Equation 1

However, alkaline WE is mainly conducted by an electrolyte to transfer the hydroxide anions to the anode, where they undergo an oxidation then return to the cathode (Schalenbach et al., 2016). Consequently, the electrochemical reactions in an alkaline water electrolysis are represented by Equation 2 and Equation 3 below (Wan et al., 2023).

Cathode: $H2O\ +\ 2\,e- \rightarrow\ H2\ +\ 2\,OH^{-}$

Equation 2

Anode: $2OH^{-} \rightarrow ½\, O2 + H2O + 2\, e$

Equation 3

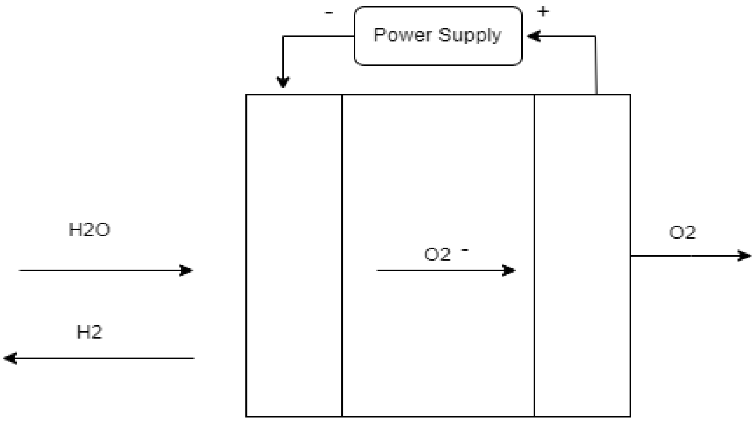

Figure 2 Electrochemical cell of an electrolyzer (Nasser et al., 2022)

2.1.1 Alkaline Electrolyzer (AEC)

AEC has its electrodes submerged in sodium hydroxide (NaOH) or potassium hydroxide (KOH) electrolyte in a range of 20 to 40 % (percent) (Y. Zhang & Wei, 2020). (Marini et al., 2012) posited that advanced alkaline water electrolyzer that has a gas removal compartment has higher efficiency and stability with cathodes and anodes optimized at 60 ◦C but limited by the need of huge amount of electrolyte around 100 g of catalyst per kilowatt (kW). Bringing the cost of the Ni catalyst below 7.4 Euro per kilowatt (€/kW) would make the manufacturing stage the key driver to higher cost than any other part of the cost different from previous generation of AEC. This investigation is interesting even if it does not concern SOEC electrolyzer but the recommendation made can also be applied by manufactures to lower its capital investment cost.

2.1.2 Polymer Electrolyte Membrane Electrolyzer

PEMEC WE is also driven by the Equation 2 and Equation 3 above while the protons are transferred from the anode to the cathode via a proton membrane powered by an external electric power. Once the protons arrive at the cathode, they are linked to yield hydrogen following the Equation 1 above. Despite, the high cost of PEMEC, Acidic environment low durability, It encountered many benefits such as high current density ,an energy production performance of 80 to 90 % (Shiva Kumar & Himabindu, 2019). PEMEC is a mature technology with 1 to 5 Megawatt (MW) scale offering high-purity gas delivery (99.99%); high compactness; commercial operation at up to 3.0 Acm2 (Minnaar et al., 2019). Besides, (Scheepers et al., 2021) argue the optimal temperature at 80 ◦C with 1.6 Volt (V) optimized the efficiency resulting in reduction of explosion from the O2 side.

2.1.3 Alkaline anion exchange membrane

To address by the Equation 2 and Equation 3 above while the protons are transferred from the anode to the cathode via a proton membrane powered by an external electric power. Once the protons arrive at the cathode, they are linked to yield hydrogen following the Equation 1 above. Despite, the high cost of PEMEC, Acidic environment low durability, It encountered many benefits such as high current density ,an energy production performance of 80 to 90 % (Shiva Kumar & Himabindu, 2019). PEMEC is a mature technology with 1 to 5 Megawatt (MW) scale offering high-purity gas delivery (99.99%); high compactness; commercial operation at up to 3.0 Acm2 (Minnaar et al., 2019). Besides, (Scheepers et al., 2021) argue the optimal temperature at 80 ◦C with 1.6 Volt (V) optimized the efficiency resulting in reduction of explosion from the O2 technology.

2.1.4 high-temperature Solid Oxide electrolysis Cell

A SOEC conduct electrolysis in a range of high temperatures between 600 and 1000 °C through an electrochemical reaction for electrolysis purposes (Jiang et al., 2021) see Figure 3 below.

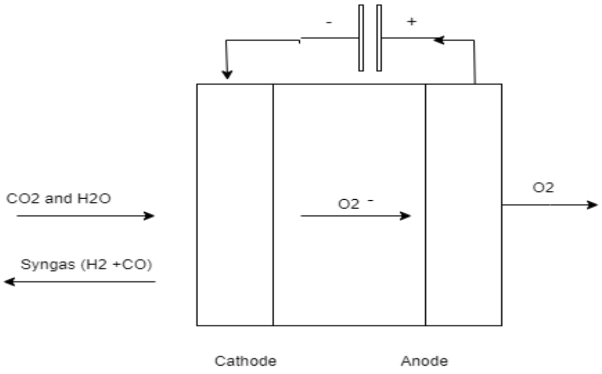

Figure 3: working Principle of SOEC for the co-electrolysis of steam/CO_2 to produce syngas and oxygen (Hong et al., 2023)

It is composed of an anode and cathode with an electrolyte sandwiched in between where the co-electrolysis of CO2/H2O take place, an interesting opportunity to reduce CO2 emission and store more RE (Stempien J, Sun Q, 2013). In regards to this discovery, our research model include power to methanol system to store energy into e-MeOH (X. Zhang et al., 2017). The SOEC ability to work over 650 °C is a remarkable opportunity to achieve higher electrolysis efficiency for CO synthesis requirement. SOEC also use low cost based electrode catalyst that result to their cost effectiveness which make it more adapted to our research objectives compared to other WE technology (Yan et al., 2014). Moreover, The SOEC ability has been assessed to produce syngas (H2 and CO) and O2 easier compared to myriads of water electrolysis methods and syngas synthesis (Wang et al., 2016). This finding is an outstanding opportunity for our research to generate CO and H2 in a single process to directly produce e-MeOH by using the CO2 and H2O coming directly from the DAC system.

The co-electrolysis of H2O and CO2 through high temperature electrolysis present a lot of advantages such as fast reaction rates, and a reduced cell resistance.

SOEC electrolyzers are environmentally friendly if supplied by renewable source like solar which would reduce the carbon footprint and limit greenhouse gas emissions of the technology (Menon et al., 2015). The co-electrolysis of H2O and CO2 in the SOEC electrolyzer is driven by electrochemical reactions as illustrated by the Equation 4, Equation 5 and Equation 6 (Xing et al., 2015).

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$$H2O + 2e^{-} \rightarrow H2O + \frac{1}{2}O2^{-}$$

Equation 4

$$CO2 \rightarrow CO + \frac{1}{2}O2^{-}$$

Equation 5

$$CO2 + H2O + 6e^{-} \rightarrow 2H2 + \mathrm{CO} + \frac{3}{2}O2$$

Equation 6

The study of (Y. Shi et al., 2015) argued that SOEC technology readiness level is still at its Research & Development level and needs deep research for more innovative discovery. They discovered that at high operating temperatures the electrolysis output gain in performance and that 30 % of the inlet energy is heat based, which is also valuable in our investigation as heat will be supplied by nearby industries to our plant. In addition, the study of (Gao et al., 2023) made a comparison between AEC, PEMEC, AEM, and SOEC to evaluate the energy efficiency and net CO2 reduction rate. Therefore, the case with SOEC was found to have more energy savings potentiality while the AEM presented more carbon reduction potential. Additionally, they discussed that conducting further research through a sensitivity analysis of uncertainty factors like renewable electricity, feedstock cost, and fuel impact provide more insight on how to reduce the cost. This methodology is beneficial in our investigation to evaluate and reduce cost efficiency losses to provide cost opportunities in the production of H2 and e-MeOH from DACE (Mukherjee et al., 2023).

2.1.5 Direct Air Capture Electrolysis process

The working process of DACE can be described as follows: an electrolyzer assembly, consisting of an anode and cathode inserted between two plates made of a porous material such as melamine sponge, is supplied with renewable energy in an open-air environment. This assembly is then immersed in a hygroscopic ionic solution, which absorbs moisture and CO2 from the air (Peters & Drewes, 2019) see Figure 4.

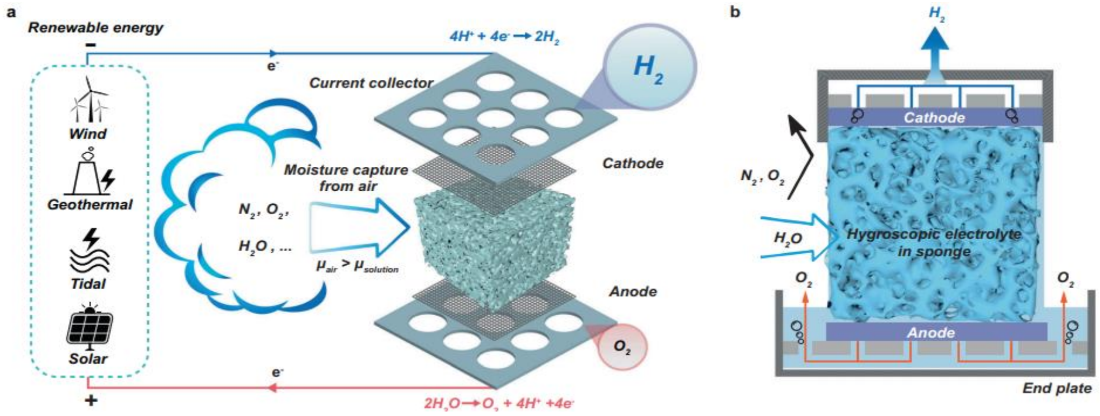

Figure 4 : DACE working principle

Two different types of DAC can be identified namely L-DAC and S-DAC, which respectively involve the removal of CO and H2O in the air captured through a chemical solution and sieving CO2/H2 (Masterson, 2022). (Temmerman & Rochette, 2023) elucidated the operational mechanism of DAC in their study.They explained how DAC operates in the open atmosphere through utilizing a series of chemical reactions to directly capture H2O and CO2 from it. S-DAC working principle consist of the adsorption of CO2/H2O through highly porous sorbents (Brilman & Veneman, 2013). While, in L-DAC a solution of hydroxide suck CO (Sankhe, Mohana Krishna, JUTURU, & Subrahmanyam). The chemical solvent is then put together with calcium hydroxide (Ca (OH)2) into a pellet reactor to get calcium carbonate (CaCO3) as a product of the reaction. Then the CaCO3 is died with a steam slaker before entering the calciner (Liu et al., 2020). The next step is to regulate the calciner temperature in a range of 800 to 900 °C for the release of Calcium oxide (CaO) and CO2 gas (Mcqueen et al., 2021).

The process energy demand for 1 Gigaton (Gt) of CO2/H2O require around 6 Exajoule (EJ) of low-carbon energy (International Energy Agency, 2022). Both S-DAC and L-DAC needs approximately 80 % of heat and 20 % of electrical energy (McQueen et al., 2020). Despite the high energy intensity of DAC technology, (Beuttler et al., 2019) investigation found that it is an outstanding technology in the domain of CO2 removal but is only relevant when produced at EOS by considering the utilization of CO2 and other products such as the water to yield H2/CO and further e-MeOH to attain cost attractiveness.

Additionally, (Erans et al., 2022) studies showed that the usage of amine sorbent in S-DAC could have an efficiency of 95% if the process is conducted through exhausted heat or low-carbon electricity. The usage of the CO2/H2O captured to generate H2 from WE and e-fuels present a major application of carbon capture to MS (Harrison & Hydrogen, 2021). As a consequence, S-DAC has been chosen in this research because of its high performance with Amin sorbent and less operational steps compared to L-DAC (Sabatino et al., 2021).

2.2 Methanol production processes

MeOH is a water-soluble liquid with an alcoholic odor, it freezes at -97.6°C (degree Celsius), boils at 64.6°C and has a density of 0.791 kilograms per cubic meter (kg/m3) at 20°C (Methanol Market services Asia, 2020). MeOH liquid fuel presents a lot of outstanding properties owing to a higher combustion efficiency than gasoline. It can also be used as the main product for derivation in the chemistry industry (Tabibian & Sharifzadeh, 2023). This caught our attention to pursue the process after the synthesis of H2 to produce e-MeOH as it is easy to handle, and transport (Sahnen, 2019). The production of MeOH relies on various carbon sources like coal, biomass, natural gas and CO2 capture through DAC technology (Olah, Goeppert, & Prakash, 2018). In addition to various alternative methods for MS from natural gas, utilizing different technologies such as steam reforming, partial oxidation, or autothermal reforming, are also available (Ott et al., 2012). These two methods can be used to produce MeOH in one-step conversion by hydrogenation of CO2 to e-MeOH or in two different paths with the transformation of CO2 into CO through the reverse water gas shift see main component of the model in Figure 5. These MS in two steps do not match with our model's working principle because the SOEC will directly co-generate H2 and CO, Then CO is combined with H2 to produce e-MeOH (Da Silva, 2016). The exothermic reaction is conductive at low temperature and high pressure but result in unfavorable efficiency, the reaction is illustrated by the following Equation 7, Equation 8, Equation 9 below (Zang et al., 2021).

$CO2 + 3H2 \rightarrow \ CH3OH + H2O$ ΔH298K = -87 kJ/mol

Equation 7

$CO2 + 2H2 \rightarrow \ CO + H20$ ΔH298K = + 41.2 kJ mol^{-1}

Equation 8

$CO + 2H2 \rightarrow \ CH3OH$ ΔH298K = - 120.5 kJ/mol

Equation 9

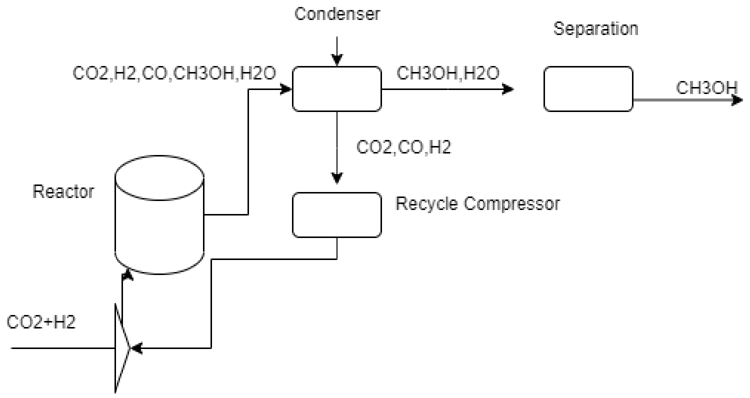

Figure 5 :main components of e-methanol synthesis from CO_2 *and* H_2O

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2.3 Green Hydrogen and e-Methanol economy

Production and storage are important parts of the H2 industry economy (F. Zhang et al., 2016). Therefore, in our study we included temporary storage capacity for H2O, CO2, CO and H2 to prepare for unexpected circumstances like technical issue or maintenance of the system while we have larger capacity for long term storage for the MS system as it is our final product. The primary goal of commercializing H2 generated through electrolysis is to reduce investment and operational expenses (Yates et al., 2020),indicating the importance to evaluate the key parameters affecting the LCOD, LCOH and LCOM for cost reduction opportunities in our research.

Together with the study of (Crabtree & Dresselhaus, n.d.) achieving the promise of H2 as an efficient, sustainable, and environmentally friendly fuel requires widespread innovation and development of the means for its production, storage, and use. Recently, H2 production from renewable sources has achieved an outstanding progress worldwide which has made the production more economically viable (Hosseini & Wahid, 2016). Besides that,(Song, 2023) assessed the level of technological understanding of e-fuel and the degree of technological knowledge through the literature. Whereas, (Solyanik, 2021) analyzes the LCOH by aggregating all expenditures of the electrolysis process. They estimated competitiveness of H2 Production from low carbon source like wind, solar and nuclear in Russian market. The evaluation of H2 production via wind energy cost approximately 2.22 Euro per kilogram (€/Kg) of H2. On the contrary, the LCOH via solar energy which is approximatively close to 3.33 €/kg of H2. This study methodology offered us more insight about how to perform the economic performance assessment of our model. Furthermore, The International Renewable Energy Agency (IRENA) reported that the main issues of H2 production remain high cost, lack of market and technical barriers. H2 present high potentiality to contribute significantly to the progress of low carbon energy transition market and synthetic e-fuels. one of the solutions to combat climate change and fasten energy transition is DAC technology that are capable to Co-electrolyze CO2 and H2O with high efficiency (Renewable & Agency, 2021). Motivating us to opt for this technology to overcome the shortage of fresh water for drinking (Debarre et al., 2022). As well as, (Eh et al., 2022) work showed that getting more investment to produce at EOS and the evaluation of the economic viability and feasibility of H2 production pathways can solve the issue of high cost due to energy intensity requirement during production processes. Improvements in efficiency are being made to stabilize operational expenses, while capacity is being expanded to reduce the costs associated with water splitting process to leverage the benefits of EOS (IRENA, 2020). Resulting in the simulation of different electrolyzer capacity in our model to assess the impact of EOS. Meanwhile ,it is also necessary to supply the electrolysis process with affordable electricity to reduce the LCOH ,which is also a relevant parameters in our sensitivity analysis (IRENA, 2019).

However, tremendous progress has been noticed in the economy of e-MeOH from hydrogenation of CO2 in presence of homogeneous catalyst while doing more research on active catalysts is crucial in a cycle CO2–MeOH (Alberico & Nielsen, 2015). To overcome this step of CO2 hydrogenation we found necessary the use of a SOEC to co-generate H2 and CO (Deka et al., 2019). e-MeOH application present a lot of benefits such as safety management and easy handling playing an important role in the RE economy, implying the transformation of the H2 produce during our investigation into e-MeOH for safety measures (Gielen et al., 2021). Notwithstanding, moving away from fossil fuel dependency is a key driver to e-MeOH production with a cost dependency on the LCOH (International Renewable Energy Agency (IRENA), 2016). In line with the study of (Ueckerdt, et al., 2021) to reduce cost of e-fuels like H2 and e-MeOH, DACE has been found as an outstanding alternative to swap fossil-based energy with green and sustainable energy like RE. In addition to EOS deployment with the necessity to revise policy and regulation support that encourage investment in the sector. Therefore, enhancing H2 and e-MeOH economy to create more job opportunities in the field of RE (CE Delft, 2021). The IRENA research showed that 12 million people worked in the RE sector ,approximately 5.6 jobs per installed MW in solar (Renewable et al., 2021). While H2 and e-fuels will create 10 million job that represent a share of about 12 to 22% in whole world power utilization (ILO, 2018).

2.4 Identification of Hydrogen and e-Methanol production efficiency losses methods

A TEA can be done to storage are important parts of the H2 industry economy (F. Zhang et al., 2016). Therefore, in our study we included temporary storage capacity for H2O, CO2, CO and H2 to prepare for unexpected circumstances like technical issue or maintenance of the system while we have larger capacity for long term storage for the MS system as it is our final product. The primary goal of commercializing H2 generated through electrolysis is to reduce investment and operational expenses (Yates et al., 2020),indicating the importance to evaluate the key parameters affecting the LCOD, LCOH and LCOM for cost reduction opportunities in our research.

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2.5 Gaps and Opportunities in the Literature

Climate change needs urgent responses like low carbon emissions (Asibey & Cobbinah, 2023). H2 and e-fuels technology represents one of the alternative solutions for future clean energy systems (Felseghi et al., 2019). Moreover, H2 has high energy density and its chemical structure enables it to be used as feedstock to create other derivative products (Society, 2018). The production of H2 by WE is an important pathway to transform electrical energy into chemical and also to produce e-fuel like MeOH (Pasini et al., 2023). MeOH is one of the most outstanding building blocks in many industries such as the chemical, and pharmaceutical industries as well as the production of synthetic hydrocarbons (Arnaiz del Pozo et al., 2022b).

In spite of the high interest in the co-electrolysis of H2 and e-MeOH production from DACE, research is still limited specifically focusing on the determination of cost efficiency losses (Breyer et al., 2019), (Green et al., 2022). (Gonzalez Sanchez et al., 2023) investigation about DAC role in climate mitigation showed that DAC presents a lot of risk such as cost efficiency losses, the need to scaled up the production capacity and lack of investment. Most of the past research focused on evaluating the cost parameters for various renewable energy technologies, such as solar and wind power, and other technology for H2 production like AEC, PEMEC, AEM, SOEC (Ennassiri et al., 2019), (Ferrero et al., 2016). Understanding the factors and parameters that contribute to the costs efficiency losses is essential in this particular process for evaluating the economic viability and potential market penetration of these e-fuels (Zang et al., 2021). Thus, it is relevant to identify and examine the key parameters that impact the LCOH, LCOD and LCOM in the context of DACE using a SOEC electrolyzer (Cames et al., 2021).

EOS can potentially reduce the overall production cost through technological advancement and increase in production volume to reduce the unit production costs by leveraging increase in production capacities to enhance output cost efficiency, and optimized resource utilization (Böhm et al., n.d.). However, the intensity to which EOS can influence the levelized costs of H2 and e-MeOH in the context of DACE remains uncertain (Yates et al., 2020).

Therefore, conducting a detailed TEA of cost components and the sensitivities of the LCOD, LCOH, LCOM, can help us in the identification of the key cost drivers.

This research will also provide more valuable insights about the potential cost reductions opportunities of H2 and e-MeOH from DACE by scaling up the production process at EOS.

3 Materials and Methods

A quantitative method was applied in this study of H_2 and e-MeOH production cost efficiency losses and EOS impact. First of all, upon sizing the model and the aggregation of the production output, two different approaches of economic analysis were applied to assess the different levelized costs and economic performance of the model. Followed by a sensitivity analysis to investigate on the most sensitive parameters affecting the Levelized costs. Then, we finally evaluate the EOS impact through a change in the system capacity and capital expenditure based on technological advancement.

3.1 Techno-Economic assessment (TEA)

The TEA was done by using Microsoft Excel software. The most outstanding economical and technical data are respectively illustrated in the section 3.1.1 and 7. The different Levelized Cost of Electricity, CO_2/H_2O captured, H_2, and e-MeOH (LCOE, LCOD, LCOH, and LCOM) were calculated at the break-even point.

3.1.1 Data and Key Assumptions

During the desk research, data were collected through many online platforms of academic research.

3.1.1.1 Data Collection Method

Data collection was conducted in the following manner: data gathering via platforms for research such as PubMed, Google Scholar, Science Direct, and in some renewable energy organization like the IPCC, IRENA, and International Energy Agency (IEA) as well as Nasa power and Global solar atlas database.

3.1.1.2 Solar Photovoltaic (PV) System

The most important techno-economic data of the PV system can be found in the Table 1 below.

Table 1 : PV system techno-economic data

Element of the system: PV	Value	Reference
CAPEX €/W_p	1.24	(Ramasamy & Margolis, 2021)
Inverter cost	110952.77	
inverter replacement after year 10 (€)	62361.6	
Annualized O&M (€/kW/Y)	44.91	(Description, 2017)
Land cost (€/m^2)	1.52	Assumed based on current cost of the m^2 in the village

3.1.1.3 Direct Air Capture (DAC) System

The DAC Techno-economic data can be found in the Table 2 below.

Table 2 : DAC system techno-economic data

Element of the system: DAC	Value	Reference
CAPEX S-DAC installation cost (€/t)	420	(International Energy Agency, 2022)
Sorbent replacement cost [11-38] €/kgCO_2, Average value is taken	24.5	
O&M %CAPEX (€)	4	(Daniel et al., 2022)
CO_2 storage Specific cost (€) % CAPEX	3.5	(Gorre et al., 2019)
HO2 Specific storage cost 1.5%CAPEX (€)	0.015	Assumed based on CO_2 storage cost
H_2O compressor €/t 1%	1	Assumed based on CO_2 compressor cost

3.1.1.4 Solid Oxide Electrolyzer Cell (SOEC) System

The SOEC economic data are introduced in the *Table 3* below.

Table 3: SOEC system techno-economic data

Element of the system: SOEC	Value	Reference
SOEC CAPEX (€/Kwe)	2072	(IEA, 2019)
CO storage (€/Nm^3)	22.5	assumed based on CO_2 storage cost
H_2 storage (€/Nm^3)	45	(Sollai et al., 2023b)
O_2 cylinder 200bar (€/t)	150	
CO Compressor € 3.5% CAPEX	0.035	Assumed based on CO2 compressor cost
H_2 Compressor (€/t) 3.5% CAPEX	0.035	(Gorre et al., 2019)
Stack replacement 4% CAPEX	0.04	(Gerloff, 2023)
O&M cost 2-3% CAPEX	0.025	(Dias et al., 2020)

3.1.1.5 Methanol Synthesis (MS) System Data

In this section, the economic data of the MS system are presented, see *Table 4*.

Table 4 : MS system techno-economic data

element of the system: MeOH	Value	Reference
Methanol reactor capex (€/t)	203.5	(Nizami & Wahyu, 2022)
MS Energy required (kW/kg)	0.039	(Bodegraven, 2021)
Methanol storage (€/kg)	8	(Dias et al., 2020)
Catalyst consumption (reactor) (kg/Y)	73	(Sollai et al., 2023b)
Catalyst lifetime 4 years (Cu/Zn/Al) (€/kg)	95.24	

3.1.1.6 Key assumption

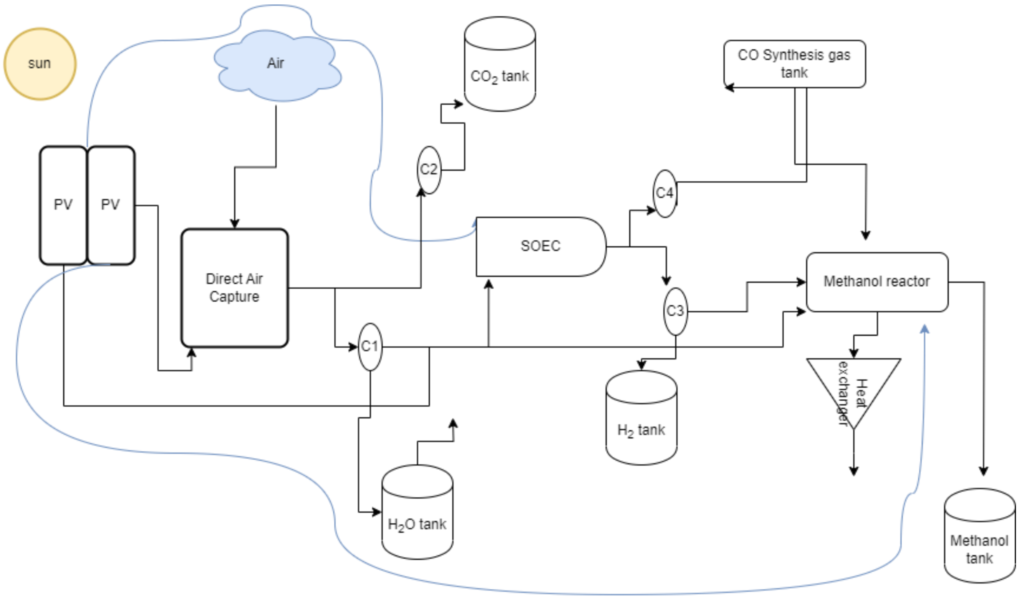
The power plant's lifetime was assumed to be 20 years, while the remaining components' lifespan were estimated at 10 years. A deterioration factor of 0.7 % was assumed for the model regarding the PV system data. Apart from this, the CO_2/H_2O ratio is assumed to be 1 based on the range [0.8,2] given by (IEA, Direct Air Capture, 2022). Additionally, the capacity factor was fixed at 0.9 for each system excepted the PV. Based on the (International Renewable Agency, n.d.-sb) findings that 1.38 t of CO_2 and 0.19 t of hydrogen were needed to produce 1 t of e-MeOH. It was assumed that 0.19 t of H_2 and 1.51 t of CO are needed to produce 1 t of MeOH. The calculation showed that 493.68 t of e-MeOH can be produced per day during 8 sun peak hours. In addition to this, the discount rate was assumed to be 8 % for the whole plant upon relying on the discount rate of Chemical plant in between [8-20 %] (Gerloff, 2023). While heat required by the SOEC and DAC system were considered to be supplied by nearby industries' waste heat. Furthermore, the two other SOEC electrolyzer used for the size simulation are commercially available for electrolysis only. So, we considered the hypothesis that they are meant for to co-electrolyze CO/H_2 by considering the same ratio of 2 as given by Sunfire for the synlink eletrolyzer to calculate their net production see 8.3 and 9. Besides that, most of the data were found in United States dollar ($) then converted in Euro (€) with an exchange rate of 0.74 € for each $ (International Monetary Fund , 2023).

3.1.1.7 Model Description

The chosen location for the project is Soutou, located in Bignona, Senegal, in the region named Ziguinchor located in the southwestern region of Senegal. According to the climate classification database (Köppen Geiger) It is characterized by a tropical wet and dry or savanna climate. In addition to this, the average temperature fluctuates between 24.1 and 28.3°C. The optimum tilt of PV modules is at 15/180 degree Celsius (°C) (Global solar Atlas).

The modeling of the proposed system was done by setting the values of parameters such as the feedstock cost, CAPEX, O&M, and the components' technical details into Microsoft Excel software see 3.1.1.4 and 7.2. The model is composed of a solar PV, DAC system, SOEC electrolyzer system and a methanol synthesis system including the compressors and heat exchanger as shown in Figure 6.

The operating mode of the model is as follow: The PV system supplied electricity to the DAC which capture CO_2 and H_2O from the air. Moreover, these two products are stored temporarily then delivered to SOEC system which is also powered by the PV system to yield syngas in a single process. This process is complied with a temporary storage of both products. Beside that CO and H_2 are delivered to the MS system to generate e-MeOH as our final product. The chemical reaction of e-MeOH synthesis between the two syngas is exothermic, as a consequence heat is released (Ha et al., 2023). C1, C2, C3, C4 represent respectively the compressor of H_2O, CO_2, H_2, and CO.



https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol

Figure 6: Overview of the e-Methanol plant via CO and H_2 co-electrolysis using SOEC electrolyzer coupled with DAC

3.1.2 Economic assessment

In this evaluation, two different approaches were adopted. Firstly, the different levelized cost were calculated at the break-even point when the Net Present Value (NPV) is equal to zero. The LCOE ,LCOD ,LCOH ,and LCOM are defined as discounted cash flows divided by the discounted energy output (Energy, 2013). They were calculated by utilizing the formula in Equation 10.

$$LCOEn = \frac{\sum_i [I_i + M_i + O_i + F]/(1+r)^i}{\frac{\sum_i E_i}{(1+r)^i}}$$

Equation 10

Where I is the investment cost in €, M stands for maintenance and service cost in €, O and M are the operational cost in Euro €, F_i is fuel (CO_2, /H_2O, H_2, CO) cost in €/kg and €/kW for the LCOE, E stands for Energy (CO_2, /H_2O, H_2, CO, CH_3OH) output in kg and kWh for electricity, r is the discount rate in %, *i* is the year, and $LCOE_n$ is in €/kg or €/kWh.

Secondly, the project viability approach was applied to calculate the NPV as the difference between the present value of the cash in and out flows as shown in the Equation 11 considering a discount rate of 8 %, 100 equity-share and an income tax rate of 20 %.

CF_{in} and CF_{out} represent respectively the present value of cash in and out flows, CI is the capital investment, IT refer to income taxes with a tax rate fixed at 20 % (Gallo, 2014).

$$NPV = \frac{\sum_i (C_{Fin} - C_{Fout}) - IT}{(1+r)^i} - CI$$

Equation 11

Currently, fossil-based methanol price is fixed at 450 €/t at the international market, which is utilized to calculate the e-MeOH selling price in this study (Sollai et al., 2023b).

while the O_2 is sold out at 0.118 €/kg based on the retailing price of 0.033 to 0.133 €/t (Renewable & Agency, n.d.). In addition to this, the excess CO_2 selling price is fixed at 91.92 €/t as given by (Carbon Credits, 2023) database for the current carbon price in Europe based on the fact that no price was fixed for West Africa. Apart from this, the excess H_2O €/t is sold out at 0.5 €/t as 1 t of water cost 0.97 €/t in Senegal (SEYE, 2023). Furthermore, the excess electricity from the PV system is sold to the Senegalese national grid 0.065 €/kWh at as the current electricity price is at 0.19 €/kWh (*DECISION N° 2023-11*, n.d.). Then, three different scenarios based on input cost, (CAPEX and storage cost) electrolyzer size, and cost prediction based on learning rate are defined within the sensitivity analysis.

3.2 Sensitivity analysis

3.2.1 Sensitivity analysis description

Due inherent uncertainties surrounding the specifications of literature-based on the emerging technology of DACE system models and their long-term evolution. Conducting a sensitivity analysis is crucial in this research. A systematic variation within a range of an increase of 5,10, and 15 % then a decrease of -5, -10, and -15 % was done for each system's capital cost while keeping the other parameters constant. Then, an observation was completed to investigate on their impact to determine the parameter that have significant outcome in the model's cost output. The sensitiveness was also carried out about the change in model capacity size, followed by a simulation of the model in a 2050 scenario to determine the impact of EOS in the production of H_2 and e-MeOH from DACE.

3.2.2 Electricity and Capital cost variation

In this section, the sensitivity analysis is conducted upon variation of several cost parameters such as the LCOE, CAPEX of the DAC, SOEC and CH_3OH, then the Methanol storage cost. The aim of this sensitivity analysis is to assess the key parameters affecting the cost efficiency of the LCOE, LCOH, LCOD, and LCOM.

3.2.3 Economies of scale impact assessment

In this scenario, the impact of EOS in the production of H_2 and e-MeOH synthesis is investigated. The cost advantages of the model are assessed with an increase in production capacity and the level of technological innovation and advancement.

3.2.3.1 Change in system Capacity

In this scenario, the impact of EOS in the production of H_2 and e-MeOH synthesis is conducted. Upon a change in the size of the DAC unit of 253.41 and 0.1 t/d of CO_2/H_2O captured paired with respectively two other SOEC electrolyzer of 100 MW and 1.1 MW that are respectively commercialized by Sunfire and Fuel Cell Energy see Table 17 and *Table 22*. Combined respectively by these MeOH reactors commercialized by Toyo and AirProduct LPMeOH see Table 18**Erreur ! Source du renvoi introuvable.**, *Table 23*. This simulation seeks to examine about how the change in electrolyzer and MeOH reactor size affects the cost per unit production to Capture H_2O/CO_2, H_2, CH_3OH in a DACE system.

3.2.3.2 Estimated Cost Reduction by 2050

To measure the effects of EOS on the system's cost attractiveness, a scenario of future power plant installation by 2050 is evaluated using the theory of technological learning. Followed by the examination of the cost per unit output of CO_2/H_2O, H_2, CH_3OH upon the impact of technological development and the potential reductions in the different Levelized cost. The learning rate quantify the slop of the learning curve. The decline in cost follows the learning rate, the faster it increases, the higher the cost decreases (Defazio & Mishchenko, n.d.). Then, we end up with the sensitivity of the technological advancement effect on the CAPEX of the PV, DAC, SOEC, and e-MeOH cost prediction by 2050 to model the scenario. The different predicted CAPEX and storage cost used in this scenario can be found in the Table 5 below.

Table 5: predicted CAPEX of the model components for a scenario 2050

System	cost	Reference
PV €/kW	355.94	(IRENA, 2019)
DAC €/tCO_2/H_2O	74	(International Energy Agency, 2022)
SOEC €/kW	296	(Christensen et al., 2022)
MeOH €/kg	119.92	(Lloyd's Register, 2019)

4 Results and discussion

In this section, result about calculations above are described in regard to determination of cost efficiency losses and EOS effects in the production of H_2 and e-MeOH from DAC. The TEA, economic performance and sensitivity analysis are also presented, then discussed.

4.1 Result

4.1.1 Techno-economic Assessment

A daily simulation of the model during 8 sun peak hours was done to calculate the total energy required by our model to work. The PV system's E_d was found equal to 54.06 MW/d with a capacity of 15.13 MW_p calculated using Equation 12 without battery storage. The PV system powered the load see

Figure 6 with 69.01 MW/d of PV output while excess electricity is sold out to the national grid. The excess electricity generated during the first year of production is equal to 25.188 Gigawatt hour (GWh). In addition to this, the power plant produces 2.25 t of CO and 0.32 t of H_2 per day to generate 493.68 t of MeOH. The plant was combined with a temporary storage capacity of 30 days for H_2O, CO_2, H_2, CO, MeOH see Table 6 below.

Table 6: storage capacity H_2O, CO_2, H_2, CO, MeOH

Product	Storage capacity in tons (t)
H_2O	28.22
CO_2	36.79
CO	2.25
H_2	2.48
MeOH	14810.40

The different levelized cost of the model were calculated by utilizing the Equation 10 above with data taken from **3.1.1** section. Whilst CO_2 and H_2O have a ratio of 1 resulting in a single process from the DAC system. The discounted cash flow was also divided by 2 to calculate the levelized cost of H_2O and CO_2 then the LCOD represents the sum of both. In contrary to the co-electrolysis of CO/H_2 from the SOEC system, the ratio H_2/CO is 2, then the LCOH is calculated by multiplying the discounted cash flow by two over three of the discounted syngas produced. The different levelized cost calculated can be found in the Figure 7 below.

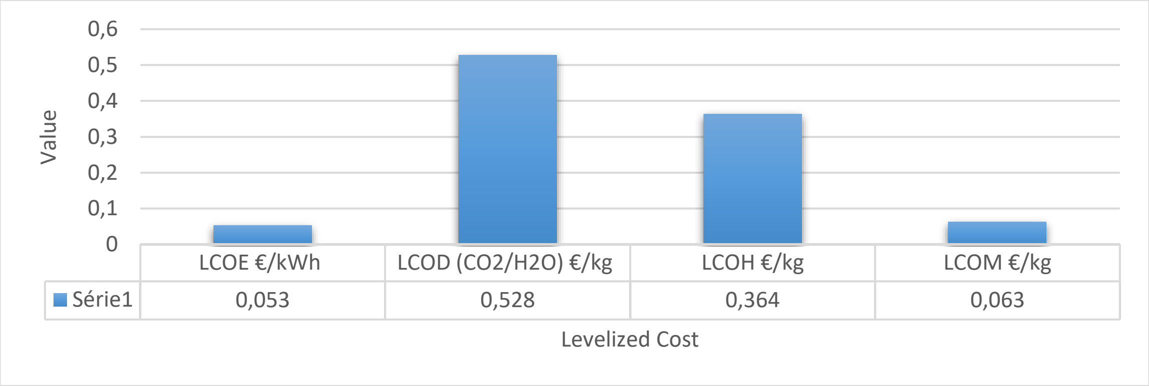


Figure 7: Levelized cost of the products (CO_2, H_2O, H_2, and MeOH)

4.1.2 Economic performance

In this study, a lifetime of 20 years excluding year 0 for plant construction was considered. A comprehensive assessment that includes economic aspects is essential to measure the potential of the DACE plant viability for implementation through NPV method. The cash inflow is equal to 0.14 and the cash outflow is 0.1 bn€ (billion euro). It can be noticed in Figure 8 that the NPV reaches -0.148 bn€.

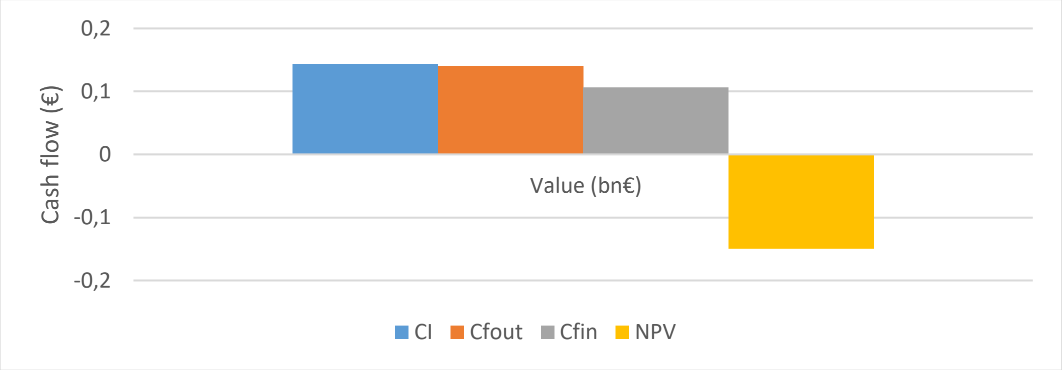


Figure 8: NPV calculation

4.1.3 Sensitivity analysis Scenario

Owing to the novelty of DAC and SOEC system models and their potential changes over time, it is essential to carry out a sensitivity analysis in this study. The input values may fluctuate as the technological innovation goes and the prevailing economic conditions change. As a result, a sensitivity analysis was performed upon a change of ±5, 10, and 15% on the LCOE, DAC, SOEC, and MS CAPEX, thereafter a change in electrolyzer size and a 2050 scenario.

4..1.3.1 Electricity and capital Cost variation

Figure 9 illustrates the relationship between an increase and decrease (±5, 10, and 15%) of the LCOE (axis-Y) in the LCOD, LCOH LCOM in terms of percentage (axis-X). The change in the LCOE result in an increase in the LCOD, respectively, of about ±4.33%, ±8.66% and ±12.99%. With a transformation of about 0.09, 0.17 and 0.26 in the LCOH, which is negligeable. the same as the LCOM with a change of respectively ±0.14,0.29, and 0.43%. The highest impact of the electricity cost is noticed on the LCOD with a significant increase and decrease of its value accordingly to the increase and decrease of the LCOE.

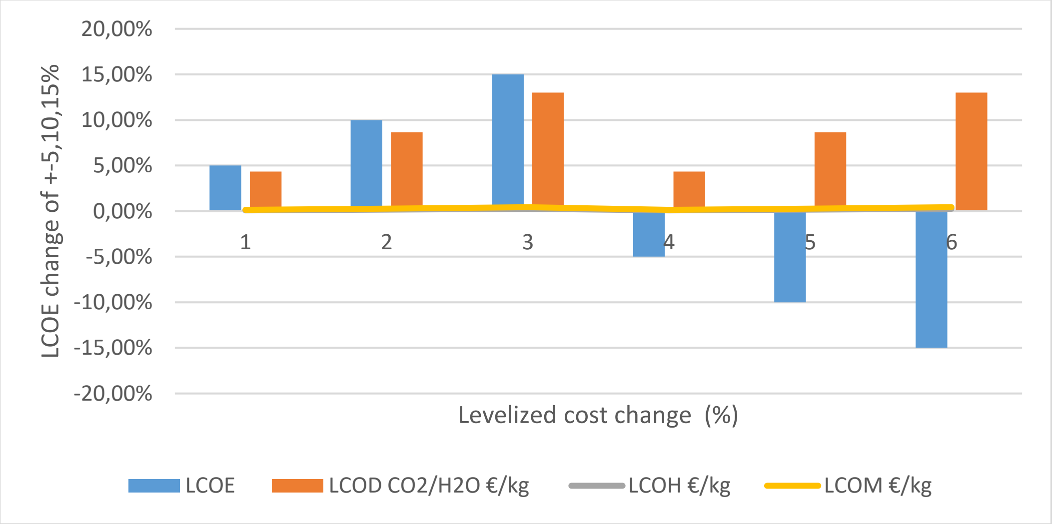


Figure 9 :sensitivity analysis about the change in LCOE

In addition to this, Figure 10 represent the effect about the change in DAC CAPEX in the LCOD, LCOH, LCOM. X-axis describes the level of change in % and the Y-axis represents the change in the different Levelized cost. The increase and decrease of DAC CAPEX has more impact in the LCOD with an increase and decrease of ±5, 10, and 15% corresponding to ±0.42,0.84, and 1.27 % of change, respectively. While its effects are meaningless in the LCOH and LCOM cases.

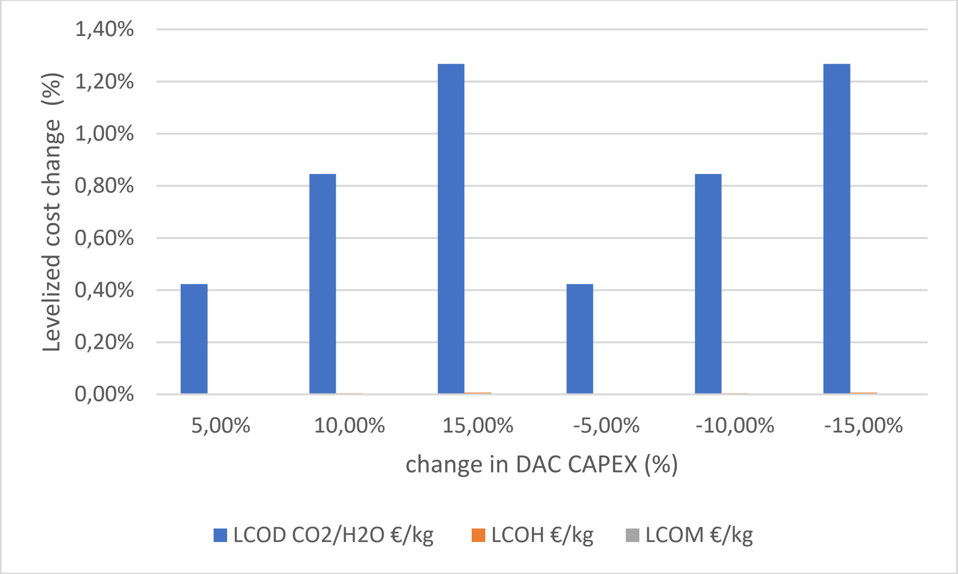


Figure 10 : sensitivity analysis about the change in DAC CAPEX change

As well as, the description of change incurred by the increase and decrease ±5, 10, and 15% in the SOEC CAPEX, in the same order of as ±2.52, 5.05, and 7.57 in the LCOH. While a change of ±0.04, 0.07, and 0.11% was observed in the LCOM see Figure 11. X-axis describe the level of change in % while Y-axis represent the change in the LCOH, and LCOM.

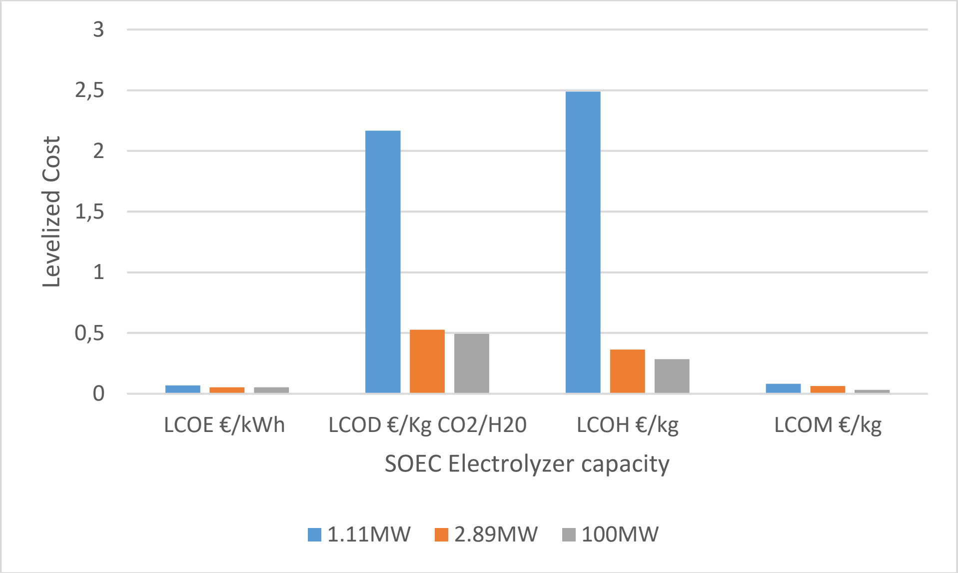


Figure 11 : sensitivity analysis about the change in SOEC CAPEX change

Furthermore, the sensitivity evaluation about the Change in MS CAPEX (see Figure 12) following the sequence of ±5,10,15% has an effect of ±0.01, 0.02, 0.03% of transformation in the LCOM which is insignificant. Consequently, it does not have too much effect on it.

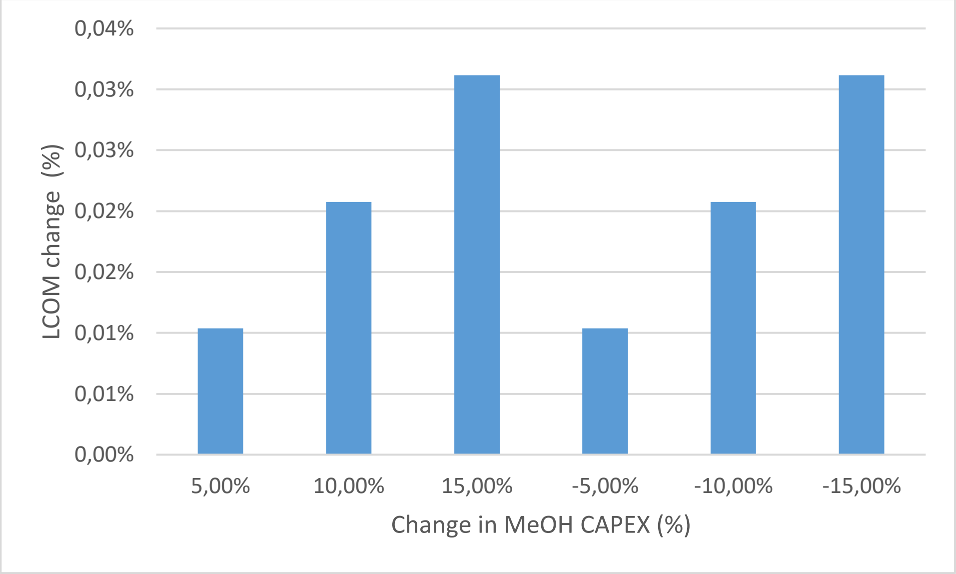


Figure 12 : sensitivity analysis about the change in MS CAPEX change

4..1.3.2 Economies of scale impact assessment

This section examines the impact of EOS in our model, focusing specifically on changes in the different system component capacity. The same as the study about projecting an implementation of the model in the year 2050 in line with the technological advancement. This analysis aims to assess the long-term impact of scaling efficiencies on the system and investigation about cost efficiencies within the process.

4..1.3.2.1 Change in System capacity

To investigate about the effects of EOS, different simulations has been done by a transition in DAC, SOEC, and Methanol reactor. A change in a DAC system of 253.41 t/d with a SOEC of 100 MW and a methanol reactor of 5000 t/d see Table 17 and Table 18, result in an E_d of 2.74 GWh/d with a PV capacity of 0.76 Gigawatt peak (GW_p). Besides that, the switch to a DAC system of 0.1 t/d of CO_2/H_2O matched with a SOEC of 1.11 MW and a MeOH reactor of 1600 t/d imply an E_d of 10 MWh/d with a PV capacity of 2.81 MW_p see respectively *Table 22* and *Table 23*. Because of this, the different levelized cost found are featured in the Figure 13 below. Our analysis outlined in this figure, showcased the impact of EOS with a change in capacity of the model. It can be observed that the lowest SOEC capacity (1.1MW) present the highest value of the LCOE, LCOD, LCOH, and LCOM. While the highest capacity (100 MW) has the lowest levelized costs' values. Thus, the increase in capacity lowers the different levelized costs of the model.

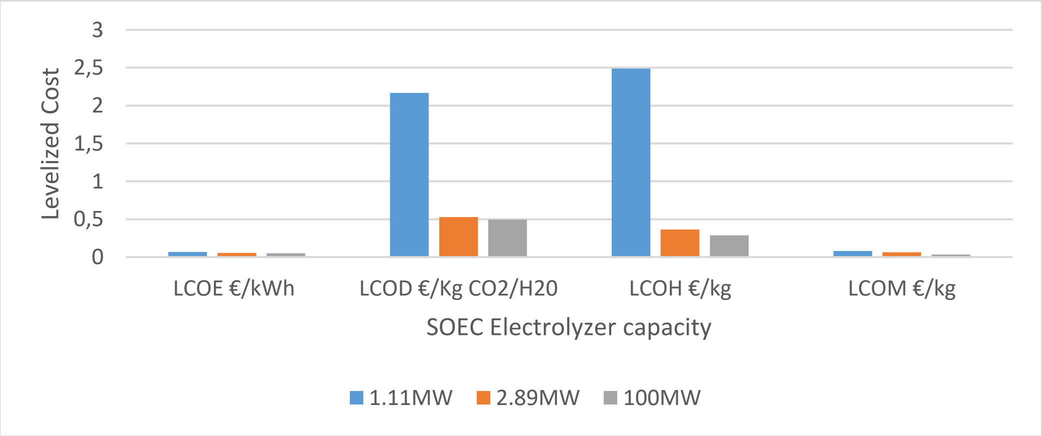


Figure 13 : Sensitivity analysis of model capacity change

4..1.3.2.2 Scenario 2050

In this scenario, the technological advancement based on learning rate is presented upon prediction of the CAPEX of the DAC, SOEC, MeOH synthesis in 2050 see Figure 16 .
This scenario is done with the technical data of the model in 755. The findings have given evidence that EOS decrease consequently the production costs see Figure 14 compared to the LCOE, LCOD, LCOH, and LCOM found in Figure 7 .

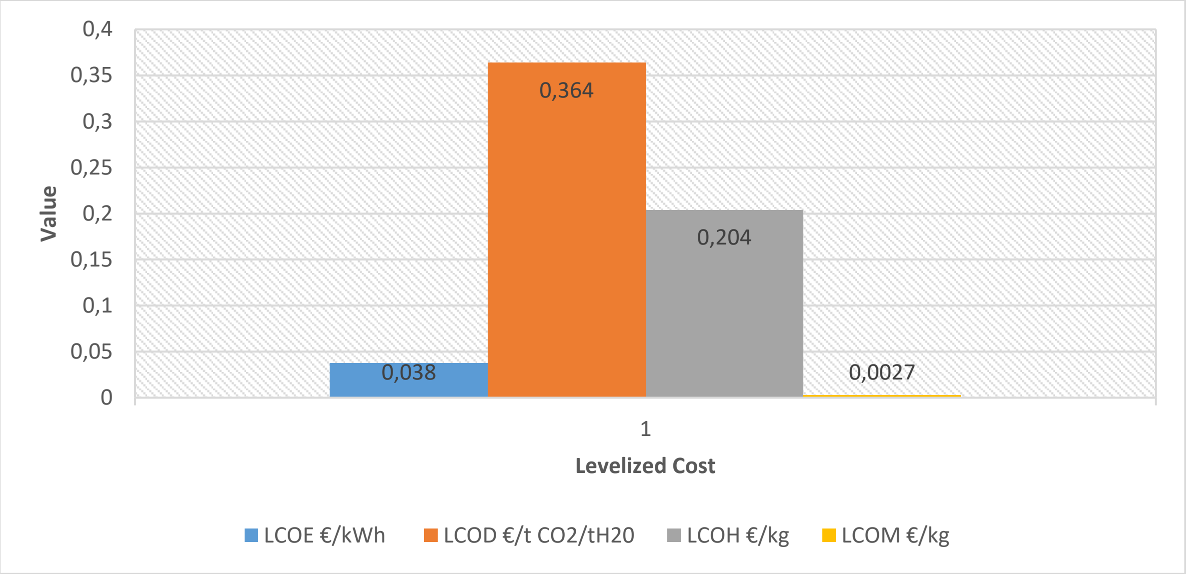


Figure 14 : determination of EOS impact in H_2 and e-MeOH production in DACE through technological advancement

4..1.3.2.3 Scenario 2050 Economic performance

The financial performance evaluation of the scenario 2050 is evaluated using the same selling price for the excess electricity, CO_2, H_2O, e-MeOH in 4.1.2. Resulting in a NPV equal to 6.84 million € see Figure 15 below.

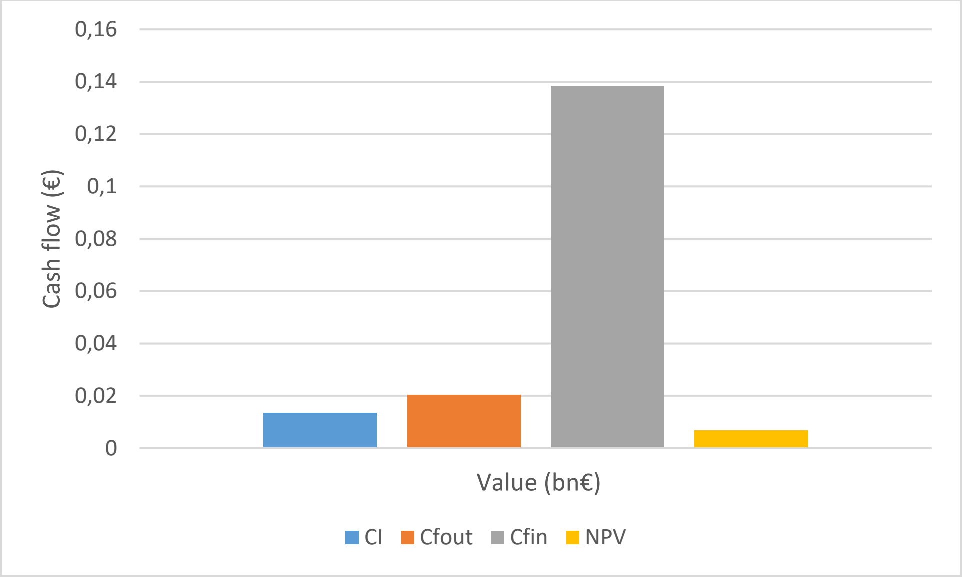


Figure 15: Scenario 2050 Economic performance analysis

4.2 Discussion

This section summed up the investigation on the LCOE, LCOD, LCOH, and the LCOM, resulting from the simulation of a DACE power plant. As well as the determination of cost efficiency and EOS impact in the production of H_2 and e-MeOH production. The comparison of our findings with the existing literature showed that according IEA investigation, the current estimated production cost of e-MeOH is between 0.59 and 1.18 € If the LCOD is between 0.22 to 0.44 €/kg of CO_2 (or 0.44 to 0.89 €/kg CO_2/H_2O).Thus, e-MeOH production costs would be in the range of 0.89 to 1.78 €/kg (Renewable Energy Agency, 2021). Additionally, the LCOH is currently in a range of 2.96 to 4.44 €/kg as given by IRENA using AEC, PEMEC, and AEMEC. Reaching a LCOH of less than 1.48 € depend highly on fostering innovation to enhance electrolyser performance, scaling up production volume and harnessing the advantages of EOS (Renewable Energy Agency, 2021).

However, our model's investigation showed that the LCOD, LCOH, LCOM are respectively equal to 0.52 €/kg (CO_2/H_2O), 0.36 €/kg, 0.063 €/kg which is slightly less than the given cost by IRENA. This can be justified using SOEC electrolyzer to co-electrolyze H_2O/CO_2. (Tanaka et al., 2015) used SOEC to co-electrolyze CO_2/H_2O found that the resulting syngas cost is between 0.689 and 0.783 €/kg resulting in an LCOH in between 0.459 and 0.522 €/kg. Besides that, (Ramdin et al., 2021) found the LCOH equal to 0.592 €/kg. Both research findings are closer to our results than the previous one.

The evaluation of the key parameters affecting the model's economic performance showed that the electricity price, DAC and SOEC CAPEX are the most influential factors in our model. Therefore, the feasibility of the project highly relies on innovation and technological advancement level of the different components such as the DAC, and SOEC system (Marchese et al., 2021). Hence, harnessing potential cost reduction opportunities by 2050 from the decrease of the DAC and SOEC CAPEX, as well as electricity cost (Fasihi & Breyer, 2020), (Gorre et al., 2019). Obviously, the estimated long term H_2 cost can reach 1.11 €/kg with a CO_2/H_2O captured price of 0.148 €/t through DAC resulting in an LCOM of 0.022 to 0.037 €/t (Renewable & Agency, 2021). Whereas (Schorn et al., 2021) predicted the LCOM to reach 0.37 to 0.6 €/kg if the LCOH is in a range of 1.35 to 2 €/kg with a LCOD at 0.2 €/kg by 2030.

Furthermore, the result of this study confirmed the statement made earlier about the positive impact that EOS has on cost savings of H_2 and e-MeOH production from DACE to level off the levelized costs. The same as, scaling up the production volume of the model (Ghaebi Panah et al., 2022) through an increase of the DAC,SOEC and MS capacity as described in the result section 3.2.3. As long as, the application of learning by doing concept which state that scaling up production enhance more expertise from project developers and also lower cost (IRENA, 2020). According to (cet al., 2019), the rate of technological advancement of S-DAC is about 10 %. Moreover, the comparison between different electrolyzer (AEC,PEMEC,SOEC) has shown that SOEC present the highest cost reduction potential of all investigated electrolysis technologies (Tichler et al., 2018) with a learning rate of 28 % see Figure 16 (Böhm et al., n.d.) ,(Schmidt et al., 2017). While the methanol synthesis system has a learning rate of 5 % (Nizami & Wahyu, 2022).

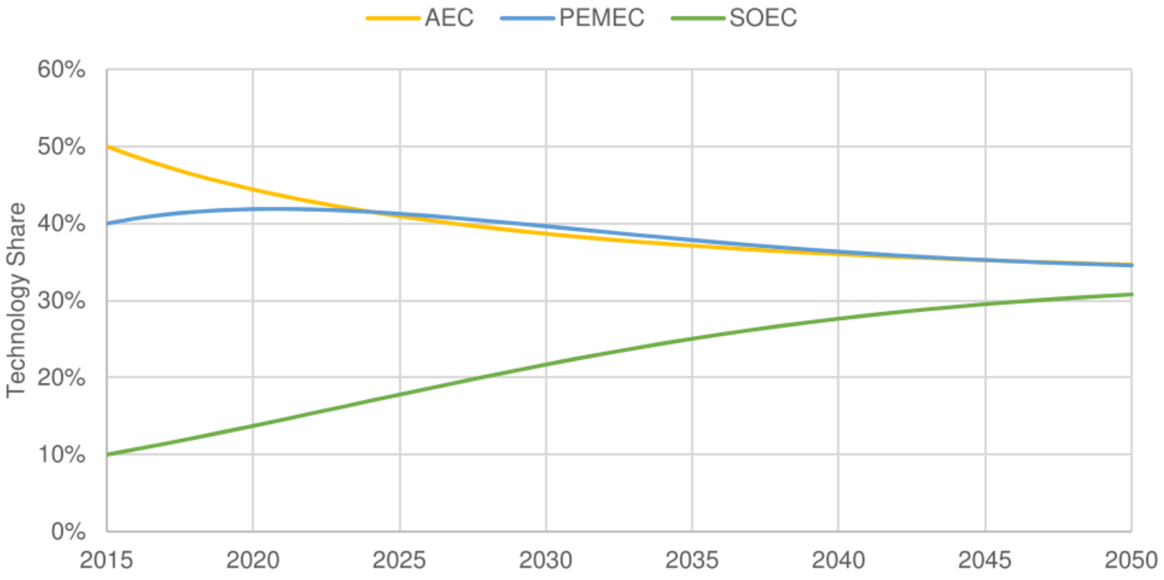


Figure 16 : Assumption on the learning rate of electrolyzers of AEC, PEMEC, and SOEC

Based on the evidence found in this investigation that EOS could lead to significant decrease of the LCOD, LCOH, and LCOM in the context of DACE, this trend could lead to prominent economic gain by 2050 (Rinaldis et al., 2021).Whereas, several research has predicted cost through a learning curve approach like in our scenario 2050, It's crucial to note that any future scenario prediction contains a level of uncertainty (Zhen et al., 2023) such as political changes, international market prices, and technological progress (Li et al., 2022).

4.2.1 Cost reduction opportunities

Different pathways for cost optimization are discussed in this research such as reduction of electricity cost, CAPEX of the system's components ,scaling up technology capacity and the advancement of technological innovation based on learning curve (Marius Holst et al., 2021). Based on our findings, the electricity price is one of the main parameters affecting the production cost (Zhang et al., 2019) specially for the DAC system along with the SOEC CAPEX. In order to reduce cost efficiency losses, given the findings about EOS effects an increase in the system capacity lead to a decrease in unit production cost (Okubo et al., 2023). In addition to this, our study on EOS based on technological advancement also provide cost benefit (Mcqueen et al., 2021) by implementing the project in a near future like 2050. Moreover, the concept of learning by doing could also imply the automation and optimization of the production process that improves efficiency and reduce O&M and material costs (Schoots et al., 2008). Based on the scenario 2050 discovery, the LCOE could reach 0.038 €/kWh which lead to a lower LCOM of 2.73 €/t. Additionally, the project also needs support of carbon credit in addition to the e-MeOH revenue, excess O_2, electricity, CO_2 and H_2O sales for a long-term strategic market condition (Sankaran, 2023). Accordingly, based on the unviability of the project now and the economic performance in 2050 results, an investment in 2050 is more profitable. The e-MeOH price is expected to become higher by 2050 than the actual price (Bellotti et al., 2019) which leads to more profit from the sales of e-MeOH. Therefore, a carbon offset market in Senegal could also lead to an alternative way to reduce cost efficiency losses by making more revenue on CO_2 captured and encourage more project implementation in the field of DACE.

5 Conclusions and Recommendations

5.1 Conclusions

This study investigated about the determination of cost efficiency losses and the EOS impact in the production of H_2 and e-MeOH from DACE. A TEA method was adopted to determine the different levelized costs and the economic performance to assess the viability of the project. Given the proposed methodology, the LCOE, LCOD, LCOH, and LCOM were respectively found equal to 0.053 €/kWh, 0.52 €/kg (CO_2/H_2O), 0.36 €/kg, 0.063 €/kg. Meanwhile, the economic performance resulted in a negative NPV of -0.148 bn€. The first research question was answered through a sensitivity analysis upon a variation of ±5,10, and 15% of the electricity cost and CAPEX of the DAC, SOEC, and MS system to evaluate cost efficiency losses. Therefore, the electricity cost, DAC and SOEC CAPEX was found to be the most sensitive parameters of the model affecting the LCOD, LCOH, and LCOM. Additionally, to answer the second research question about the EOS impact a transition to different DAC, SOEC, and MS capacities was done which result in a reduction of the levelized cost as the capacity increase. Furthermore, investigation was also done based on the technological advancement learning curve for CAPEX prediction and model simulation for the year 2050 to give a response to the third research question. The different levelized costs found were 0.038 €/kWh, 0.365 (CO_2/H_2O), 0.203 €/kg, 0.003 €/kg in the same order as LCOE, LCOD, LCOH, and LCOM very competitive compared to the levelized costs in Figure 7 meaning that the technological advancement has an important role to play in cost efficiency losses reduction. Although the current economic performance assessed has yet to be competitive, the scenario 2050 economic assessment resulted in a positive NPV of 6.84 million € which support the EOS approach to level off cost through technological advancement. These findings are interesting and useful in the economy field by assessing the relevant parameters affecting the production to look for alternative cost savings opportunities. The outcomes of this study contributed to the literature with more clarity on cost efficiency losses and potential advantages of economies of scale. The production pathway also provided a cleaner method of H_2 and e-MeOH production to avoid greenhouse gases emission to mitigate climate change.

5.2 Limitation

Most of the data in this study have been collected from the literature while some of them were based on estimation. This is due to the early development stage of the technologies studied.

On the other hand, most studies done about e-MeOH are based on CO_2 hydrogenation and H_2 synthesis while this study is about CO and H_2 to directly produce e-MeOH. Furthermore, the model is also limited by the software performance to automate the simulation that is why we assumed the amount of CO to be combined with H_2 as stated above in the Data and Key Assumptions. This cannot only limit the model output by unknowing the exact amount of input of CO needed for the e-MeOH synthesis but also affect the different levelized cost. We also recognize the limitation of the scenario 2050 that has been simulated based on cost prediction which is not always reflecting the reality. Consequently, conducting more research about how to optimize the main parameters affecting the LCOD, LCOH, and LCOM while developing strategies to mitigate the responsiveness is crucial for further studies. Additionally, scaling up the technology capacity of DAC, SOEC, and MS could foster EOS regarding the market demand and available capacity to level off production cost.

5.3 Recommendations

Our investigation findings provided significant insights into the determination of cost efficiency losses and the impact of the EOS in the production of H_2 and e-MeOH from DACE. In regard to this conclusion, the following recommendations are proposed:

- Conducting regular evaluations of sensitive parameters to determine areas of cost efficiency losses can guide to strategic decision-making.
- Adoption of participatory modeling for strong Collaboration of different stakeholders (government, private sector, local population) that are directly or indirectly affected) by the project would provide more valuable insight for long-term assessment of the project to reduce cost efficiency losses.
- Foster collaboration between academic institutions and industries to accelerate research and discovery about DACE.
- Establishment of national and international policies for H_2 and e-fuels to facilitate international trade and enable more potential competitive economic performance.
- Guaranteeing that monitoring and maintenance are done frequently to optimize the production resulting in a more cost competitive production to ensure the economic profitability of the project.
- Enhancing investment in research, innovation, and development of technologies such as PV, DAC, SOEC, and MS system to achieve advanced technological development

in 2050 can significantly impact the cost competitiveness of H_2 and Me-OH from DACE.

6 References

Ababneh, H., & Hameed, B. H. (2022). Electrofuels as emerging new green alternative fuel: A review of recent literature. *Energy Conversion and Management*, *254*, 115213. https://doi.org/10.1016/J.ENCONMAN.2022.115213

Ahmed, U. (2021). Techno-economic analysis of dual methanol and hydrogen production using energy mix systems with CO2 capture. *Energy Conversion and Management*, *228*, 113663. https://doi.org/10.1016/J.ENCONMAN.2020.113663

Alenazey, F., Alyousef, Y., Almisned, O., Almutairi, G., Ghouse, M., Montinaro, D., & Ghigliazza, F. (2015). Production of synthesis gas (H2 and CO) by high-temperature Co-electrolysis of H2O and CO2. *International Journal of Hydrogen Energy*, *40*(32), 10274–10280. https://doi.org/10.1016/J.IJHYDENE.2015.06.034

Arnaiz del Pozo, C., Cloete, S., & Jiménez Álvaro, Á. (2022). Techno-economic assessment of long-term methanol production from natural gas and renewables. *Energy Conversion and Management*, *266*, 115785. https://doi.org/10.1016/j.enconman.2022.115785

Attari, K., Elyaakoubi, A., & Asselman, A. (2016). Performance analysis and investigation of a grid-connected photovoltaic installation in Morocco. *Energy Reports*, *2*(December 2015), 261–266. https://doi.org/10.1016/j.egyr.2016.10.004

Bellotti, D., Rivarolo, M., & Magistri, L. (2019). Economic feasibility of methanol synthesis as a method for CO2 reduction and energy storage. *Energy Procedia*, *158*(2018), 4721–4728. https://doi.org/10.1016/j.egypro.2019.01.730

Bhandari, R., & Shah, R. R. (2021). Hydrogen as energy carrier : Techno-economic assessment of decentralized hydrogen production in Germany. *Renewable Energy*, *177*, 915–931. https://doi.org/10.1016/j.renene.2021.05.149

Bisotti, F., Fedeli, M., Prifti, K., Galeazzi, A., Dell'Angelo, A., & Manenti, F. (2022). Impact of Kinetic Models on Methanol Synthesis Reactor Predictions: In Silico Assessment and

Comparison with Industrial Data. *Industrial and Engineering Chemistry Research*, *61*(5), 2206–2226. https://doi.org/10.1021/acs.iecr.1c04476

Bodegraven, M. Van. (n.d.). *Air to methanol via the micro-plant approach An ex-ante life cycle assessment*.

Böhm, H., Goers, S., & Zauner, A. (n.d.). *Estimating Future Cost Development of Power-to-Gas Technologies – A Component-based Approach to Evaluate Technological Learning Keywords*. *44*(2019), 30789–30805.

Breyer, C., Bogdanov, D., Aghahosseini, A., Gulagi, A., Child, M., Oyewo, A. S., Farfan, J., Sadovskaia, K., & Vainikka, P. (2018). Solar photovoltaics demand for the global energy transition in the power sector. *Progress in Photovoltaics: Research and Applications*, *26*(8), 505–523. https://doi.org/10.1002/pip.2950

Chauvy, R., & Dubois, L. (2022). Life cycle and techno-economic assessments of direct air capture processes: An integrated review. *International Journal of Energy Research*, *46*(8), 10320–10344. https://doi.org/10.1002/er.7884

Christensen, A., Wehrle, L., Schmider, D., Dailly, J., Banerjee, A., Deutschmann, O., IEA, Nami, H. B. G. C. N. J. B. F. H. L. H. P. V., Arnaiz del Pozo, C., Cloete, S., Jiménez Álvaro, Á., Colella, W., James, B., Moron, J., Saur, G., Ramsden, T., & Release, P. (2022). MarE-fuel: Energy efficiencies in synthesising green fuels and their expected cost, MarE-fuel project report 9/9-2021, DTU Energy. *Applied Energy*, *266*(February), 1–73. https://doi.org/10.1016/j.apenergy.2022.119143

Daniel, T., Masini, A., Milne, C., Nourshagh, N., Iranpour, C., & Xuan, J. (2022). Techno-economic Analysis of Direct Air Carbon Capture with CO2 Utilisation. *Carbon Capture Science and Technology*, *2*(December 2021), 100025. https://doi.org/10.1016/j.ccst.2021.100025

DECISION N° 2023-11.pdf. (n.d.).

Defazio, A., & Mishchenko, K. (n.d.). *Learning-Rate-Free Learning by D-Adaptation*. 1–46.

Dias, V., Pochet, M., Contino, F., & Jeanmart, H. (2020). *Energy and Economic Costs of Chemical Storage*. *6*(May). https://doi.org/10.3389/fmech.2020.00021

Energy, O. of. (2013). Levelized Cost of Energy (LCOE). *US Department of Energy*, 9.

Erans, M., Sanz-Pérez, E. S., Hanak, D. P., Clulow, Z., Reiner, D. M., & Mutch, G. A. (2022). Direct air capture: process technology, techno-economic and socio-political challenges. *Energy and Environmental Science*, *15*(4), 1360–1405. https://doi.org/10.1039/d1ee03523a

Falkner, R. (2016). The Paris agreement and the new logic of international climate politics. *International Affairs*, *92*(5), 1107–1125. https://doi.org/10.1111/1468-2346.12708

Fasihi, M., & Breyer, C. (2020). Baseload electricity and hydrogen supply based on hybrid PV-wind power plants. *Journal of Cleaner Production*, *243*, 118466. https://doi.org/10.1016/j.jclepro.2019.118466

Fasihi, M., Efimova, O., & Breyer, C. (2019). Techno-economic assessment of CO 2 direct air capture plants. *Journal of Cleaner Production*, *224*, 957–980. https://doi.org/10.1016/j.jclepro.2019.03.086

FuelCellEnergy. (n.d.). *Solid Oxide*. 25.

Gallo, A. (2014). A Refresher on Net Present Value. Harvard Business Review. *Harvard Business Review*, *19*, 1–6.

Gerloff, N. (2023). Economic analysis of hydrogen production in Germany with a focus on green hydrogen, considering all three major water electrolysis technologies. *Sustainable Energy & Fuels*, 1893–1907. https://doi.org/10.1039/d3se00073g

Ghaebi Panah, P., Cui, X., Bornapour, M., Hooshmand, R. A., & Guerrero, J. M. (2022). Marketability analysis of green hydrogen production in Denmark: Scale-up effects on grid-connected electrolysis. *International Journal of Hydrogen Energy*, *47*(25), 12443–

12455. https://doi.org/10.1016/J.IJHYDENE.2022.01.254

Gorre, J., Ortloff, F., & van Leeuwen, C. (2019). Production costs for synthetic methane in 2030 and 2050 of an optimized Power-to-Gas plant with intermediate hydrogen storage. *Applied Energy*, *253*(August), 113594. https://doi.org/10.1016/j.apenergy.2019.113594

Guo, J., Zhang, Y., Zavabeti, A., Chen, K., Guo, Y., Hu, G., Fan, X., & Li, G. K. (2022). Hydrogen production from the air. *Nature Communications*, *13*(1), 1–9. https://doi.org/10.1038/s41467-022-32652-y

Ha, C., Wang, C., Qin, J., Liu, Z., & Liu, H. (2023). Experimental study of performance enhancement strategies for hydrogen production-purification systems in packed-bed reactors under power fluctuations. *Applied Thermal Engineering*, *232*, 121052. https://doi.org/10.1016/J.APPLTHERMALENG.2023.121052

Haberl, H., Beringer, T., Bhattacharya, S. C., Erb, K. H., & Hoogwijk, M. (2010). The global technical potential of bio-energy in 2050 considering sustainability constraints. *Current Opinion in Environmental Sustainability*, *2*(5–6), 394–403. https://doi.org/10.1016/J.COSUST.2010.10.007

Hafeez, S., Harkou, E., Al-Salem, S. M., Goula, M. A., Dimitratos, N., Charisiou, N. D., Villa, A., Bansode, A., Leeke, G., Manos, G., & Constantinou, A. (2022). Hydrogenation of carbon dioxide (CO2) to fuels in microreactors: a review of set-ups and value-added chemicals production. *Reaction Chemistry and Engineering*, *7*(4), 795–812. https://doi.org/10.1039/d1re00479d

Haldor Topsoe. (2020). *Superior performance across the world ' s most challenging industries*.

Hong, G. H., Lee, J., Cho, Y., & Hwang, S. (2023). Techno-economic analysis of CO2/steam co-electrolysis process and synfuel production process coupled with steel manufacturing process. *Korean Journal of Chemical Engineering*, *40*(4), 740–753.

https://doi.org/10.1007/s11814-022-1331-9

IEA. (2019). The Future of Hydrogen. *The Future of Hydrogen, June*. https://doi.org/10.1787/1e0514c4-en

International Energy Agency. (2022). Direct Air Capture: A key technology for net zero. *International Encyclopedia of Geography*, 1–76. https://iea.blob.core.windows.net/assets/78633715-15c0-44e1-81df-41123c556d57/DirectAirCapture_Akeytechnologyfornetzero.pdf

IRENA. (2019). Future of solar photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: paper). In *International Renewable Energy Agency: Vol. November*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Oct/IRENA_Future_of_wind_2019.pdf

IRENA. (2020). Green Hydrogen Cost Reduction. In */publications/2020/Dec/Green-hydrogen-cost-reduction*.

Jalili, M., Ghazanfari Holagh, S., Chitsaz, A., Song, J., & Markides, C. N. (2023). Electrolyzer cell-methanation/Sabatier reactors integration for power-to-gas energy storage: Thermo-economic analysis and multi-objective optimization. *Applied Energy*, *329*, 120268. https://doi.org/10.1016/J.APENERGY.2022.120268

Jena, P. (2011). Materials for hydrogen storage: Past, present, and future. *Journal of Physical Chemistry Letters*, *2*(3), 206–211. https://doi.org/10.1021/jz1015372

Kumar, S. S., & Lim, H. (2022). An overview of water electrolysis technologies for green hydrogen production. *Energy Reports*, *8*, 13793–13813. https://doi.org/10.1016/j.egyr.2022.10.127

Kwasi-Effah C, I, O. A., & A, A. F. (2015). A Review on Electrolytic Method of Hydrogen Production from Water. *American Journal of Renewable and Sustainable Energy*, *1*(2), 51–57. http://www.aiscience.org/journal/ajrsehttp://creativecommons.org/licenses/bync/4.0/

Li, X., Li, Z., Su, C. W., Umar, M., & Shao, X. (2022). Exploring the asymmetric impact of economic policy uncertainty on China's carbon emissions trading market price: Do different types of uncertainty matter? *Technological Forecasting and Social Change*, *178*, 121601. https://doi.org/10.1016/J.TECHFORE.2022.121601

Lloyd's Register. (2019). Fuel production cost estimates and assumptions. *Lloyds Register*, 44. https://www.lr.org/en-gb/insights/global-marine-trends-2030/https://sustainableworldports.org/wp-content/uploads/Lloyds-Register_2019_Fuel-production-cost-estimates-and-assumptions-report.pdf

Mac Dowell, N., Fennell, P. S., Shah, N., & Maitland, G. C. (2017). The role of CO2 capture and utilization in mitigating climate change. *Nature Climate Change*, *7*(4), 243–249. https://doi.org/10.1038/nclimate3231

Malins, C. (2017). What role is there for electrofuel technologies in European transport's low carbon future? *Cerulogy*, *November*, 1–86.

Marchese, M., Buffo, G., Santarelli, M., & Lanzini, A. (2021). CO2from direct air capture as carbon feedstock for Fischer-Tropsch chemicals and fuels: Energy and economic analysis. *Journal of CO2 Utilization*, *46*, 101487. https://doi.org/10.1016/j.jcou.2021.101487

Marius Holst, Stefan Aschbrenner, Tom Smolinka, Christopher Voglstätter, & Gunter Grimm. (2021). Cost Forecast for Low-Temperature Electrolysis - Technology driven bottom-up prognosis for PEM and Alkaline water electrolysis systems. *Fraunhofer Institute for Solar Energy Systems*.

Mcqueen, N., Gomes, K. V., Mccormick, C., & Blumanthal, K. (2021). *A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future Progress in Energy OPEN ACCESS A review of direct air capture (DAC): scaling up* *commercial technologies and innovating for the future*.

Nasser, M., Megahed, T. F., Ookawara, S., & Hassan, H. (2022). A review of water electrolysis–based systems for hydrogen production using hybrid/solar/wind energy systems. *Environmental Science and Pollution Research*, *29*(58), 86994–87018. https://doi.org/10.1007/s11356-022-23323-y

Nizami, M., & Wahyu, W. (2022). Solar PV based power-to-methanol via direct CO 2 hydrogenation and H 2 O electrolysis : Techno-economic and environmental assessment. *Journal of CO2 Utilization*, *65*(October), 102253. https://doi.org/10.1016/j.jcou.2022.102253

Okubo, T., Shimizu, T., Hasegawa, K., Kikuchi, Y., Manzhos, S., & Ihara, M. (2023). Factors affecting the techno-economic and environmental performance of on-grid distributed hydrogen energy storage systems with solar panels. *Energy*, *269*, 126736. https://doi.org/10.1016/J.ENERGY.2023.126736

Olabi, A. G., Obaideen, K., Elsaid, K., Wilberforce, T., Sayed, E. T., Maghrabie, H. M., & Abdelkareem, M. A. (2022). Assessment of the pre-combustion carbon capture contribution into sustainable development goals SDGs using novel indicators. *Renewable and Sustainable Energy Reviews*, *153*, 111710. https://doi.org/10.1016/J.RSER.2021.111710

Physical, T., & Basis, S. (2020). Bulletin of the Chinese Academy of Sciences. *Bulletin of the Chinese Academy of Sciences*, *34*(2), F0003–F0003. https://doi.org/10.3724/sp.j.7103161536

Raazia, I. (2023). *Global Climate Change and Human Security Nexus : A Case of Pakistan*. https://doi.org/10.31703/gfpr.2023(VI-I).04

Ramasamy, V., & Margolis, R. (2021). Floating Photovoltaic System Cost Benchmark: Q1 2021 Installations on Artificial Water Bodies. *National Renewable Energy Laboratory*

(NREL), *1*(10), 1–15.

Ramdin, M., De Mot, B., Morrison, A. R. T., Breugelmans, T., Van Den Broeke, L. J. P., Trusler, J. P. M., Kortlever, R., De Jong, W., Moultos, O. A., Xiao, P., Webley, P. A., & Vlugt, T. J. H. (2021). Electroreduction of CO2/CO to C2Products: Process Modeling, Downstream Separation, System Integration, and Economic Analysis. *Industrial and Engineering Chemistry Research*, *60*(49), 17862–17880. https://doi.org/10.1021/acs.iecr.1c03592

Realmonte, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A. C., & Tavoni, M. (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nature Communications*, *10*(1), 1–12. https://doi.org/10.1038/s41467-019-10842-5

Renewable Energy Agency, I. (2021). *Policy and Tech Cost GH*. www.irena.org

Renewable, I., & Agency, E. (n.d.). *INNOVATION OUTLOOK RENEWABLE*.

Rinaldis, S. De, Manager, T. I., & Innovation, T. (2021). *GREEN HYDROGEN AS INDUSTRIAL COMPLEXES FEEDSTOCK AND*. 1–9.

Sahoo, S. K., Das, A. K., Samanta, S., & Goswami, S. S. (2023). Assessing the Role of Sustainable Development in Mitigating the Issue of Global Warming. *Journal of Process Management and New Technologies*, *11*(1–2), 1–21. https://doi.org/10.5937/jpmnt11-44122

Sankaran, K. (2023). *Renewable Methanol from Industrial Carbon Emissions: A Dead End or Sustainable Way Forward?* https://doi.org/10.1021/acsomega.3c02441

Sarr, A., Mohammed, C., Kebe, F., & Ndiaye, A. (2020). *Analysis and feasibility of 50 kWp self-consumption solar photovoltaic system for four Senegalese typical climatic zones using PVsyst software*. *15*(4), 201–212. https://doi.org/10.5897/IJPS2020.4916

Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J., & Few, S. (2017). Future cost and performance of water electrolysis: An expert elicitation study. *International Journal of Hydrogen Energy*, *42*(52), 30470–30492. https://doi.org/10.1016/j.ijhydene.2017.10.045

Schoots, K., Ferioli, F., Kramer, G. J., & van der Zwaan, B. C. C. (2008). Learning curves for hydrogen production technology: An assessment of observed cost reductions. *International Journal of Hydrogen Energy*, *33*(11), 2630–2645. https://doi.org/10.1016/J.IJHYDENE.2008.03.011

Schorn, F., Breuer, J. L., Samsun, R. C., Schnorbus, T., Heuser, B., Peters, R., & Stolten, D. (2021). Methanol as a renewable energy carrier: An assessment of production and transportation costs for selected global locations. *Advances in Applied Energy*, *3*(June), 100050. https://doi.org/10.1016/j.adapen.2021.100050

Shi, J., Zhu, Y., Feng, Y., Yang, J., & Xia, C. (2023). A Prompt Decarbonization Pathway for Shipping: Green Hydrogen, Ammonia, and Methanol Production and Utilization in Marine Engines. *Atmosphere*, *14*(3). https://doi.org/10.3390/atmos14030584

Sollai, S., Porcu, A., Tola, V., Ferrara, F., & Pettinau, A. (2023a). Renewable methanol production from green hydrogen and captured CO 2 : A techno-economic assessment. *Journal of CO2 Utilization*, *68*(November 2022), 102345. https://doi.org/10.1016/j.jcou.2022.102345

Sollai, S., Porcu, A., Tola, V., Ferrara, F., & Pettinau, A. (2023b). Renewable methanol production from green hydrogen and captured CO2: A techno-economic assessment. *Journal of CO2 Utilization*, *68*(December 2022), 102345. https://doi.org/10.1016/j.jcou.2022.102345

Sunfire GmbH. (2020). *Renewable syngas for e-fuel and chemicals production- Sunfire-Synlink SOEC*. 2.

Tanaka, Y., Kato, T., Nagata, S., & Negishi, A. (2015). Development of a Tubular Solid

Oxide Cell for Co-Electrolysis of H 2 O and CO 2 for Syngas Production . *ECS Meeting Abstracts*, *MA2015-03*(1), 99–99. https://doi.org/10.1149/ma2015-03/1/99

Tichler, R., Böhm, H., Zauner, A., Goers, S., & Kroon, P. (2018). *Innovative large-scale energy storage tech-nologies and Power-to-Gas concepts after optimization: Report on experience curves and economies of scale*. *691797*.

Towanou, O. J., Elagnon, H., Donnou, V., Gobi, G. K. N., Leod, A. E., & Kounouh, B. (2023). *Sciences Solar Energy Storage by Fuel Cell Technology at*. *5*, 1–7.

United Nation. (2021). Summary Progress Update 2021 : SDG 6 — water and sanitation for all. *UN-Water Integrated Monitoring Initiative*, 1–58. https://www.unwater.org/new-data-on-global-progress-towards-ensuring-water-and-sanitation-for-all-by-2030/

Zhang, H., Wang, L., van Herle, J., Maréchal, F., & Desideri, U. (2019). Techno-economic optimization of CO2-to-methanol with solid-oxide electrolyzer. *Energies*, *12*(19). https://doi.org/10.3390/en12193742

Zhen, Z., Wang, Y., Wang, Y., Wang, X., Ou, X., & Zhou, S. (2023). Hydrogen production paths in China based on learning curve and discrete choice model. *Journal of Cleaner Production*, *415*, 137848. https://doi.org/10.1016/J.JCLEPRO.2023.137848

1 (kein Datum). Von Author name(s), first name(s) (abbreviated): Title, full URL (internet address), year of publication (if abgerufen

2 Basile, A., & Dalena, F. (2017). *Methanol: Science and Engineering.*

3 Carbon Credits. (2023). Von https://carboncredits.com/carbon-prices-today/?gclid=CjwKCAjwq4imBhBQEiwA9Nx1BrQnz92pzIw5ENfbrAdaV1DIE602mpuo9SX7qVUka9oaDSlhZZVMrBoCLOcQAvD_BwE abgerufen

4 CE Delft. (2021). Jobs from investment in green hydrogen. Von http://www.cedelft.eu/ abgerufen

5 DNV. (2022). Energy and the labour force: Transferring skills. Von https://www.dnv.com/power-renewables/publications/podcasts/energy-and-the-labour-force-transferring-skills.html?utm_campaign=ES_ADV_GLOB_22Q1_PROM_Podcast_S12_EP4&utm_medium abgerufen

6 El Sherif, D., & James, C. K. (2005). International Space Station Carbon Dioxide Removal Assembly (ISS CDRA) Concepts and Advancements. 9. doi:https://doi.org/10.4271/2005-01-2892

7 Global solar Atlas. (kein Datum). Von https://globalsolaratlas.info/map?s=12.801133,-16.22897&m=site&c=12.801133,-16.22897,11 abgerufen

8 IEA. (2022). *Direct Air Capture.* Paris. Von https://www.iea.org/reports/direct-air-capture abgerufen

9 IEA. (2022). *Electrolysers.* Paris: IEA. Von https://www.iea.org/reports/electrolysers abgerufen

10 IEA. (2022). *Electrolysers.* Paris: IEA. Retrieved from https://www.iea.org/reports/electrolysers

11 ILO. (2018). World Employment Social Outlook - Greening with jobs.

12 International Monetary Fund . (2023). doi:https://www.imf.org/external/np/fin/data/param_rms_mth.aspx

13 Köppen Geiger. (kein Datum). doi:https://de.climate-data.org/afrika/senegal-187/

14 Li, C., & Baek, J. (2021). The promise of hydrogen production from alkaline Anion exchange membrane electrolyzer. *Nano energy*.

15 Masterson, V. (2022). *Companies are sucking carbon from the atmosphere using 'direct air capture'. How does it work?* World Economic Forum.

16 Methanol Market services Asia. (2020). Methanol price and supply and demand. *Methanol institute*. doi:https://www.methanol.org/methanol-price-supply-demand/

17 NASA power. (2021). doi:https://power.larc.nasa.gov/data-access-viewer/

18 NASA Power. (2021). Von https://power.larc.nasa.gov/data-access-viewer/ abgerufen

19 Olah, G., Goeppert, A., & Prakash, G. (2018). *Beyond oil and gas: the methanol economy.* John Wiley & Sons.

20 Peters, S., & Drewes, D. (2019). *Materials in progress: innovations for designers and architects.* Birkhäuser.

21 Sankhe, S., Mohana Krishna, S., JUTURU, R., & Subrahmanyam, C. (kein Datum). Power-to-X (PtX) Technologies and their Potential Role in the Transition towards a Fossil-Free Energy Future: A Review of eFuels Synthesis and Direct Air Capture (DAC) Technology. S. 16. doi: https://doi.org/10.4271/2023-28-1333

22 SEYE, B. S. (2023). L’eau au centre des préoccupations . Von https://www.enqueteplus.com/content/budget-2023-minist%C3%A8re-de-leau-et-de-l%E2%80%99assainissement-l%E2%80%99eau-au-centre-des-pr%C3%A9occupations#:~:text=Il%20s'agit%20de%20la,pour%2041%20m3%20et%20plus. abgerufen

23 Ueckerdt, F., Bauer, C., Dirnaichner, A., Everall, J., Sacchi, R., & Luderer , G. (2021). Potential and risks of hydrogen-based e-fuels in climate change mitigation. *11*, S. 384–393. doi:https://doi.org/10.1038/s41558-021-01032-7

24 UN HABITAT. (2011). *Cities and Climate Change.* earthscan. Von https://unhabitat.org/sites/default/files/download-manager-files/Cities%20and%20Climate%20Change%20Global%20Report%20on%20Human%20Settlements%202011.pdf abgerufen

25 Wagner, E., Delp, E., & Mishra, R. (2023). Energy Storage with Highly-Efficient Electrolysis and Fuel Cells: Experimental Evaluation of Bifunctional Catalyst Structures. *Topics in Catalysis*, 1-14. doi:s11244-022-01771-7

7 Appendix A: Technical Specification

7.1 Description of solar Photovoltaic installation

Solar climate data was retrieved from the NASA power database to obtain the daily average solar irradiation per month (NASA Power, 2021). The minimum hourly solar radiation available was 4.51kilowatt hour per meter square per day (kWh/m^2/d) during the month of August. The average monthly solar radiation per day is presented in Figure 17 (Global solar Atlas).Besides that, a daily simulation was done to determine the model's energy need for a work of 8 sun peak hours per day. Moreover, the aggregation of the Energy demand (E_d) provided us the daily energy need to further calculate the yearly (365 days) E_d in regard to the SOEC of 2.89 MW.

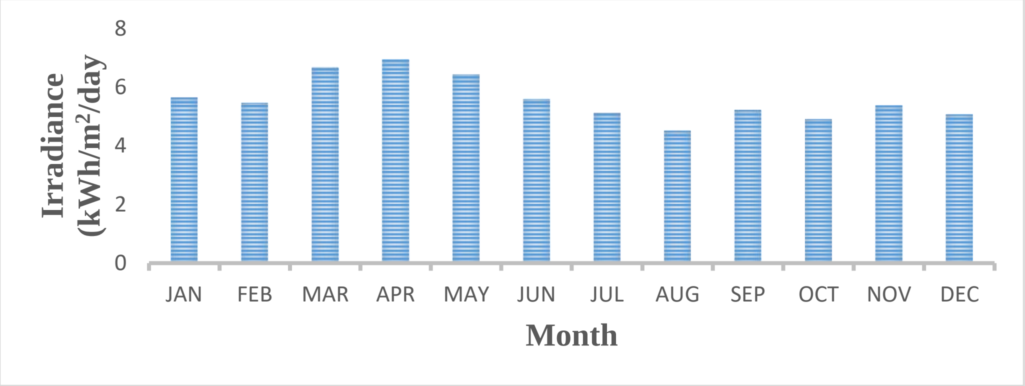


Figure 17 : Daily average solar radiation per month of Soutou (NASA Power, 2021)

afterwards, the Equation 12 below was used to calculate the PV system capacity (P_{peak}) (Bhandari & Shah, 2021).

$$\text{Ppeak kWÞ} = \frac{\text{Ed kWhÞ} * \text{Istc}\left(\frac{\text{kW}}{\text{m2}}\right)}{\text{G}\left(\frac{\text{kWh}}{\text{m2}}\right) * \text{Q}}$$

Equation 12

where P_{peak} corresponds to the required solar PV size in kilowatt peak (kW$_p$, E_d refers to the energy demand in kWh/d, I_{stc} represent the solar radiation at standard test conditions in kW/m^2 with a value of 1kW/m^2, G is the global solar radiation in kWh/m^2/d with a value of 5.65 taken from (Global solar Atlas), and Q represents the quality factor or performance ratio. For Ziguinchor (the region where Soutou is located), Q is equal to 0.792 (Sarr et al., 2020). The detail calculation of the PV capacity is presented in Table 7. Additionally, the PV output data was taken from Global Solar Atlas then multiplied by the capacity to find our system power output see Table 8. The technical details about the PV panels used in this study can be found in the *Table 9* below.

Table 7: Solar PV dimensioning

	SOEC	DAC	Pa	Pa CO_2	Pa H_2O	Pa MeOH	Pa CO	MS
$E_{consumption}$ (kW)	2966.66	1216.69	39.2	49.5	14.7	14.7	49.	2406.9
hours/day	1	1	1	1	1	1	1	1
00.01-1.00	0	0	0	0	0	0	0	0
1.01-2	0	0	0	0	0	0	0	0
2.01-3	0	0	0	0	0	0	0	0
3.01-4	0	0	0	0	0	0	0	0
4.01-5	0	0	0	0	0	0	0	0
5.01-6	0	0	0	0	0	0	0	0
6.01-7	0	0	0	0	0	0	0	0
7.01-8	0	0	0	0	0	0	0	0
8.01-9	0	0	0	0	0	0	0	0
9.01-10	0	0	0	0	0	0	0	0
10.01-11	1	1	1	1	1	1	1	1
11.01-12	1	1	1	1	1	1	1	1
12.01-13	1	1	1	1	1	1	1	1
13.01-14	1	1	1	1	1	1	1	1
14.01-15	1	1	1	1	1	1	1	1
15.01-16	1	1	1	1	1	1	1	1
16.01-17	1	1	1	1	1	1	1	1

17.01-18	1	1	1	1	1	1	1	1
18.01-19	0	0	0	0	0	0	0	0
19.01-20	0	0	0	0	0	0	0	0
20.01-21	0	0	0	0	0	0	0	0
21.01-22	0	0	0	0	0	0	0	0
22.01-23	0	0	0	0	0	0	0	0
23.01-24	0	0	0	0	0	0	0	0
Total h /d	8	8	8	8	8	8	8	8
$E_{consumption}$ kWh/d	237339	9733	313	396	117.6	117.6	396	19253
total E_d (kWh/d)	54060							

Table 8 :PV system performance parameters

Months	Reference yield E_r=G/Istc (kWh/kW$_p$ /d)	Array Yield $E_a=E_{pv}/P_{nominal}$ (kWh/kW$_p$/ d)	PV output E_{PV} (kWh/kW$_p$ /d)	quality factor (%) $Q=E_a/E_r$ (kWh/kW$_p$ /d)	Array capture losses $Lc=E_r-E_a$ (kWh/kW$_p$ /d)	Reference
January	5.65	4.835	73177.661	0.855	0.815	(Attari et al., 2016)
February	5.46	5.026	76068.444	0.920	0.434	
March	6.67	5.19	78550.582	0.778	1.48	
Avril	6.95	5.217	78959.226	0.750	1.733	
May	6.44	4.785	72420.912	0.743	1.655	
Jun	5.6	4.102	62083.716	0.7325	1.498	
July	5.13	3.765	56983.2257	0.733	1.365	

August	4.51	3.784	57270.790	0.839	0.726	
September	5.22	4.187	63370.1902	0.802	1.033	
October	4.91	4.538	68682.570	0.924	0.372	
November	5.38	4.717	71391.733	0.876	0.663	
December	5.07	4.613	69817.6946	0.909	0.457	
Year	5.58	4.563	69064.729	0.817	1.016	

Table 9 : PV system parameters

element of the system: PV	Value	Reference
Module type	Silicone-polycrystalline	(Sarr et al., 2020)
Pm in Watt peak (Wp)	280	
efficiency%	16.7	
Temperature coefficient °C	-0.44	
Quality factor Q	0.792	
Dr (degradation rate of)	0.7	(Ramasamy & Margolis, 2021)

7.1.1 Direct Air Capture (DAC) System Sizing

The DAC system was sized in regards to the specific humidity (Q_vM) representing the moisture content in gram per kilogram (g/kg) of air captured see Figure 18 (NASA power, 2021). The sizing was done as follow. The month that has the worse of moisture availability in the air was fixed with the minimum air to be captured to be 84198.38 kilogram per day (kg/d).

This allowed us to meet the demand of the SOEC electrolyzer by capturing at least 730 kg CO_2/H_2O per hour that is allocated to the SOEC. In such cases, it is assumed that the excess CO_2/H_2O captured is going to be sold. Furthermore, the co-electrolysis of the CO_2 and H_2O from the DAC to the SOEC generated CO and H_2. Technical specifications of the DAC technology are described in *Table 11*. The production of the DAC system is subsequently delivered to the methanol synthesis system, electrified by the PV system to produce e-MeOH.

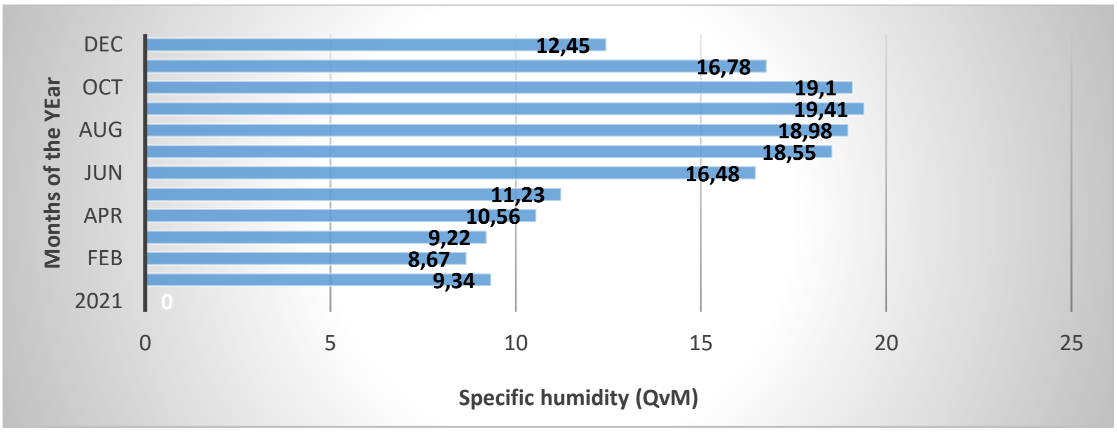


Figure 18 :daily average QvM in g/kg of air *(NASA power, 2021)*

Table 10: DAC system sizing

Months	QvM	Mass H_2O/CO_2 (kg/d)	excess CO_2 (kg/d)	Excess H_2O (kg/d)	mass H_2O/CO_2 (kg/Month)	Reference
January	9.34	786.41	56.412	226.412	24378.8	(NASA power, 2021)
February	8.67	730	3.08E-08	170	20440	
March	9.22	776.309	46.309	216.309	24065.582	
Avril	10.56	889.134	159.134	329.134	26674.048	
May	11.23	945.547	215.547	385.547	29311.98	
Jun	16.48	1387.589	657.589	827.589	41627.681	
July	18.55	1561.88	831.880	1001.88	48418.281	
August	18.98	1598.085	868.085	1038.085	49540.645	
September	19.41	1634.29	904.290	1074.29	49028.719	
October	19.1	1608.189	878.189	1048.189	49853.863	
November	16.78	1412.848	682.848	852.848	42385.467	
December	12.45	1048.269	318.269	488.269	32496.366	
Year	14.28	1202.352	472.352	642.352	438221.44	

Table 11 : DAC system Parameters

Element of the system: DAC	Value	Reference
Module type	S-DAC climwork	
Required temperature of thermal energy (◦C)	[80, 120]	(Mcqueen et al., n.d.)
Adsorption process cycle time in minute (mn)	[40,75]	
Desorption T (◦C)	100	
Share as electricity consumption (%) [20-25]	20	(International Energy Agency, 2022)
Regeneration temperature °C	80-100	
Regeneration pressure	Vacuum	
Modular Capture capacity tCO_2/year per unit	50	
CO_2/H_2O concentration after treatment (%)	100	
DAC efficiency around %	90	
1 kg CO_2/H_2O captured require in kilo Watt hour (kWh)	1.67	
Sorbent lifetime Y (Year)	1	
Sorbent replacement [0.25-38kg/tCO_2] kg/tCO_2	1	

capacity factor %	90	assumed for the model based on the SOEC technical data
Gas compressor replacement (Y)	10	(Sollai et al., 2023a)
Power absorption compressors (pa) CO_2 kW	49.5	
Pa H_2O kW	14.7	
Depreciation for the rest of the plant (Y)	10	Assumed based on the compressor lifetime

7.2 Solid Oxide Cell Electrolyzer and Methanol Synthesis system Technical Specification

The engineering data about the SOEC and MS used are introduced in the Table 12 and Table 13 below.

Table 12 :Sunfire Synlink SOEC technical parameters

Element of the system: Sunfire SOEC	Value	Reference
Net production rate in Normal cubic meter per hour (Nm3/h)	750	(Sunfire GmbH, 2020)
System electrical efficiency %	82	
Production capacity dynamic range	5 to 100	

Available H_2:CO ratios [1.5,3.5]	2	
System power rating (AC) kW	2,890	
Specific power consumption at system level (AC) kWh/kg	3.6	
Steam input		
Consumption kg/h	560	
CO_2 input		
Consumption kg/h	730	
Land footprint m^2	300	
pa H_2 (kW)	39.2	(Sollai et al., 2023) Assumed based on CO2 compressor
pa CO (kW)	49.5	

Table 13: MeOH system parameters with a capacity of 1800 t/d

Element of the system: MeOH reactor	Value	Reference
Reactor type from Lurgi	BWR	(Bisotti et al., 2022)
Flow	Axial	
catalyst location	shell side	
heat exchanger	tubular	
Conversion efficiency for CO_2 hydrogenation then	36%	
MeOH outlet (mol %)	8−12	
capacity (t/day) <2200	1800	

Land footprint assumed m^2 for a capacity 5000 t/d of MeOH	300	
synthesis efficiency with a stoichiometric syngas and limited amount of inert 0.79-0.8(%)	0.8	(International Energy Agency, 2022)
Catalyst consumption (reactor) kg/Y	73	(Sollai et al., 2023a)

8 Appendix B: Change in model Capacity Sensitivity analysis with a SOEC of 100MW

The technical details about system sizing of the technologies used 3.2 are introduced in this section.

8.1 Solar Photovoltaic System Sizing and Performance

The same sizing method of 7.1 section was applied see Table 14. In addition, the details about the PV arrays, output and other performance parameters are presented in Table 15.

Table 14 : PV system Sizing

	SOEC	DAC	Pa H_2	Pa CO_2	Pa H_2O	Pa MeOH	Pa CO	MeOH
$E_{consumption}$ (kW)	147827.44	58660.61	39.2	49.5	14.7	14.7	49.5	136914
Operational hours	1	1	1	1	1	1	1	1
00.01-1.00	0	0	0	0	0	0	0	0
1.01-2	0	0	0	0	0	0	0	0
2.01-3	0	0	0	0	0	0	0	0
3.01-4	0	0	0	0	0	0	0	0

4.01-5	0	0	0	0	0	0	0	0
5.01-6	0	0	0	0	0	0	0	0
6.01-7	0	0	0	0	0	0	0	0
7.01-8	0	0	0	0	0	0	0	0
8.01-9	0	0	0	0	0	0	0	0
9.01-10	0	0	0	0	0	0	0	0
10.01-11	1	1	1	1	1	1	1	1
11.01-12	1	1	1	1	1	1	1	1
12.01-13	1	1	1	1	1	1	1	1
13.01-14	1	1	1	1	1	1	1	1
14.01-15	1	1	1	1	1	1	1	1
15.01-16	1	1	1	1	1	1	1	1
16.01-17	1	1	1	1	1	1	1	1
17.01-18	1	1	1	1	1	1	1	1
18.01-19	0	0	0	0	0	0	0	0
19.01-20	0	0	0	0	0	0	0	0
20.01-21	0	0	0	0	0	0	0	0
21.01-22	0	0	0	0	0	0	0	0
22.01-23	0	0	0	0	0	0	0	0
23.01-24	0	0	0	0	0	0	0	0
Total h usage/d	8	8	8	8	8	8	8	8
$E_{consumption}$ kWh/d	1182619.55	469284.9	313.6	396	117.6	117.6	396	1095312
total E_d (kWh/d)	2748557.08							

Table 15: PV system performance

Months	Reference yield Er=G/Istc kWh/kW$_p$/d	Array Yield E_a=E_{pv}/Pnom	E_{PV}	Q=E_a/Er	Array capture losses Lc=E_r-E_a
January	5.65	4.835	3720484.64	0.855	0.815
February	5.46	5.026	3867457.25	0.92	0.434
March	6.67	5.19	3993653.62	0.778	1.48
Avril	6.95	5.217	4014429.86	0.750	1.733
May	6.44	4.785	3682010.13	0.743	1.655
Jun	5.6	4.102	3156448.39	0.7325	1.498
July	5.13	3.765	2897130.23	0.733	1.365
August	4.51	3.784	2911750.54	0.839	0.726
September	5.22	4.187	3221855.05	0.802	1.033
October	4.91	4.538	3491946.08	0.924	0.372
November	5.38	4.717	3629684.81	0.876	0.663
December	5.07	4.613	3549657.84	0.909	0.457
Year	5.58	4.563	3511375.7	0.817	1.0167

8.2 DAC sizing

The sizing of the DAC system was done by adopting the same approach of 7.1.1 with the minimum air to be captured fixed at 4059.56 t/h see Table 16.

Table 16 : DAC system sizing

Months	Q_VM (g/kg)	Daily production H_2O/CO_2 (kg/d)	excess CO2 (kg/d)	Excess H_2O (kg/d)	Monthly production H_2O/CO_2 (kg)
January	9.34	37916.2641	2719.903	10916.264	1175404.188
February	8.67	35196.360	-3.9996E-08	8196.360	985498.103
March	9.22	37429.117	2232.756	10429.117	1160302.635
Avril	10.56	42868.923	7672.563	15868.923	1286067.717
May	11.23	45588.827	10392.4664	18588.827	1413253.644
Jun	16.48	66901.502	31705.141	39901.502	2007045.074
July	18.55	75304.785	40108.425	48304.785	2334448.361
August	18.98	77050.395	41854.034	50050.395	2388562.258
September	19.41	78796.00	43599.644	51796.005	2363880.151
October	19.1	77537.5423	42341.181	50537.542	2403663.811
November	16.78	68119.3696	32923.008	41119.369	2043581.088
December	12.45	50541.487	15345.126	23541.486	1566786.097
Year	14.28	57970.476	22774.115	30970.476	21128493.13

8.3 Solid Oxid Electrolyzer and Methanol synthesis system

The technical specification of the SOEC and MS systems are correspondingly described in the Table 17 and Table 18 below.

Table 17 : SOEC system parameters

Element of the system: SOEC	Value	Reference
Net production rate (Nm^3/h)	42,667	(Haldor Topsoe, 2020)
Production capacity dynamic range %	[10, 100]	
System power rating (AC) kW	100,000	
Specific power consumption at system level (AC)	3.28	
System electrical efficiency (%)	64	
Steam input		
Consumption (kg/h)	27,000	
CO_2 input		
Consumption kg/h	35196.36	
Land footprint (m^2)	8,400	

Table 18 : MeOH reactor system parameters

Element of the system: MeOH reactor	Value	Reference
Licensor	Toyo	(Bisotti et al., 2022)
Reactor type	BWR	
Flow	axial/radial	
catalyst location	shell side	
heat exchanger	bayonets	
conversion efficiency	0.6	
capacity (t/day)	5000	
Land footprint assumed m^2 for a capacity 5000 t	1000	

9 Appendix C: Solar PV Sizing for the SOEC of 1.1MW

This present section describes the dimensioning and performance of the PV system as illustrated by the following Table 19 and

Table 19 : PV system Sizing

	SOEC	DAC	Pa H_2	Pa CO_2	Pa H_2O	Pa MeOH	Pa CO	MeOH
$E_{consumption}$ (kW)	985	23.578	39.2	49.5	14.7	14.7	49.5	80.22
Operational hours/d	1	1	1	1	1	1	1	1
00.01-1.00	0	0	0	0	0	0	0	0
1.01-2	0	0	0	0	0	0	0	0
2.01-3	0	0	0	0	0	0	0	0
3.01-4	0	0	0	0	0	0	0	0
4.01-5	0	0	0	0	0	0	0	0
5.01-6	0	0	0	0	0	0	0	0
6.01-7	0	0	0	0	0	0	0	0
7.01-8	0	0	0	0	0	0	0	0
8.01-9	0	0	0	0	0	0	0	0
9.01-10	0	0	0	0	0	0	0	0
10.01-11	1	1	1	1	1	1	1	1
11.01-12	1	1	1	1	1	1	1	1
12.01-13	1	1	1	1	1	1	1	1
13.01-14	1	1	1	1	1	1	1	1
14.01-15	1	1	1	1	1	1	1	1
15.01-16	1	1	1	1	1	1	1	1
16.01-17	1	1	1	1	1	1	1	1

17.01-18	1	1	1	1	1	1	1	1
18.01-19	0	0	0	0	0	0	0	0
19.01-20	0	0	0	0	0	0	0	0
20.01-21	0	0	0	0	0	0	0	0
21.01-22	0	0	0	0	0	0	0	0
22.01-23	0	0	0	0	0	0	0	0
23.01-24	0	0	0	0	0	0	0	0
Total	8	8	8	8	8	8	8	8
Total h usage/d	8	8	8	8	8	8	8	8
E cons kWh/d	7880	188.630	313.6	396	117.6	117.6	396	641.784
total Ed(kWh/d)	10051.214							

Table 20 : PV system performance

	Reference yield $Er=G/Istc$ ($kWh/kW_p/d$)	Array Yield $E_a=E_{pv}/Pnominal$ ($kWh/kW_p/d$)	E_{PV} ($kWh/kW_p/d$)	$Q=E_a/Er$ (%)	Array capture losses $Lc=E_r-E_a$ (kWh/kWp/d)
January	5.65	4.835	13605.4623	0.855752212	0.815
February	5.46	5.026	14142.9273	0.920512821	0.434
March	6.67	5.19	14604.4156	0.778110945	1.48

Avril	6.95	5.217	14680.3923	0.750647482	1.733
May	6.44	4.785	13464.7646	0.743012422	1.655
Jun	5.6	4.102	11542.8348	0.7325	1.498
July	5.13	3.765	10594.5327	0.733918129	1.365
August	4.51	3.784	10647.9978	0.83902439	0.726
September	5.22	4.187	11782.0208	0.80210728	1.033
October	4.91	4.538	12769.7183	0.924236253	0.372
November	5.38	4.717	13273.4158	0.876765799	0.663
December	5.07	4.613	12980.7647	0.909861933	0.457
Year	5.58	4.56325	12840.7706	0.817786738	1.01675

9.1 Direct Air Capture System sizing

The sizing of the DAC was done with the same method adopted previously in 7.1.1. A minimum air of 1631.75 kg is the reference value to be captured.

Table 21 : DAC sizing

	Q_VM	Production H_2O/CO_2 (kg/d)	excess CO2 (kg/d)	Excess H_2O (kg/d)	Monthly production H_2O/CO_2 (kg)
January	9.34	15.240	1.093	1.009	472.4569784
February	8.67	14.147	-3.04E-09	-0.083558333	396.1236999

March	9.22	15.044	0.897	0.813904325	466.3868673
Avril	10.56	17.231	3.084	3.000449711	516.9384912
May	11.23	18.324	4.177	4.093722404	568.0612278
Jun	16.48	26.891	12.743	12.66041142	806.7373424
July	18.55	30.268	16.121	16.03813451	938.3380031
August	18.98	30.970	16.823	16.73978714	960.0892345
September	19.41	31.672	17.524	17.44143976	950.1681927
October	19.1	31.166	17.0191	16.93559717	966.1593455
November	16.78	27.38	13.233	13.1499365	821.423095
December	12.45	20.315	6.168	6.084457756	629.7740237
Year	14.28	23.301	9.1541	9.070560783	8492.656501

9.2 Solid Oxid Electrolyzer and Methanol synthesis system

The following *Table 22* and *Table 23* represent the technical specification of the SOEC and MS systems.

Table 22 : SOEC parameters with a capacity of 1.1 MW

Element of the system: Sunfire SOEC	Value	Reference
Net production rate (Nm^3/h)	23	(FuelCellEnergy, n.d.)
Production capacity dynamic range	[5, 100]	
System power rating (AC) (kW)	1,100	
Specific power consumption at system level (AC)	39.4	
System electrical efficiency with heat	100	
Steam input		
Consumption kg/h	10.85	

CO_2 input (56.5891% calculated based on sun fire SOEC co-electrolyzer (2890)		
Consumption kg/h	14.14	
Land footprint (m^2)	349.62	

Table 23 : MeOH reactor system parameters with a capacity of 1600 t/d

Element of the system: MeOH reactor	Value	Reference
licensor	AirProduct LPMeOH	(Bisotti et al., 2022)
Reactor type	slurry	
flow	axial/radial	
catalyst location	shell side	
heat exchanger	tubular	
conversion efficiency for CO2 hydrogenation	[20, 50]	
MeOH outlet frac (mol %	[8, 12]	
capacity (t/d) <2000	1600	
Land footprint assumed m^2 for a capacity 5000	300	

10 DECLARATION OF AUTHORSHIP

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

I do solemnly swear that:

1. Where I have consulted the published work of others or myself, this is always clearly attributed.
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6. During the preparation of this work, I used PubMed, Google Scholar, Science Direct, and in documents from dome renewable energy organizations like the IPCC, IRENA, and International Energy Agency (IEA) as well as Nasa power and Global solar atlas database to edit the writing of the thesis.

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