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Economics/Policies/Infrastructures and Green Hydrogen Technology

Characterization of efficiency losses and their possible impacts on the cost competitiveness of e-methanol production from green hydrogen and captured CO_2.

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Dedication

This thesis is dedicated to my parents, Nino Mendes and Julia da Silva (both not alive). I wish they were here to witness this victory of ours.

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Abstract

The present study investigates the characterization of efficiency losses and their possible impacts on the cost competitiveness of the e-methanol produced from green hydrogen and captured CO_2. The research methodology applied in this thesis involves a literature review to acquire existing knowledge on the technologies of direct air capture, solid oxide electrolyser cell and methanol synthesis reactor. The amount of carbon dioxide and green hydrogen needed to produce e-methanol was estimated using a stoichiometric reaction. Furthermore, the study uses a cost modelling of e-methanol production, considering factors such as capital expenditures and operational expenditures. Levelized cost and cost-benefit analysis were used to determine the cost competitiveness and viability of the technology, respectively. Finally, sensitivity analysis was carried out considering different scenarios, such as economies of scale, discount rate and future scenarios. The results of levelized costs of methanol for all the scenarios range between USD1576.77/ton and USD 804.16/ton, a value which is around 1.87 to 4 times more expensive than the current methanol market value at USD 438.35/ton. The scenario with a 10% discount rate is the worst. The future scenario which is based on technological advancement appears to be the best one. Net present value is negative in all scenarios, with the percentage losses ranging from 14.34% to 60.7%. This analysis confirms that e-methanol production from green hydrogen is not yet competitive, and it is not expected to reach competitiveness until 2030, even with advances in technologies which will culminate in the reduction of the cost of the PV+ battery and solid oxide electrolyser cell by almost 60%. Hydrogen is identified as the largest cost component in the production of e-methanol, and the area for improving the cost efficiency is in photovoltaic battery storage system capital expenditures, solid oxide electrolyser, and electrolyser stack replacement.

The findings of this thesis contribute to a better understanding of the efficiency loss drivers of e-methanol, which could help policymakers and investors make informed decisions about the adoption and commercialization of e-methanol.

Keywords: e-methanol, green hydrogen, cost-benefit analysis, cost efficiency, direct air capture.

Resumé

Le présent mémoire étudie la caractérisation des pertes d'efficacité et leurs impacts possibles sur la compétitivité coûts de l'e-méthanol produit à partir de l'hydrogène vert et du CO_2 capturé. La méthodologie de recherche appliquée dans cette ce mémoire implique une revue de la littérature afin d'acquérir les connaissances existantes sur les technologies de capture directe de l'air, de cellule d'électrolyse à oxyde solide et de réacteur de synthèse du méthanol. La quantité de dioxyde de carbone et d'hydrogène vert nécessaire à la production d'e-méthanol a été estimée à l'aide d'une réaction stœchiométrique. En outre, l'étude a utilisé une modélisation des coûts de production de l'e-méthanol, en tenant compte de facteurs tels que les dépenses d'investissement et les dépenses opérationnelles. Le coût nivelé et l'analyse coût-bénéfice ont été utilisés pour déterminer la compétitivité des coûts et la viabilité de la technologie, respectivement. Enfin, l'analyse de sensibilité a été utilisée, en considérant différents scénarios, tels que les économies d'échelle, le taux d'actualisation et les scénarios futurs. Les résultats des coûts nivelés du méthanol pour tous les scénarios simulés se situent entre USD1576.77/ton and USD 804.16/ton , une valeur qui est environ 1,87 à 4 fois plus chère que la valeur actuelle du marché du méthanol, qui est de 438,35 USD/tonne. Le scénario avec un taux d'actualisation de 10 % est le plus défavorable. Le scénario futur basé sur le progrès technologique est le meilleur. La valeur actuelle nette est négative dans tous les scénarios, avec des pertes en pourcentage allant de 14,34 % à 60,7 %. Cette analyse a confirmé que la production d'e-méthanol à partir d'hydrogène vert n'est pas encore compétitive et qu'elle ne devrait pas l'être avant 2030, même avec les progrès technologiques qui aboutiront à la réduction du coût de la batterie PV+ et de la cellule d'électrolyse à oxyde solide de près de 60 %. L'hydrogène a été identifié comme l'élément de coût le plus important dans la production d'e-méthanol, et le domaine d'amélioration de l'efficacité des coûts se situe dans les dépenses d'investissement du système de stockage de la batterie photovoltaïque, de l'électrolyseur à oxyde solide et du remplacement de la pile d'électrolyseur.

Les résultats de cette thèse contribuent à une meilleure compréhension des facteurs déterminants la perte d'efficacité de l'e-méthanol, ce qui pourrait aider les décideurs politiques et les investisseurs à prendre une décision éclairée sur l'adoption et la commercialisation de l'e-méthanol.

Mots clés : e-méthanol, hydrogène vert, analyse coûts-bénéfices, efficacité des couts, direct air capture

Acronyms and abbreviations

CAPEX	Capital expenditures
CH3OH	Methanol chemical formula
CO	Carbon monoxide
CO2	carbon dioxide
DAC	Direct air capture
DAE	Direct air electrolyser
DOD	Depth of discharge
GHGs	Greenhouse gases
GT	Gigaton
GWh	Giga watt-hour
H2O	Water chemical formula
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
L-DAC	Liquid DAC
LCO	levelized costs
LCOCO2	Levelized cost of carbon dioxide
LCOE	Levelized cost of electricity
LCOH	Levelized cost of hydrogen

LCOM	levelized cost of e-methanol
LCOW	Levelized cost of water
MR	Methanol reactor
MW	Megawatt
MWh	Megawatt hour
NOX	nitrogen oxide
NPV	net present value
OPEX	operating expenditures
PEM	Proton exchange membrane electrolyser
PM	particulate matter
PV	photovoltaic
PVF	Present Value Factor
RWGS	reverse reaction of the gas with water
S-DAC	Solid DAC
SOEC	Solid oxide electrolysis cells
SOX	sulfur oxide
USD	US dollar

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CHAPTER I: INTRODUCTION

1.1. Background

Energy is an essential element for daily life. Its absence would have a significant impact on the structure and standards of living of a society (Sharma et al., 2021). For decades, the share of fossil fuels in the global energy mix has been persistently high, at around 80% (IEA, 2022). According to the Intergovernmental Panel on Climate Change (IPCC), as stated in its third assessment report, the main driver of global warming is the release of greenhouse gases (GHGs), particularly carbon dioxide (CO_2), resulting from the burning of fossil fuels (Cooper et al., 2002). To strengthen the global response to the threat of climate change, the Paris Agreement establishes an action plan by limiting global warming to well below 2 °C and pursuing efforts to keep it to 1.5 °C above pre-industrial levels (*The Paris Agreement | UNFCCC*, n.d.). One of the promising options for lowering CO_2 emissions is to convert it into valuable products through a variety of processes (Azhari et al., 2022). According to Guil-López et al. (2019), methanol is among the most interesting products that can be produced from CO_2. Currently, e-methanol, also called renewable methanol is produced from non-fossil fuels resources, with the purpose of producing green H2 from water electrolysis using renewable resources and CO2 captured from the ambient air (Ullah et al., 2023).

E-methanol produced using CO_2 captured and green hydrogen can play a bigger role in decarbonizing specific sectors where options are currently limited, such as a feedstock in the chemical industry or as a fuel in road and maritime transport (IRENA, 2021). It has the potential to cut the emissions of CO_2 by up to 95% and nitrogen oxide (NO_X) by up to 80%. Furthermore, it eliminates sulfur oxide (SO_X) and particulate matter (PM) emissions (IRENA, 2021).

This study is part of DryHy project that aims to integrate solar photovoltaics systems, Direct Air Capture (DAC), Solid Oxide Electrolyser Cell (SOEC), and Methanol Synthesis Reactor in order to produce green hydrogen, e-fuels, specifically e-methanol using renewable electricity and CO_2 from the ambient air in arid zone of Ivory Coast.

1.2. Research problem

Renewable methanol produced from green hydrogen and carbon dioxide extracted from the atmosphere is the most appealing choice for stabilizing the planets climate. This fuel is clean and safe and reduces atmospheric carbon dioxide levels. (Hashar, 2022). For the adoption and commercialization of this new technology, it is essential to study its cost efficiency. Based on the information collected from the literature review, it is unfortunate to note that there are a limited number of studies focused on cost modelling or cost efficiency of the different technologies that make up the DryHy project. Furthermore, none of the studies considers bringing together these technologies and breaking down their costs. The majority of the studies reviewed primarily concentrate on technical aspects of technology development. Understanding the variables that affect cost efficiency in the production of e-methanol from green hydrogen and captured carbon dioxide, as well as how those variables impact this technology cost competitiveness, is the key research problem of this thesis. This can be broken into the following specific problems:

i. Identify and analyse the key cost drivers in e-methanol production. This includes assessing the cost across the entire value chains for the production of e-methanol, starting from solar photovoltaic systems, going through direct air capture and green hydrogen production costs until reaching the cost required for the e-methanol production process. As a result, the study will determine the major factors impacting the overall cost of e-methanol production.
ii. Evaluate the impacts of cost efficiency on the overall cost competitiveness of e-methanol from green hydrogen and captured CO_2. This includes doing a comparative analysis of the cost of e-methanol production with traditional methanol.

1.3. Research questions

This thesis will answer the following research questions:

i. What are the key factors that create the inefficiency in the e-methanol production from captured CO_2 and green hydrogen and how can these factors be characterized and quantified?
ii. How do efficiency losses impact the cost of e-methanol production from captured CO_2 and green hydrogen production?
iii. What strategies could be used to improve the efficiency of the technology and increase its cost competitiveness?

1.4. Research Objective

The main objective of this study is to characterize efficiency losses and analyse their possible impact on the cost competitiveness of e-methanol production by using captured CO_2 and green hydrogen production. The objective can be broken down into the following tasks:

i. identify and quantify the sources of efficiency losses in e-methanol production from captured CO_2 and green hydrogen production.
ii. compare the cost of e-methanol produced from CO_2 captured and green hydrogen to traditional methanol.
iii. provide recommendations for the adoption of the technology, considering the results of this research.

1.5. Significance of the study

This thesis topic is relevant for many reasons:

i. The study contributes to a better understanding of the efficiency losses of e-methanol produced by using captured CO_2 from the atmosphere and green hydrogen.
ii. The study offers useful insights into the cost competitiveness of e-methanol production from captured CO_2 and green hydrogen in comparison to traditional ways of producing methanol. This is critical information for the effective commercialization of e-methanol.
iii. The outcomes of this research help policymakers, and investors, to make an informed decision about the adoption and commercialization of e-methanol produced by using CO_2 and green hydrogen.
iv. Finally, this thesis can contribute to global efforts towards energy transition.

1.6. Organization of the study

The study is structured into five (5) chapters:

Chapter one of the study, introduction, presents the background of the study, problem statement, the research questions, the objective of the research and the organization of the study.

Chapter two consists of literature review, where the technologies advancement and the work of the other researchers are assessed.

Chapter three outlines methods used in the study, including detail results of the literature review, cost modelling, levelized cost, cost-benefit analysis and sensitivity analysis.

Chapter four comprises results and discussion. This chapter interprets the findings and discusses their implications.

Chapter five brings the conclusion of the study, the limitations faced in the work and the recommendations considered pertinent for future studies.

CHAPTER II: LITERATURE REVIEW

A detailed literature review is undertaken to acquire existing knowledge on the technologies of direct air capture, solid oxide electrolyser, and methanol synthesis reactor, all of which are components of the DryHy technology

2.1. Description of the DAC

Direct air capture (DAC) is one of the primary technological solutions to combat climate change. It extracts CO2 directly from the atmosphere, lowering the CO2 atmospheric concentration by only using renewable energy, energy from waste, or waste heat as energy sources. The captured CO2 can be permanently stored deep underground, and used in food processing, or synthetic fuel production (Climeworks, 2022).

The main components of DAC are sorbents, contact area, and regeneration module. The sorbent can be a solid or liquid material that attracts CO2 either chemically or physically. For CO2 capture to take place, ambient air is exposed to the sorbent material through the contact area, and upon saturation with CO2 or as desired, the sorbent material undergoes regeneration in which it is separated from the captured CO2 to get a concentrated CO2 stream. The sorbent material should be reversible so that it can be reused. The removal of CO2 from ultra-diluted air by heating, cooling, air compression or using membranes requires an extremely high-energy energy.

2.2. Status of DAC technology

DAC is now rated as “technology readiness level” 6, meaning it is not yet ready for full commercial deployment. But this also means there is ample opportunity to optimize performance and minimize costs through learning from early iterations of the technology(Lebling et al., 2022)

The leading industrial developers of DAC today are Carbon Engineering, Climeworks, and Global Thermostat(McQueen et al., 2021).

Carbon Engineering is the pioneer company of DAC. It was founded in Canada in 2009 and has been capturing CO2 from the atmosphere since 2015 and converting it into fuels since 2017.

Climeworks was started in Switzerland in 2009, and by 2013, they had built the first working prototype of their DAC technology. They opened the first commercial DAC plant four years later. They have set the goal of capturing 225 million tonnes of CO_2 from the atmosphere by the year 2025, which corresponds approximately to 1% of global CO_2 emissions (McQueen et al., 2021; Sodiq et al., 2023).

Global Thermostat, the third commercial DAC initiative, is located in the United States. Global Thermostat, which was founded in 2010, now operates two experimental DAC facilities with the capacity to capture 3000-4000 tonnes of CO_2 per year (McQueen et al., 2021)

Two different methods are currently being employed to extract CO2 from the atmosphere: solid and liquid DAC. S-DAC is based on solid adsorbents that work at ambient to low pressure (i.e., under a vacuum) and medium temperature (80-120°C) (IEA, 2023). Those adsorbents offer the possibility of low energy input, low operating costs, and applicability across a wide range of scales (Keith et al., 2018).

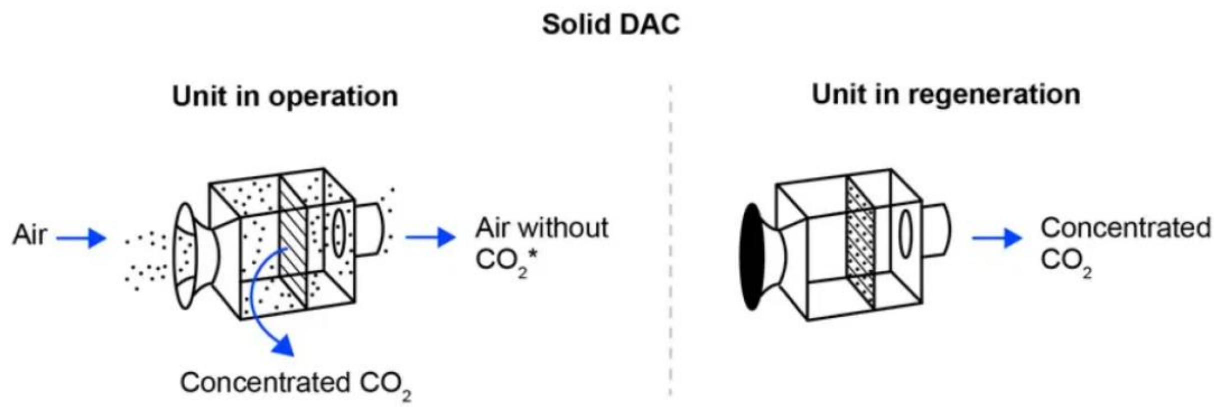

Figure 1: Solid DAC working principles

Source: Carbon Credits (2022)

Air is sucked into the collector where the CO_2 is absorbed by a filter. Once the filter is saturated, the collector is closed and heated to release the captured CO_2 (regeneration). On the other side, Liquid DAC (L-DAC) uses an aqueous basic solution (such as potassium hydroxide) to release collected CO_2 via a series of high-temperature units (between 300°C and 900°C) (IEA, 2022).

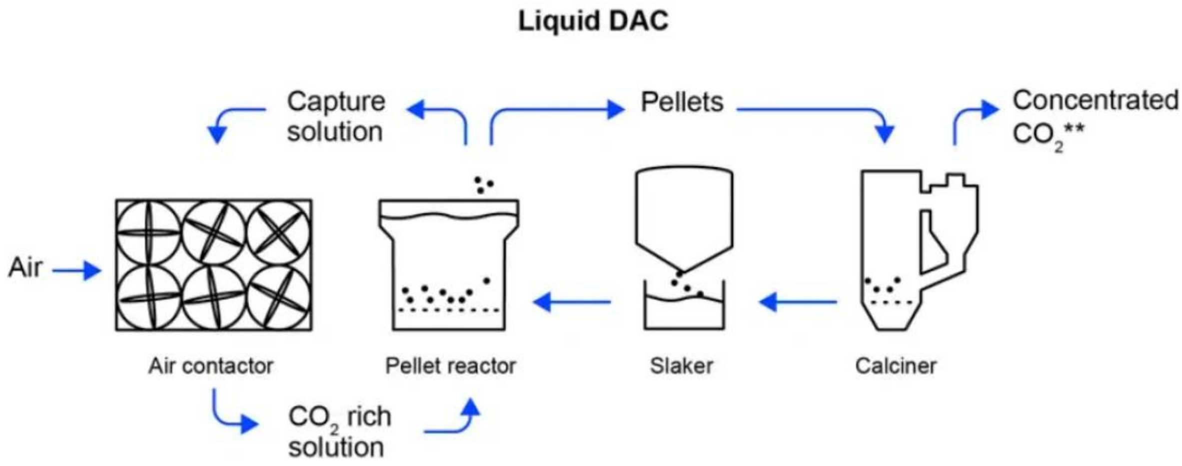

Figure 2: Liquid DAC working principle

Source: Carbon Credits (2022)

The CO_2 in the air is combined with the capture solution to generate a carbonate salt. The salt is separated into small pellets, which are then burned in a calciner to produce pure CO2 gas. Pellets that have been processed are hydrated in a tank and recycled back into the capture solution.

According to the (IEA, 2023), 27 operational DAC plants are running in Europe, North America, Japan and the Middle East, capturing about 0.01MtCO_2/year. All these facilities are small-scale, with only a few having commercial agreements in place to sell or store the captured CO2. The remaining plants are operated for testing and demonstration purposes (IEA, 2023).

An advanced development project for a plant with the potential to capture 1MtCO_2/year is ongoing in the United States. The project will use DAC technology from Canada Engineering. It has a scalable setup consisting of air contactors that pull in atmospheric air with a potassium hydroxide solution to bind and extract the CO_2. This technique produces clean, compressed steam of CO_2 through a series of chemical processes, which is then delivered to geologic storage sites to permanently remove this carbon from the atmosphere which reacts (IEA, 2021). Another big DAC project with the potential of 36 kt CO2/year is now under construction, projected to be operational in 2024 in Iceland. (IEA, 2023)

Table 1: Current DAC plants and projects

Company		Plant type/status	Location	CO2 removal capacity (metric tons/yr)	Sorbent type	Thermal energy source	Market application	Date of operation
Climeworks		14 Pilot & Commercial Plants/Operational	Across Europe	Net: 2,000	Solid	Geothermal, Waste heat, etc.	Renewable fuels, food, beverages, and agriculture	2015–2020
		Pilot plant/Operational	Kanton Zurich (Switzerland)	900	Solid	Waste Incineration	Greenhouse	2017
		1 Commercial plant/Operational	Hellisheidi (Iceland)	4,000	Solid	Geothermal	CDR services - Microsoft, Shopify, Audi & Storage by	2021

							mineralization	
Carbon Engineering (Gallucci, 2021)		Pilot plant/Operational	Squamish, British Columbia (Canada)	350	Liquid	Natural Gas	Carbon neutral Fuel	2015
		Innovation centre/Under construction	Squamish, British Columbia (Canada)	1500	N/A	N/A	CO_2 capture and storage for Shopify and Virgin	2022
		Commercial plant/ Under construction	Permian Basin, Texas (USA)	1,000,000	N/A	N/A	Enhanced oil recovery and Carbon sequestration	Mid-2020s

Global Thermostat (The GT Solution, 2022)		Pilot plant (DAC + Flue)/ Nonoperating	Menlo Park, California (USA)	10,000	Direct CO2 capture from air	Residual heat from Industry	Not for Commercial use	2013
		Pilot plant/Nonoperating	Huntsville, Alabama (USA)	4,000	N/A	Wind power	Not for Commercial use	2019
		Pilot plant/planning	Magallanes (Chile)	250 kg/h	N/A	Natural Gas	Synthetic Gasoline	2022
		2 Commercial plants / Under construction	Sapulpa, Oklahoma (USA) 2	2,000 / Plant	N/A	N/A	CO2 based fuel, CO2 as industrial gas	2021

Source: Adapted from (Ozkan, 2021).

2.3. Breakdown cost of the DAC

The technique for capturing 1 million tons of CO_2 annually from the ambient air designed by (Keith et al., 2018) has a breakdown cost that includes capital and engineering expenditures. The breakdown of capital costs was developed using data from an independent assessment. The authors present an engineering cost foundation for a commercial DAC system, which includes the design and cost of all major components. The levelized cost of DAC, according to this study is 94 – USD 232/tCO_2. Unfortunately, not enough engineering detail has been supplied in this study to allow for an impartial evaluation. A plant with the same annual capacity was simulated to estimate CAPEX and OPEX of the solid and liquid DAC under different scenarios. The optimal and pessimistic scenarios for solid DAC presented CAPEX of USD 13.93/t CO2 and USD1027.9 and OPEX of USD 4.1/t CO2 and USD 8.9/t CO2 respectively. The pessimistic scenario for liquid DAC has a CAPEX and OPEX of USD 150.6/t CO2 and USD 78/t CO2, respectively, whereas the low scenario calls for USD 81/t CO2 and USD 41/t CO2. A big difference verified here in results is due to the type of material used for a specific part, taking into account new technologies and different suppliers (Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration et al., 2019; Ozkan et al., 2022).

Fasihi et al. (Fasihi et al., 2019) estimate DAC capital and operating expenditures under two scenarios for DAC capacities and financial learning rates in the period of 2020 to 2050. This study does not provide specific details about the breakdown of cost. The authors' presentation of the total CAPEX and OPEX per ton of CO2 captured was constrained, and they did not include the components taken into account. Their findings showed the cost of the DAC is predicted to drop to the same level as point source carbon capture systems after being widely implemented in the year 2050s. The study carried out by (Daniel et al., 2022) proposes and designs a novel direct air carbon capture process coupled with a solid oxide electrolysis cell for the chemical utilization of the captured CO_2. A detailed techno-economic analysis is performed to determine if the addition of CO_2 utilization can offset the high cost of carbon capture. Another study that presented the cost model of direct air capture of CO2 was conducted (Azarabadi & Lackner, 2019). The results of this study emphasize the importance of sorbent's long lifetime and stability in reducing the total cost of the system (Azarabadi & Lackner, 2019; Sutherland, 2019). (McQueen et al., 2020) report details specific CAPEX and OPEX for three DAC systems of varying heat sources, all at a capacity of 100ktCO2 annually.

2.4. Green Hydrogen Production

Hydrogen is recognized as the carbon-neutral alternative energy carrier with the highest energy density. Presently, around 95% of hydrogen production technologies depend on fossil fuels, resulting in greenhouse gases (Vostakola et al., 2023). Hydrocarbon reforming and pyrolysis are the main hydrogen production technology (Megía et al., 2021). Water electrolysis is seen as a relevant alternative process because it is the cleanest way to produce hydrogen. This technology consists of splitting water into hydrogen and oxygen through the use of an electrical current (Matošec, 2023; Nechache & Hody, 2021).

Hydrogen Production based on Solid oxide electrolysis cells (SOEC) is a promising technology as it involves less electrical energy per unit of hydrogen produced compared to conventional low-temperature water electrolysis (Polymer Electrolyte Membrane electrolysis, Alkaline electrolysis). Consequently, it is the more favourable thermodynamic and electrochemical kinetics conditions for the reaction (Brisse et al., 2008; Nechache et al., 2014). According to (Topsoe, 2023), without heat integration, SOEC is 20% more efficient than alkaline and PEM electrolysers and is 30% more efficient with heat integration compared to alkaline and PEM. This technology is still in early-stage commercialization (Samuel, 2021).

Currently, hydrogen is predominantly used by industry, specifically in oil refining, ammonia, methanol, and steel production. Practically, all the supply source is from fossil fuels. Hydrogen-based fuels can be used in the transport sector, being the low-fuel option for shipping and aviation. In power generation, hydrogen can be used to store renewable energy. It can also be used in gas turbines to increase power system flexibility. (IEA, 2019)

Based on the factors above described, it can be said that green hydrogen can significantly contribute to minimizing emissions.

Operating principle of SOECs

A SOEC consists of two porous electrodes, an oxygen electrode (Anode) and a hydrogen electrode(cathode) separated by a dense oxide ion-conducting electrolyte. The electrochemical reduction reaction takes place on the cathode side. Oxide ions move to the anode side through the electrolyte, where they are reoxidized to gaseous oxygen (O_2)(Nechache & Hody, 2021).

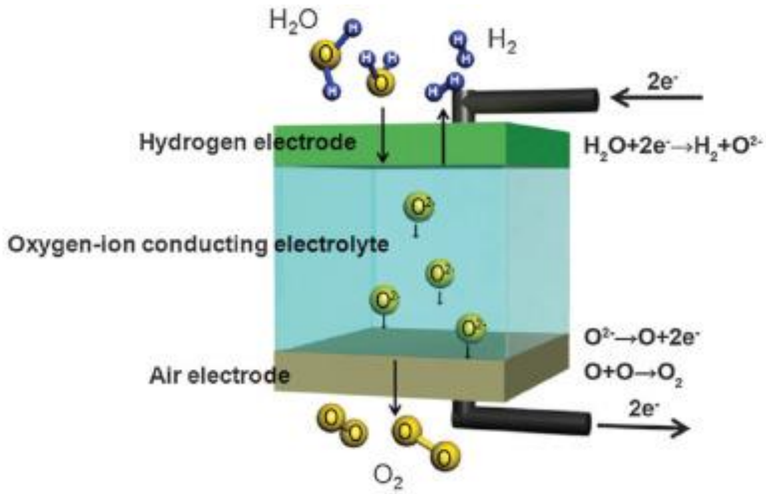

Figure 3: SOEC working principle

Source: Adapted from (Nechache & Hody, 2021).

Table 2: Characteristics of SOECs

Electrolyte	The SOEC uses a ceramic-metal compound as the electrolyte, enabling operation at significantly higher temperatures
Temperatures	The SOEC runs at high temperatures ranging from 650 to 1000°C.
Working Pressure	The SOEC's working pressure is normally kept below 1 MPa
Hydrogen Purity	The SOEC can achieve a hydrogen purity level of 99.9% or more.
Voltage Efficiency	The SOEC's voltage efficiency is less than 110, showing that the cell is effective at turning electrical energy into chemical energy during the electrolysis process.

Source: Adapted from (Samuel, 2021)

In 2022 Sunfire, one of the leading electrolysis manufacturers, installed the first world's multi-megawatt solid oxide electrolyser (SOEC) in the scope of the EU-funded demonstration project MultiPLHY to produce green hydrogen at Neste's renewable products refinery in Rotterdam. The electrolyser capacity is 2.6 MW and it is expected to produce 60 kg of H2 per hour. (Sunfire). This record has been broken with a 4MW solid oxide electrolyser cell (SOEC) system installed at NASA's Ames Research Center in California(Bloom Energy, 2023; IEA, 2023). The world's first industrial-scale solid oxide electrolyser facility with a yearly capacity of 500 MW is being constructed by Topsoe in Herning, Denmark. It is expected to be operational by 2025 with a production of 125,000 tons of green hydrogen per year (Topsoe, 2023). Recently, DENSO challenged itself to develop a solid oxide electrolyser cell (SOEC). “The aim is to create an MW-class system by packing a 40-ft container with small kW-class modules” (DENSO, 2023).

2.5. Methanol production

As mentioned earlier in the introduction, carbon dioxide (CO_2) is the main greenhouse responsible for global warming (Cooper et al., 2002). A way to mitigate CO_2 emissions to the atmosphere is the conversion of CO_2 into valuable products like methanol (Borisut & Nuchitprasittichai, 2019).

Traditionally, methanol is produced from carbon monoxide and hydrogen utilizing low-pressure methanol synthesis. Generally, this synthesis of gas can be obtained by using natural gas in steam-reforming, auto-thermal reforming and partial oxidation(Schorn et al., 2021). In contrast, e-methanol is acquired by using CO_2 captured from renewable sources (i.e., solar PV) direct air capture (DAC) and green hydrogen(IRENA, 2021).

Methanol is used in numerous items such as cosmetics, plastics, paints, and fuels. It also serves as an energy source in the marine, automotive, and electricity sectors Methanol Institute.

Technologies to produce methanol

According to (Mäyrä & Leiviskä, 2018), the existing technologies to produce methanol are:

• Gas-phase technologies

- Adiabatic reactors
- Isothermal reactors (for example, the Lurgi process)
- Gas-phase fluidized bed converter

• Liquid-phase technologies

- Membrane reactors
- One-step technologies

E-methanol Production Cost

(Sollai et al., 2023) conducted a study on the techno-economic assessment of renewable methanol production through CO2 hydrogenation and its successful implementation in Iceland. They found that the levelized cost of methanol was 1066 $/ton, which is twice the assumed market price of $500 /ton. Another study by (Bos et al., 2020) demonstrated the achievement of $888/ton of methanol using a combination of captured CO_2 from the atmosphere and green hydrogen with renewable energy sources. Meanwhile, (Schorn et al., 2021) demonstrated that renewable methanol could be imported for 400-$666 if the hydrogen production cost decreases to 1.5-$2.22/kg and CO_2 at $100/ton in the producing country. Notably, none of these studies considered putting together those technologies, PV, DAC, SOEC, Methanol synthesis reactor. Pérez-Fortes et al., (2016) assessed a methanol facility with an annual production capacity of 440,000 tons of methanol. The main cost of equipment in this plant is the compression system. They concluded that for the plant to be financially feasible, the current market price of methanol must double, or the cost of hydrogen needs to decrease by 2.5 times, or carbon dioxide should be sold at $244/ton.

Table 3: Estimated cost of e-methanol up to 2050

		Estimated costs in		
		2015-2018	2030	2050
Green hydrogen cost (USD/t H_2)		4000-8000	1800-3200	900-2000
Methanol through CO2 from combined renewable sources				
CO2 cost (USD/t CO2		10-50	15-70	20-150
Methanol cost (USD/t CO2)	With no carbon credit	820-1620	410-750	250-630
	With a credit of USD 50/t CO2	730-1540	320-660	160-550
	With a credit of USD 100/t CO2	640-1450	240-580	70-460
Methanol through CO2 from DAC only				
CO_2 cost from DAC (USD/t CO_2)		300-600	150-300	50-150
	With no carbon credit	1220-2380	600-1070	290-630

Methanol cost ($USD/t\ CO_2$)	With a credit of USD 50/t CO_2	1130-2300	510-980	200-550
	With a credit of USD 100/t CO_2	1040-2210	420-890	120-460

Source: Adapted from (IRENA, 2021)

From the Table 3, the cost of renewable methanol production is decreasing as the technology advances and becomes more economically viable. This slows down the reduction due to the factors such as carbon credit application and green hydrogen costs.

CHAPTER III: METHODOLOGY

This section consists of detail results of the literature review, cost modelling, levelized cost, cost-benefit analysis and sensitivity analysis.

3.1. Description of the research design

The methodology in this thesis is divided into five parts. First, a detailed literature review is undertaken to acquire existing knowledge on the technologies of direct air capture, solid oxide electrolyser, and methanol synthesis reactor, all of which are components of the DryHy technology.

The second part of the thesis methodology is cost modelling where Excel is used to simulate the production of methanol from green hydrogen and capture $C0_2$, with an annual output of 6,000 tons. Beforehand, all inputs, outputs and resources needed were identified and quantified using stoichiometric reaction. Still, in the second part of the thesis, capital expenditures (CAPEX) and operating expenditures (OPEX) are considered in the simulation to compare production costs for each option. In the third part of the methodology, the levelized cost is used to determine the cost of energy, water, carbon dioxide hydrogen and finally to compare the levelized cost of e-methanol produced using DryHy technology to the current methanol fossil-based market value in Europe. Cost-benefit analysis was used in the fourth part of the methodology to determine the economic feasibility of the technology. Lastly, the sensitivity analysis is used. As part of the sensitivity analysis, three different scenarios are created:

1. Scenario 1 represents the economies of scale, where the yearly methanol output is increased from 6,000 tons to 600,000 tons and Lower investment per unit of electrolyser capacity (from USD 1943/kW to USD 1304/kW) was considered.
2. Scenario 2 looks at discount rates of 6 and 10% to see how this financial parameter affects LCOM.
3. Scenario 3 takes into account the technological advancement by 2030, where the cost of PV+battery is reduced by about 60% and the cost of SOEC dropped from USD 1943/kW to USD 999/kW. Finally, the electrolyser stack is replaced only 3 times instead of 5 times.

3.2. Process description of DryHy Technology

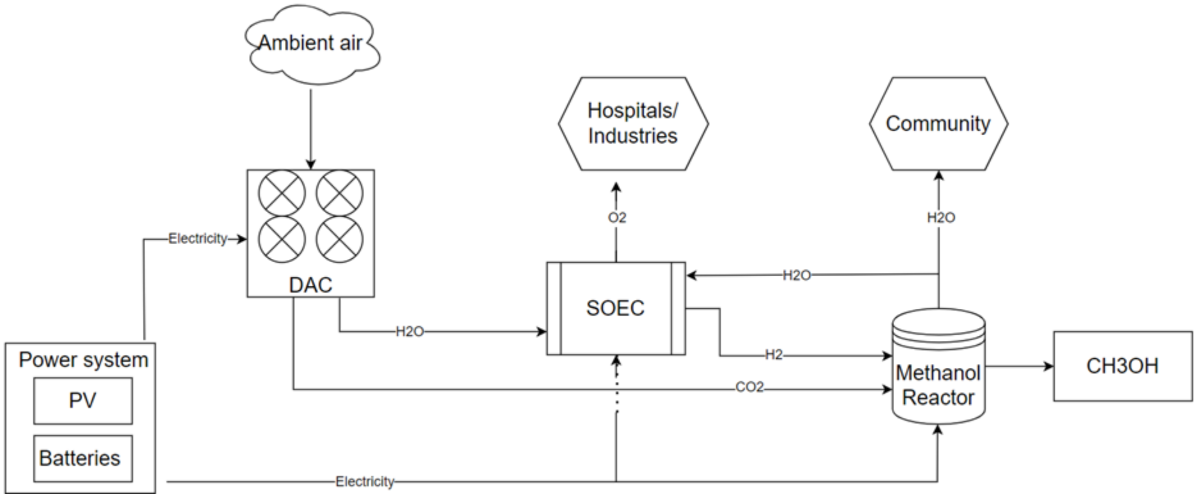

Figure 4: DryHy flowchart

Source: Own illustration

The technology working principle is the following:

- Solar PV panels harness the energy from the sun to generate electricity, which is then Utilized by the entire process, starting with direct air capture (DAC), passing by solid oxide electrolyser (SOEC) until the methanol synthesis reactor.
- DAC is a technology which extracts carbon dioxide (CO_2) from the atmosphere. The heat required for the DAC process is assumed to be supplied by a nearby natural gas power plant (not considered in this thesis).
- The water produced by the DAC is used as input for the electrolysis process in a solid oxide electrolyser (SOEC). This process splits the water into hydrogen and oxygen. The oxygen can be sold to various industries, hospitals, or other users, while the hydrogen is combined with the CO_2 captured by DAC to produce the methanol.

During the process of producing methanol, water is also obtained as a by-product.

It is noted that assuming a ratio of CO_2 to water 1:1, the water obtained from the DAC process is not enough for the overall process. Therefore, additional water needs to be purchased to ensure adequate production of methanol. Once the process is operational, the water released in the reactor can be fed back to the solid oxide electrolyser for further use. The remaining water which is not required for the process can be provided to the community, for agriculture purposes for instance.

3.3. Results of detailed literature review

3.3.1. Stochiometric analysis

The reactions described above could serve as a starting point for understanding the connection between Direct Air Capture, Solid Oxide Electrolyser Cells, and Methanol Synthesis.

Table 4: Reactions involved in the synthesis of CH3OH

No.	**Reaction**	**$\Delta_{rx}H_{298\ K}$ [kJ/mol]**
1	$\mathbf{CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O}$ (1)	− 49.51
2	$\mathbf{CO_2 + H_2 \leftrightarrow CO + H_2O}$ (2)	41.17
3	$\mathbf{CO + 2H_2 \leftrightarrow CH_3OH}$ (3)	− 90.68

The reactions described above could serve as a starting point for understanding the connection between Direct Air Capture, Solid Oxide Electrolyser Cells, and Methanol Synthesis.

The reaction (1) is the reaction of CO2 with hydrogen to produce methanol and water. It is followed by Reaction (2),the reverse reaction of the gas with water (RWGS), which consumes the same reactants but is unwanted in the process (the hydrogenation of CO_2 into CH_3OH). CO formation using RWGS opens up a new channel for methanol synthesis: CO hydrogenation Reaction (3). RWGS is endothermic, whereas Reactions (1) and (3) are exothermic.

Reaction (1) can be expressed in terms of the atomic masses of the involved atoms.

as $12 + 2 \times 16 + 3 \times 2 \leftrightarrow 12 + 3 + 16 + 1 + 2 + 16$ (g/mol)

or $44 + 6 \leftrightarrow 32 + 18$ (g/mol)

Where:

$M_{CH3OH} = 44g/mol$; $M_{H2} = 6g/mol$; $M_{CH3OH} =$ 32g/mol; $M_{H2O} =$ 18g/mol

From reaction (1) it can be seen that one molecule of CO_2 reacts with three molecules of H_2 to form one molecule of CH_3OH and one molecule of water.

The following relationships can be stated in dependence on the produced mass of methanol and the masses of matter involved in the process, respectively mH_2 for the mass of hydrogen, mCO_2 for the mass of carbon dioxide, and mH_2O for the mass of water.

$$\boldsymbol{m_{H2}} = \frac{M_{H2}}{M_{CH3OH}} \times \boldsymbol{m_{CH3OH}} \quad (4)$$

$$\boldsymbol{m_{CO2}} = \frac{M_{CO2}}{M_{CH3OH}} \times \boldsymbol{m_{CH3OH}} \quad (5)$$

$$\boldsymbol{m_{H2O}} = \frac{M_{H2O}}{M_{CH3OH}} \times \boldsymbol{m_{CH3OH}} \quad (6)$$

The masses of hydrogen and carbon dioxide needed the for production of 6,000 tons of methanol can be calculated using equations (4) and (5).

$$m_{H2} = \frac{6g/mol}{32g/mol} \times 6{,}000 \times 10^6\ g\ =\ 1{,}225\times 10^6 g = 1{,}125 \text{ tons}$$

$$m_{CO2} = \frac{44g/mol}{32g/mol} \times 6{,}000 \times 10^6\ g\ =\ 8{,}250\times 10^6\ g = 8{,}250 \text{ tons}$$

The mass of water produced by the reactor was calculated using equation (6):

$$m_{H2O} = \frac{18g/mol}{32g/mol} \times 6{,}000 \times 10^6\ g\ =\ 8250\times 10^6\ g = 3{,}375 \text{ tons}$$

The electrolyzer produces simultaneously the required hydrogen and an additional amount of oxygen, which is calculated based on the atomic masses of the reactants in the equation (7):

$$2H_2O \rightarrow 2H_2 + O_2 \quad (7)$$

2×2+2×16 →2×2+2×16

4+32→4+32 (g/mol)

Where:

$M_{H20} = $ 36g/mol; M_{H2} = 4g/mol and $M_{O2} = $ 32g/mol

The amount of water needed for the production of 1125 tons of hydrogen and the oxygen produced by the electrolyser can be calculated using equations (8) and (9):

$$\boldsymbol{m_{H2O}} = \frac{\boldsymbol{M_{H2O}}}{\boldsymbol{M_{H2}}} \times \boldsymbol{m_{H2}} \tag{8}$$

$m_{H2O} = \frac{36g/mol}{4g/mol} \times 1{,}125 \times 10^6 g \rightarrow m_{H2O}$ =10,125 tons

$$\boldsymbol{m_{O2}} = \frac{\boldsymbol{M_{O2}}}{\boldsymbol{M_{H2}}} \times \boldsymbol{m_{H2}} \tag{9}$$

$m_{O2} = \frac{32g/mol}{36g/mol} \times 1{,}125 \times 10^6 g \rightarrow m_{H2O}$ =9,000 tons

These calculations were based on the work of (Rufer, 2022).

The target of the thesis is to simulate a methanol plant with a capacity of 6,000 tons per year. According to the previous calculations, 8,250 tons of CO_2 and 1,125 tons of hydrogen are required to produce 6000 tons of methanol. In addition, 10,125 tons of water are required for hydrogen synthesis. According to (Schorn et al., 2021) during the CO_2 capture process, 0.8 to 2 tons of water are derived for each ton of CO_2. For this thesis, the carbon dioxide-to-water ratio is set to be 1:1, which indicates that there will be 8,250 tons of H_2O as well, which will not be adequate for the process, leaving a shortfall of 1,875 tons of water. To produce the required amount of water, at least 1.23 tons of water must be produced during the production of one ton of CO2.

To solve the water shortfall problem the following is proposed:

Additional water needs to be purchased to ensure adequate production of e-methanol. Once the process is operational, the water released in the reactor can be fed back to the solid oxide electrolyser for further use.

3.3.2. Assumptions for economic analysis

Table 5: Main economic assumptions

	Value	References
Plant operational years	20 years	(Terlouw et al., 2021)
Yearly operating hours	7884hours	(Sollai et al., 2023)
Discount rate	8%	(Sollai et al., 2023)
Exchange rate	July 2023	(*Euro to US Dollar Exchange Rate History For 12 July 2023 (12/07/23)*)

The Plant is projected to operate for 20 years, which aligns with the estimated lifetime of the technologies used in the DryHy project (Fasihi et al., 2019a; Gerloff, 2023; Sollai et al., 2023; Terlouw et al., 2021). However solar PV typically operate for more than 20 years(Huang, 2022; Sodhi et al., 2022).

The annual operating hour of the plant is assumed to be 7884h, which corresponds to a capacity factor of 0.9, the same thing as saying the plant is expected to work at 90% of its maximum capacity throughout the year.

According to (Sollai et al., 2023), a discount rate of 8% is typically applied to investments in the energy-intensive industry sector.

Finally, all costs are expressed in USD. An exchange rate of USD1.11 / € is assumed when the original value is in € (*Euro to US Dollar Exchange Rate History For 12 July 2023 (12/07/23)*, n.d.) , and USD 0.0017/XOF when the original value is in CFA Francs (Valuta Ex., July 2023).

3.3.3. Energy requirement

Table 6. Input, output and energy requirement for DryHy technology

	Technologies		
	DAC	**SOEC**	**MR**
Input	Energy, ambient air	Renewable electricity, water	Carbon dioxide, hydrogen
Output	Carbon dioxide, water	Hydrogen, Oxygen	Methanol
The energy required per ton	0.306 MWh (Jiang et al., 2023)	36.14 MWh (Mehmeti et al., 2018)	0.1544 MWh (Schorn et al., 2021)
Yearly energy demand per ton	2524.5 MWh	40657.5 MWh	926.67 MWh
Daily energy demand per ton	6.92 MWh	111.39 MWh	2.54 MWh
Total annual energy demand per ton	**44108.67 MWh**		
Total daily energy demand per ton	**120.85MWh**		

The Table 6 shows the inputs, outputs, and energy required, for Direct Air Capture (DAC), Solid Oxide Electrolyser Cell (SOEC), and the Methanol Reactor, three different technologies of the DryHy Project.

DAC technology extracts carbon dioxide and water by using energy and ambient air inputs. It requires 0.250 MWh (Fasihi et al., 2019a) of energy per ton of production, excluding heat. SOEC produces hydrogen and oxygen using renewable electricity and water. SOEC has the greatest energy share in the DryHy technology, with 36.14 MWh per ton of output (Mehmeti et al., 2018).

The Methanol reactor uses less energy than the rest of the system, roughly 0.1544 MWh per ton of methanol (Schorn et al., 2021), and it takes in carbon dioxide and hydrogen.

The total energy needed annually is calculated by multiplying the energy required per ton of output by the annual amount of methanol, carbon dioxide, and hydrogen set to be generated (6000ton, 8250ton, and 1125ton respectively).

The total energy required annually is divided by 365 to calculate the total energy per day.

Solar PV Capacity, Battery Sizing and Land Surface Calculations

Solar PV capacity was calculated using the equation (10).

$$\boldsymbol{P} = \frac{\boldsymbol{E_p \times E_s}}{\boldsymbol{H_A \times C \times K}} \tag{10}$$

Where E_P is the daily power generation in kWh; H_A is the total horizontal solar radiation in kWh/m^2; P is the installed PV capacity in kW; E_S is the irradiance under standard conditions, taking the constant 1 kW/m^2; C is the tilted surface radiation coefficient, generally taking the value of 1.05 to 1.15; and K is the comprehensive efficiency coefficient. K is affected by a variety of factors, including inverter efficiency, collector line loss, step-up transformer loss, light use rate, PV module surface pollution correction factor, etc. In general, the value of K is 75% to 85% (Huang et al., 2023).

For this study, the following values were assumed:

$E_p =$ 120.85 MWh

$E_S =$ 0.001 MW/m^2

$H_A =$ 0.00532 MW/m^2/day (*Global Solar Atlas*, n.d.)

C $=$ 1.15

K $=$ 85%

$$P = \frac{120.85 \times 0.001}{0.00532 \times 1.15 \times 0.85} = 23.24 \text{ MW}$$

Battery sizing

The general equation used to do battery sizing (Bhandari & Shah, 2021b), equation (11) was applied to calculate the size of the battery.

$$\textbf{Battery size } (\boldsymbol{kWh}) = \frac{\boldsymbol{E_{avg}}(\boldsymbol{kWh})\times \boldsymbol{Autonomous\ Days}}{(\boldsymbol{DOD}\times \boldsymbol{\eta_{sys}}} \tag{11}$$

Where:

E_{avg}= Daily average energy demand

Autonomy days- Number of days the battery has to supply power independently (1 day)

DOD – Depth of discharge of the battery (100% for lithium-ion battery) (Nizami et al., 2022)

η_{sys} – Overall battery system efficiency (80%) (Bhandari & Shah, 2021a)

The equation (11) is used to calculate the battery size in kWh for a specific application, based on the energy demand of the system and the desired autonomy days. The daily average energy demand is multiplied by the number of autonomous days and divided by the product of the depth of discharge and the overall battery system efficiency. This resulted in the required battery size in kWh.

Surface area for Solar PV plant

The surface area was calculated based on the Agua Caliente PV plant (Arizona) example (Rufer, 2022)

This plant has an area of 971 ha and produces an annual net output of 727 GWh. The annual production per ha of this real plant is then:

$$Y_{prod\_ha} = \frac{727GWh}{971ha} = 784MWh/ha$$

$$\text{Land surface } = \frac{43646.7\ MWh}{784\ MWh/ha} = 55.7 \text{ ha}$$

In this study, the cost of land was assumed by taking the average cost of four different places in the Ivory Coast.

3.3.4. Estimation of the land cost

Table 7: Land cost estimation

Location	Bingerville Adjin	Mondoukou	Bonoua	Yamoussoukro
Cost per hectare	USD 81,600.00	USD 15,657.89	USD 85,000.00	USD 25,500.00
Average cost/ha	$51,939.47			

Source: Adapted from (*Land for Sale in Ivory Coast*)

3.4. Cost modelling

Table 8: Solar PV breakdown costs

CAPEX			
Parameters	Unit cost (USD/kW)	Base case cost (USD)	References
PV system	600.00	13,796,884.95	(Nizami et al., 2022)
Battery	200.00	29,894,975.34	(Nizami et al., 2022)
Land use USD/ha	51,939.47	2,891,562.18	(*Land for Sale in Ivory Coast*)
Total CAPEX		46,583,422.48	
OPEX			
Parameters	Unit cost (USD/kW)	Actual cost (USD)	References
PV OPEX	9.00	206,953.27	(Nizami et al., 2022)
Battery OPEX	0.3	4,484.25	(Bhandari & Shah, 2021a)
Battery replacement	200.00	29,894,975.34	(Bhandari & Shah, 2021a; Nizami et al., 2022)
Insurance, local taxes and fees	1% of the CAPEX	465,834.22	(Collodi et al., 2017)

CAPEX represents the total cost of building the plant, while OPEX stands for the cost of running the plant (Rated Power, 2022). To obtain the total cost of the photovoltaic (PV) system and battery, the cost per unit of each was multiplied by their respective capacities. The cost of the land was calculated by multiplying the cost per hectare by the land area required for the PV system. The battery is expected to last for 10 years, therefore it will be replaced once during the lifetime of the project(Bhandari & Shah, 2021a).

Table 9: DAC breakdown costs

CAPEX		
Parameters	Cost per unit (USD/CO_2)	Base case cost (USD)
CAPEX	810	6,682,500.00
OPEX		
Land use cost	USD51,939.47/ha	72,845.11
OPEX	32.4	267,300.00
Insurance, local taxes and fees	1% of the CAPEX	66,825.00 (Collodi et al., 2017)

Source: Adapted from (Fasihi et al., 2019a)

CAPEX represents the total cost of building the plant, while OPEX stands for the cost of running the plant (Rated Power, 2022).

The last column of capital expenditure (CAPEX) and operational expenditure (OPEX) in Table 9 represents the Direct air capture (DAC) CAPEX and OPEX of the base case. The results were obtained by multiplying the unit costs of each parameter by the amount of carbon dioxide (CO2) needed, 8250 tons per year.

The lifespan of the DAC system is estimated to be for 20 years (Fasihi et al., 2019a).

Table 10: SOEC breakdown costs

Parameters	Value	Base case cost (USD)	Reference
SOEC Electrolyser	USD 1943/kW	9,874,690.31	(Gerloff, 2023)
Compressor	USD 0.09/kgH_2	101,250.00	(Peterson et al.,2020)
Land use cost	U SD51,939.47/ha	1,214.24	(Topsoe, 2023)
Total CAPEX		9,977,154.56	
OPEX			
compressor	3.2% of compressor	3,240	(Huang, 2022)
Insurance, local taxes, and fees	1% of the CAPEX	99,771.55	(Collodi et al., 2017)
Stack replacement	24% of the CAPEX	2,369,925.68	(Gerloff, 2023)

To obtain the overall cost of the electrolyser and compressor, their costs per unit were multiplied by the installed electrolyser capacity (5.16 MW) and the kilograms of hydrogen required (1125 tons/year) to produce 6,000 tons of methanol.

To ensure the adequate production of methanol during the first hour, the amount of missing water needs to be determined. This can be calculated by dividing the yearly missing water of 1875 tons by the yearly operating hour of 7884.

The electrolyser land use is estimated based on the ongoing construction of the industrial-scale SOEC facility with an annual capacity of 500MW, in Herning, Denmark. This facility occupies an area of 23,000 square meters(2.3ha) (Topsoe, 2023). Based on this information, the capacity of our electrolyser, which is 5.16 MW is multiplied by 2.3ha and divided by 500MW to get the surface area, which comes out to be 240m^2 (0.024ha).

According to (Gerloff, 2023), for the electrolyser to work at 8000h, the stack must be replaced five times throughout the course of a 20-year operational plant. The replacement cost is 24% of the electrolyser CAPEX. The stack will be replaced in years 4, 8, 12, 16 and 20, respectively. The operational hours in the thesis instance are 7884 hours per year, as mentioned above.

Table 11: Methanol breakdown costs

Parameters	Unit cost (USD/ton)	Base case cost (USD)
Feed compressor CO2	$108.76	$652,560.00
Feed Compressor H2	$38.13	$228,780.00
Reactor	$32.87	$197,220.00
Distillation	$8.08	$48,480.00
Total CAPEX		1,270,040.00
	OPEX	
Insurance, local taxes, and fees	1% of CAPEX	11,270.40 (Collodi et al., 2017)
Total OPEX		

Source: Adapted from (Bos et al., 2020).

The table represents the CAPEX and OPEX of the methanol synthesis reactor. Unit costs of the different parameters were multiplied by the annual amount of methanol needed in the base case (6,000 tons) to obtain the total costs.

Insurance, local taxes and fees were the only OPEX considered in this technology.

3.5. The Levelized Cost Calculation

For the calculation of levelized costs (LCO) of Solar PV, CO_2, H_2O, H_2, and methanol, the following inputs were used: CAPEX, OPEX, discount rate, Plant lifetime, Present Value of the OPEX and discounted production of each technology.

Plant lifetime is assumed to be 20 years and the discount rate is 8% as mentioned previously.

To obtain the present value of the future costs and production, the discount factor was considered for each year with a range from 92.59% to 21.45%. Finally, LCO is calculated by dividing the lifecycle cost by the lifecycle production.

- **Levelized Cost of Electricity**

$$\text{LCOE} = \frac{CAPEX + \sum_{t=1}^{T} \frac{OPEX}{(1+r)^t}}{\sum_{t=1}^{T} \frac{Energy\ produced}{(1+r)^t}}$$

The annuity present value factor was calculated as follows:

$$\text{PVF} = \sum_{t=1}^{T} \frac{1}{(1+i)^t}$$

Where:

T – Lifetime of the Project

i – Discount rate

The results of present value factor were multiplied by the OPEX.

- **Levelized cost of H_2O and CO_2**

The DAC system produces two outputs: water and carbon dioxide. The ratio of CO_2 to H_2O is set at 1:1, and the CAPEX and OPEX of the DAC are assumed to be divided equally to determine the levelized cost of H_2O and CO_2.

$$\text{LCOW} = \frac{50\%\ CAPEX_{DAC} + \sum_{t=1}^{T} \frac{OPEX}{(1+r)^t}}{\sum_{t=1}^{T} \frac{water\ produced}{(1+r)^t}}$$

$$\text{LCOCO}_2 = \frac{50\%\ CAPEX_{DAC} + \sum_{t=1}^{T} \frac{OPEX}{(1+r)^t}}{\sum_{t=1}^{T} \frac{CO2\ produced}{(1+r)^t}}$$

- **Levelized cost of Hydrogen**

$$\text{COH} = \frac{CAPEX + \sum_{t=1}^{T} \frac{OPEX}{(1+r)^t}}{\sum_{t=1}^{T} \frac{Hydrogen\ produced}{(1+r)^t}}$$

- **Levelized Cost of Methanol**

$$\text{LCOM} = \frac{CAPEX + \sum_{t=1}^{T} \frac{OPEX}{(1+r)^t}}{\sum_{t=1}^{T} \frac{Methanol\ produced}{(1+r)^t}}$$

The levelized cost of methanol was calculated by including the levelized costs of hydrogen and carbon dioxide in the OPEX.

3.6. Cost-Benefit Analysis

Cost-benefit analysis is used to assess the viability of producing e-methanol from green hydrogen and captured CO2.

The following table summarizes the Cost of the DryHy technology

Benefits of DryHy technology

Table 12: Economic benefit of the DryHy technology

Benefits type	Sale prices	Quantity	Benefits	References
Oxygen selling	$ 167.00	9,000tons	$ 1,503,000	(Sollai et al., 2023)
methanol selling	$ 438.45	6,000tons	$ 2,630,700.00	(Methanex, 2023)

To obtain the benefit of the DryHy technology, the price for selling methanol and oxygen was fixed.

To obtain the benefit of selling methanol, $438.45 is multiplied amount of methanol produced (6,000 tons/year) and for the oxygen, $167 is multiplied by 9000 tons of oxygen.

The net present value (NPV) metric is used for the cost-benefit analysis determination, where the time value of money is adjusted for 20 years and the total cost is subtracted from the total benefits.

NPV = ∑ Present Value of Future Benefits – ∑ Present Value of Future Costs

Sources of the revenue

The main sources of revenue in DRYHY technology are the sale of methanol produced and the sale of by-product oxygen. The price of methanol will be assumed to be equal to the market current price of methanol in Europe, which is about $438.45/ton (Methanex, 2023). The oxygen can be compressed and stocked in cylinders and sold at a market value of $167/ton. This price represents the typical value for industrial oxygen in volumes without storage and transport (Sollai et al., 2023).

Two additional sources of revenue were not monetized in this study. The first is the potential revenue from renewable energy projects, specifically the installation of PV (photovoltaic) systems that contribute to greenhouse gas emissions reduction. Renewable projects could benefit from government incentives and carbon credit. It was not monetized because, on the Ivry Coast, there is no policy related to incentives and carbon credits.

The second is direct air capture, which can also help in reducing greenhouse gas emissions and accelerate the transition. One possibility is to sell the carbon removed through direct air capture in the voluntary carbon market, which is self-regulated by non-governmental entities (IEA, 2023).

Socioeconomic benefit

A solar PV plant can help expand energy access. Energy access brings several socio-economic benefits.

Access to electricity enables improved communication through mobile phone charging, subsequently promoting economic transactions and fostering rural market development. Moreover, the availability of better lighting in homes and schools contributes to the advancement of education and skills-building. Additionally, energy access plays a significant role in enhancing healthcare by providing cold storage for medicines and enabling the use of electricity-dependent medical equipment (*Renewable Energy Benefits Leveraging Local Capacity for Solar PV*, 2017). Furthermore, access to electricity decreases or prevents theft or assault, thereby increasing community safety.

Another benefit is the excess water which will be given to the community for the Excess water will be given to the community for agricultural purposes.

Remember that all the value chains of the DRYHY technology (PV, DAC, SOEC, and MR) require a certain number of workers to be operated. This can lead to local job opportunities. Finally, the realization of this project can motivate the opening of new industries, thus boosting the local economy.

3.7. Sensitivity Analysis

As part of the sensitivity analysis, three different scenarios are created to see the influence of economies of scale, discount rate and CAPEX of the PV+battery and SOEC CAPEX.

- **Scenario 1**

In this scenario two things will be considered:

- The yearly methanol output will be increased from 6,000 tons to 600,000 tons, consequently, CO_2 captured and Water derived from DAC needed will be 825,000 and 112,500 tons per year respectively.
- Lower investment per unit of electrolyser capacity.

  (Gerloff, 2023), states that the cost of an electrolyser with a capacity of up to 100MW is USD 1304/kW.

  Apart from the volume of production, the only change in this scenario is about electrolyser.

- **Scenario 2**

This scenario will look at discount rates of 6 and 10% to see how this financial parameter affects the price at which methanol must be sold for the project to break even. These discount rates will be applied to the Base case and scenario 1 and their results will be compared.

In this scenario, no inputs change compared to the base case, apart from changing the discount rate all other parameters remain unchanged.

- **Future scenario**

This scenario will be built to forecast the levelized cost of methanol by the year 2030 as the overall cost of PV system is expected to drop by 50% by this year, and the cost of solid oxide electrolyser cell (SOEC) with a capacity up to 100MW, operating 8000 hours over a lifetime of 20 years, is expected also to decrease from USD 1943 to USD 999/kW. The stacks are expected to be replaced only three times (Gerloff, 2023).

CHAPTER IV: RESULTS AND DISCUSSION

The primary cost drivers for DryHy technology, LCOM, Investment Profitability, and Sensitivity Analysis are presented and discussed in this chapter.

4.1. Cost drivers

To identify the area where the efficiency losses could impact the final cost of e-methanol, the cost of all technologies included in the DryHY project will be broken down.

- **Solar PV technology**

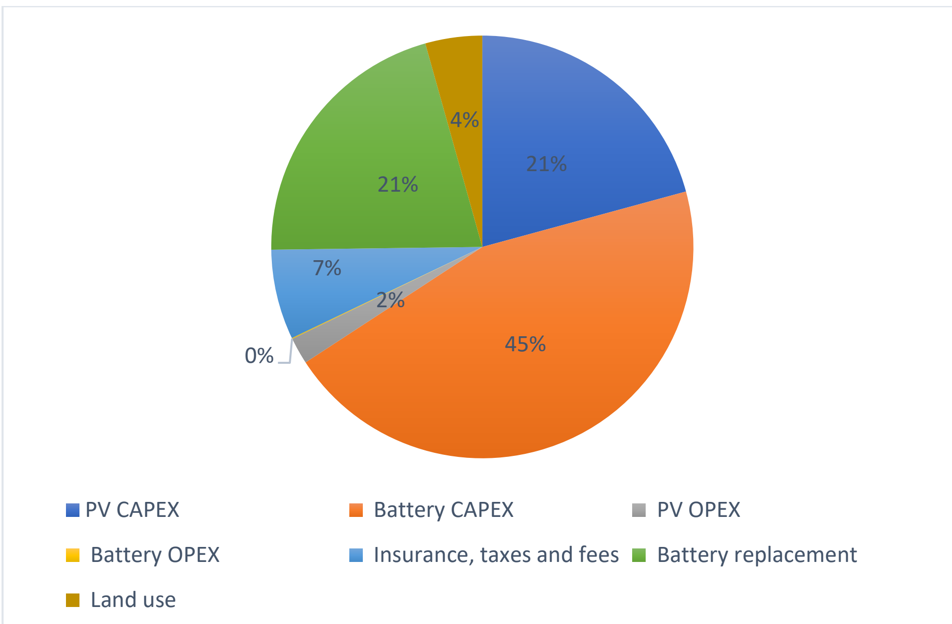

Figure 5: Solar PV breakdown cost

From the Figure 5, it can be seen that the parameter with the greatest influence on the overall cost of the PV + battery system is the battery, representing 66% of the net present value (NPV) breakdown, including its replacement. The second most significant expense is the initial investment in photovoltaic (PV) systems, accounting for 21%. Costs associated with insurance, taxes and local fees represent 7% while operating maintenance and land use costs each contribute 4% and 2% respectively. The smallest cost expense within the system is attributed to battery maintenance, having less than 1% of the NPV.

- **DAC technology**

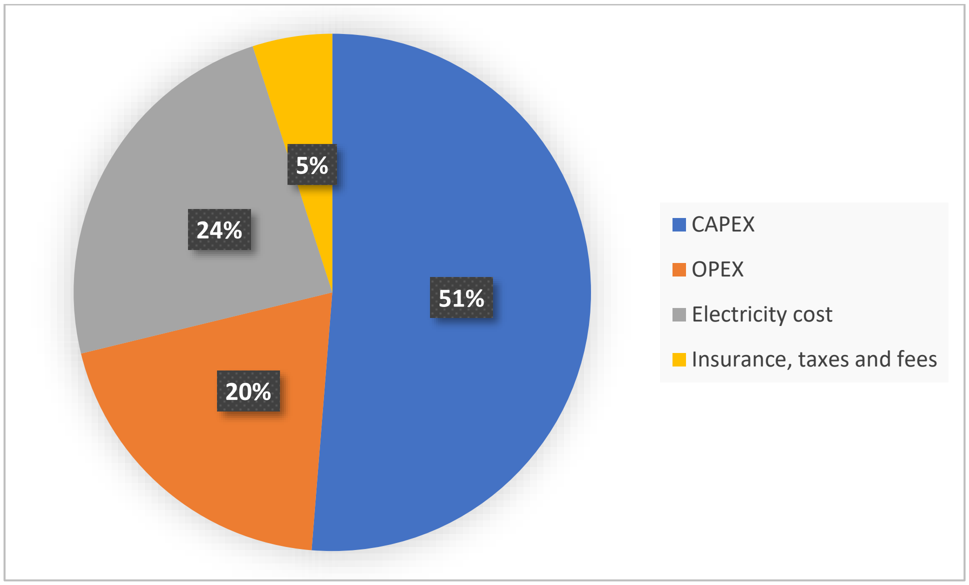

Figure 6: DAC breakdown cost

The results from the Figure 6 show that the main cost component in direct air capture (DAC) technology is CAPEX, which accounts for more than 50% of the net present value (NPV). OPEX, excluding electricity, insurance, taxes and fees, makes up approximately 20%. Taking those components into consideration, OPEX makes up around 49%.

- **SOEC technology**

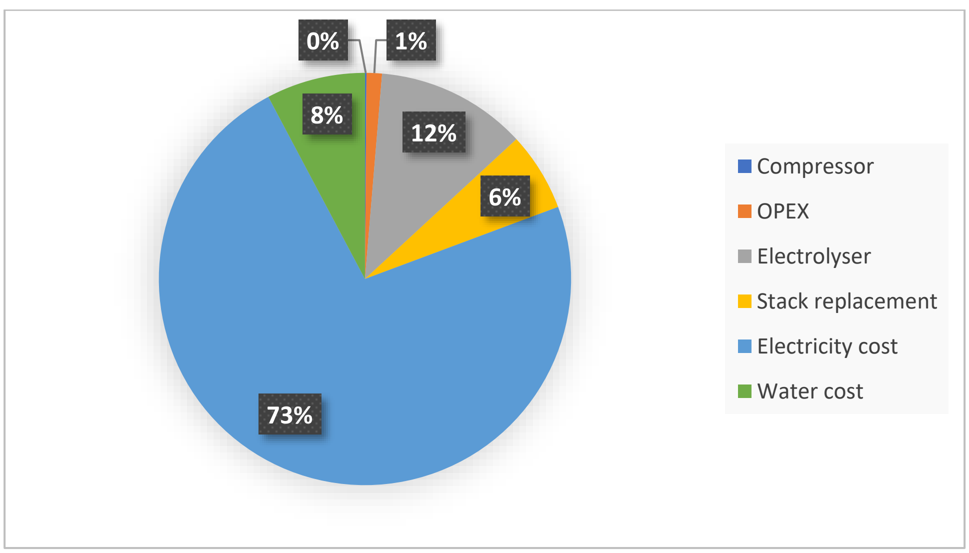

Figure 7: SOEC breakdown cost

From the Figure 7, it is possible to see that in the production of green hydrogen, electricity represents the main cost, having around 73% of the expenses, followed by electrolyser with 12%. Replacement of the electrolyser stack makes up 6%.

Water comprises 8% of the SOEC net present value. The value is significantly high because its source is from the DAC. The levelized cost of water from the DAC is not comparable with the price of potable water.

- **Methanol Reactor Technology**

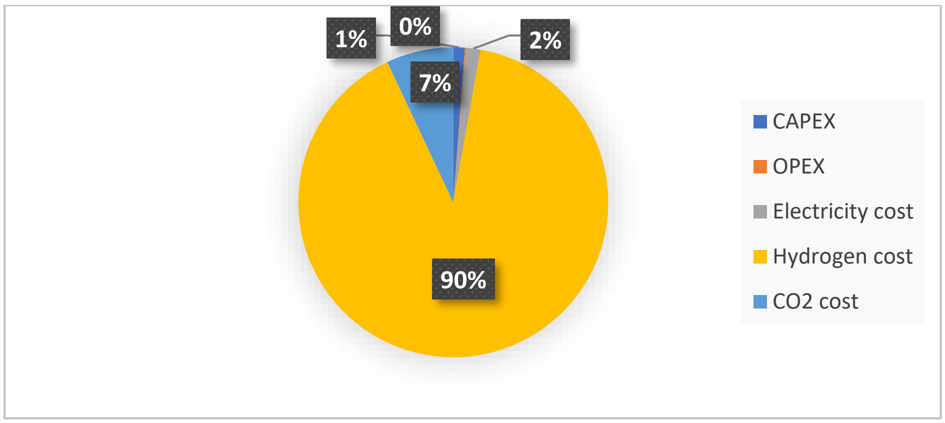

Figure 8: E-methanol breakdown cost

The Figure 8 shows that the cost of e-methanol production is dominated by the OPEX, being green hydrogen as the largest cost component with 90% of the total cost of the 20 years of the project. CAPEX represents only 7% of the net present value of this technology.

Now that is clear that hydrogen is the major cost driver in the system, it is worth going back and seeing what the parameters behind this scenario are.

Looking at the Figure 7, is visible that the responsible for high hydrogen cost is renewable electricity and electrolyser. The reason behind the high levelized cost of electricity in the production of green hydrogen is the CAPEX of PV+ battery.

To improve the cost efficiency of the system it will be necessary to look at the following areas: CAPEX of the PV+ battery, solid oxide electrolyser (SOEC) and direct air capture CAPEX.

SOEC is a new technology that is still in the preliminary commercialization stage, meaning that is not as mature as a PEM electrolyser or Alkaline electrolyser. At this stage, it is normal that there is a high level of inefficiency, which makes it so expensive. Over time the technology gains experience and becomes more efficient and as a result, the cost of e-methanol will be more efficient as well.

4.2. Levelized costs

Levelized costs of the different technologies were calculated based on this subsection.

Table 13: Levelized costs in USD/ton from this study

LCOE	LCOW	$LCOCO_2$	LCOH	LCOM
USD 154.96/MWh	USD 81.3/ton	USD 81.3/ton	USD 7.680/kg	USD 1596.77/ton

From the Table 13, it can be seen, that the levelized cost of e-methanol (LCOM) is found to be USD 1596.77/ton, a cost which is three times higher than the current methanol market value in Europe.

Table 14: LCOM findings from the literature

LCOM	USD 888/ton	USD 1066/ton	USD2430/ton
References	(Bos et al., 2020)	(Sollai et al., 2023)	(González-Garay et al., 2019)

The findings of earlier studies mentioned in Table 14 indicate that the costs are approximately 2 to 6 times higher than the current value of methanol, which is USD 438.35/ton in the European market (Methanex, 2023).

It could be concluded that e-methanol produced from green hydrogen and captured CO_2 is still not competitive with the traditional one.

Viktorsson et al. (2017) conducted a study in which they determined that the Levelized Cost of Hydrogen (LCOH) for a hydrogen refuelling station (HRS) using an alkaline electrolyser, powered by grid electricity, was 13.9 €/kg or USD 15.43/kg. They took into account a system lifetime of 20 years as well. and included the costs of storage. There is a large difference compared to the LCOH calculated in this thesis, which could be attributed to assumptions made. For instance, the thesis case did not consider the cost of hydrogen storage tank. Another hydrogen refuelling station (HRS) was designed using alkaline electrolyser powered by on-grid PV to supply taxi under the different scenarios. It was concluded that the cost of green hydrogen varies depending on the size of the HRS, with larger stations costing USD 8.96/kg, and smaller ones costing USD 13.55/kg (Bhandari & Shah, 2021b; Micena et al., 2020). The levelized cost of green hydrogen (LCOH) ranges between USD 3.2/kg and USD 7.7/kg (IEA, 2022). The base case LCOH calculated in this thesis falls into the range of LCOH estimated by IEA.

The levelized cost of Direct air capture was calculated by Fasihi et al. (2019) by considering two scenarios: utilisation of free waste heat and non-utilisation of free waste heat. The LCOD with free waste heat was USD 148/t CO_2 and LCOD without free waste heat was USD 246/t CO_2. The LCOD from our study (LCOW+LCOCO_2) is USD 163/t CO_2, value which is closer to the scenarios with free waste heat.

LCOE was not compared due to the lack of study where DAC, SOEC and methanol reactor were combined and their individual energy consumption was taken into account.

4.3. Cost-benefit analysis

The total present value of future costs corresponds to USD 94,064,167.53, and the total present value of future benefits is equal to USD 40,579,385.05.

NPV = ∑ Present Value of Future Benefits – ∑ Present Value of Future Costs

NPV = USD 40,579,385.05– USD 94,064,167.53

NPV = – USD 53,484,782.48

Potential percentage loss = (53,484,782.48/ 94,064,167.53) × 100%

Potential percentage loss = 56.86%

The project registered a negative net present value of USD 53,484,782.48. This number tells us that, at least for now, the production of methanol from green hydrogen and CO_2 captured is not profitable when it is sold at the current market price.

If 6,000 tons of methanol are produced annually, even after selling the extra benefit of oxygen, there will be an efficiency loss of 56.86%.

It concluded that from an economic point of view such as project should not be undertaken.

4.4. Sensitivity analysis

To deal with the inefficiency in NPV we will adjust the discount rate increase the volume of production and change the CAPEX of the PV battery and electrolyser in the sensitivity analysis.

Scenario 1

The annual production of 600,000tons of methanol resulted in the following changes:

- The levelized cost of electricity remains quite the same, from USD 154.96 /MWh to / USD 154.85 MWh.
- The LCOCO2 and LCOW remain unchanged.
- The LCOH dropped from 7.659 /kg to USD 6.602 /kg
- The LCOM declined from USD 1592.78/ton to USD 1,394.67 /ton.

It can be said that increasing production volume and decreasing electrolyser cost per unit did not cause changes in the levelized cost of electricity, water and carbon respectively. On the other hand, there was a decrease in the levelized cost of hydrogen and methanol. The levelized cost of hydrogen fell by 13.8% and consequently, there was a 12.44% decrease in the levelized cost of methanol.

It is visible that economies of scale can help the production of e-methanol to become more efficient.

Scenario 2

In the second scenario, a discount rate of 6 and 10% was applied in the annual production of 6000 tons to analyze the impact of the discount rate on the LCOM.

The following results were obtained, after applying 6 and 10% discount rates to the base case.

Table 15: Influence of discount rate on levelized costs

Discount rate	6%	10%	Unit
LCOE	140.33	170.32	$/MWh
LCOCO2	70.5	89.63	$/ton
LCOW	70.5	89.63	$/ton
LCOH	6,976.5	8,422.9	$/ton
LCOM	1,449	1,752.8	$/ton

The Levelized LCOE at a discount rate of 6% is found to be USD 140.33/MWh, while the $LCOCO_2$ and LCOW are USD 70.5/ton. The LCOH and LCOM are USD 6,976.5/ton and USD1,449/ton respectively.

At a discount rate of 10%, the LCOE is around USD 170.32/MWh. The LCOCO2 and LCOW are both USD 89.63/ton. The LCOH and LCOM are USD 8,422.9/ton and USD 1752.8/ton respectively.

Comparing the results of the 6% discount rate with the base case, it is possible to observe that the LCOE dropped by 9%. The LCOCO2 and LCOW by 10%. Finally, the LCOH and LCOM fell by 9%.

When the base case is compared to the scenario with a 10% discount rate, the following is found: All levelized costs have registered a 10% increase.

Assuming that the discount rate of the project is 6%, the LCOM will drop from USD 1596.77/ton to USD1,449/ton. In case the project discount rate is 10%, the LCOM will rise from USD 1752.8/ton to USD 1596.77/ton.

The most favourable situation for the financial sustainability of the project is the one with the lowest discount rate, but to achieve it, the level of financial stability must be high, there should be long-term planning and the project should present lower risks.

Future scenario

The future scenario is developed to forecast the economic viability of the e-methanol production from green hydrogen and CO_2 captured by 2030.

Table 16. Levelized costs of the future scenario

Levelized costs	Future scenario	Unit
LCOE	66.49	$/MWh
LCOCO2	70.3	$/ton
LCOW	70.3	$/ton
LCOH	3,606.8	$/ton
LCOM	804.16	$/ton

The table summarizes the projected levelized costs for the future scenario, where the LCOM is 804.16 /ton, a value which is still high when compared to the current value of methanol in the European market. From USD 1596.77/ton to USD 804.16/ton is a great improvement but not enough yet to be economically competitive.

- **NPV of the future scenario**

With the change in certain parameters contributing to the efficiency losses, the following result was obtained:

NPV = ∑ Present Value of Future Benefits – ∑ Present Value of Future Costs
NPV = 40,579,385.05 – USD 47,372,309.25
NPV = – USD 6,792,924.20

Under this scenario, the net present value of the project is – USD 6,792,924.20, representing 14.34% of the loss. From a financial perspective, the project should not be pursued, otherwise, it will run into losses.

The constant negative net present value in all the scenarios is due to the high initial cost required to start the DryHy project, such as CAPEX of PV+battery, SOEC and its stack replacement. These aspects result in expensive green hydrogen and subsequently, the cost of e-methanol becomes less efficient. Another thing that may influence this negative NPV is the discount rate.

The changes in the cost of Photovoltaic, battery storage, and solid oxide electrolysers will not be enough to make e-methanol produced from green hydrogen and captured carbon competitive until 2030, even considering the additional sale of oxygen.

For e-methanol produced by using green hydrogen and captured carbon to be competitive, more advancement in technology will be needed. There should be a policy support and incentive for this novel technology. One concrete example is in the Figure 5, where the cost associated with insurance, taxes, local fees and land represent together around 11% of the net present value of the Photovoltaic (PV) system. These factors could create obstacles for investors. If the government decide to reduce or exempt the cost related to those components, it could significantly decrease the initial investment in the technology.

Another aspect that could also help in saving costs is the carbon tax. If the carbon tax was a reality in the Ivory Coast as in South Africa(Walker, 2023), it would certainly contribute to the project being more efficient.

In short, it can be said that the joint effort between Industries, scientific communities, university institutions, governments and other relevant stakeholders could help to accelerate the development of the technology and make it more efficient.

4.5. Implications of the results

Field of research

The results of this thesis can help researchers understand better the current level of cost efficiency in the production of renewable methanol from green hydrogen and captured CO_2 and point out areas that still require development and improvement. One can use the information of this study to explore a new way to improve cost efficiency.

Society

Once there is an improvement on the areas highlighted previously, the cost efficiency will increase. Increasing the cost efficiency could result in a switch from fossil methanol to e-methanol. The adoption of e-methanol will subsequently contribute to the decarbonization of the many sectors such as industry and transportation. This latter results in a cleaner and more sustainable society. Another advantage of using e-methanol as a fuel is that it can reduce dependence on fossil fuels and improve energy security.

Economy

- E-methanol can become more economically competitive than traditional fossil fuel-based methanol if its cost efficiency is improved. This can make it an attractive option for investors.
- It can stimulate a local economic growth by creating a new job opportunity in the sectors of chemical and renewables.
- Lastly, improving e-methanol cost efficiency can help countries reduce or stop relying on market oil prices, thus making their economies less vulnerable.

CHAPTER V: CONCLUSION, LIMITATIONS AND RECOMMENDATIONS

This chapter presents the conclusion of the study, the limitations faced in the present work and the recommendations considered pertinent for future studies.

5.1. Conclusion

The characterization of efficiency losses and their possible impacts on the cost competitiveness of e-methanol from green hydrogen and captured CO_2 was investigated in this study.

E-methanol production has been modelled, and it has been shown that efficiency losses have an impact on the cost competitiveness of the methanol produced using this technology. The results of different LCOM ranges between USD 804.16/ton to USD 1576.77/ton, a value which is 2 to 4 times higher than the current methanol value in the European market, and all the scenarios registered a negative net present value, with a percentage loss ranges between 14.34% to 60.70%. Being the future scenario the best among them.

High capital costs for the necessary equipment and infrastructure for solar photovoltaics systems, high electricity costs for the electrolysis of water to produce green hydrogen and high costs associated with solid oxide electrolyser cells and direct air capture CAPEX were identified as the potential key factors that create inefficiency and pointed out as areas for further improvements. solid oxide electrolyser cell is the area with the greatest opportunity to reduce costs due to its immaturity stage. Furthermore, the efficiency losses make the production of e-methanol from green hydrogen and captured CO_2 non-profitable and far away from competing with methanol-based fossil fuels even when considering the extra benefit of selling oxygen. The negative return on investment can lead to reduced investment in the technology. Finally, to improve the cost efficiency and make e-methanol competitive, more technological advancements, policies that stimulate investment, subsidies from the government and private institutions, production on a large scale, collaboration among stakeholders and minimization of risks associated with the project are required.

5.2. Limitations

Throughout this study, some limitations were faced. One of the main limitations is associated with the fact this study is essentially based on secondary data, rather than primary data. When this is the case, the reliability of the results obtained can be questioned.

From the collected data, it was not easy to unravel the parameters taken into account within the CAPEX and OPEX of the different technologies.

Two possible sources of revenue and cost saving, carbon dioxide and renewable projects were not monetized due to a lack of government incentive for the renewable project and Carbon tax in the Ivory Coast. Likewise, it was not possible to monetize the socioeconomic and environmental benefits.

Finally, the study was conducted within a short timeframe, which did not allow modelling the production in Python using Monte Carlo Simulation for uncertainty analysis instead of building scenarios using Excel.

5.3. Recommendations

As recommendations for the future studies on the same topic, the importance of carrying out the study for enough time that allow to collect the detailed data for all technologies as much as possible is highlighted. Any cost or benefit left out may be crucial for the results of the study. As the study deals with novel technology and coupled with the fact that the topic is very sensitive, it would be great to have the data coming from industry or at least have an interview with industry professionals and scientists working on the DryHy project as proposed in the expose. The data come from industry and interviews suggested could provide a deeper understanding of the technology and could allow for more credible results.

Future studies should consider simulating methanol production using only photovoltaics (PV) and PV + battery storage to verify which option would be more cost-efficient.

An effort to include the monetization of external costs, and socioeconomic and environmental benefits should be made. If possible, the researcher could go to the supposed country where the project is planned to be implemented to obtain some pertinent data that were assumed in such a sensible way in this thesis.

Finally, next studies should focus on improving cost efficiency on the following areas: CAPEX of the PV+ battery, solid oxide electrolyser (SOEC) and direct air capture CAPEX.

DECLARATION OF AUTHORSHIP

I, ***Divaldino MENDES***,

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

I do solemnly swear that:

1. Where I have consulted the published work of others or myself, this is always clearly attributed.
2. Where I have quoted from the work of others or myself, the source is always given. This thesis is entirely my work, except for such quotations.
3. I have acknowledged all major sources of assistance.
4. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.
5. None of this work has been published before submission.
6. During the preparation of this work, I used *QuillBot* to paraphrase and improve the writing in certain parts of the thesis. After using this tool, I reviewed and edited the content as needed and took full responsibility for the content.

Date: August 24th, 2023.   Signature: **Divaldino MENDES**

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