Université Cheikh Anta Diop de Dakar

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INTERNATIONAL MASTER PROGRAMME IN ENERGY AND GREEN HYDROGEN (IMP-EGH)

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MASTER THESIS

Speciality : Economics/Policies/Infrastructures and Green Hydrogen Technology

Topic :

Start-up management and measures to reduce losses in value creation

Presented the 24/08/2023 by :

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DEDICATION

I dedicate this work to my father and my mother.

DECLARATION OF AUTHORSHIP

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

I do solemnly swear that:

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

Date: 14/09/2023 Signature:

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ABSTRACT

Climate change's impact on water security in arid regions is evident through rising temperatures. The root cause, increased carbon dioxide levels in the atmosphere, necessitates urgent reduction of anthropogenic emissions from industrial and transport sectors. E-methanol emerges as a promising solution due to its compatibility with existing infrastructure and to it carbon-negativity. This study aims to propose a sustainable business model and a comprehensive analysis of the losses in the value creation of a e-methanol power plant in cote ivoire. To achive that, a case study method supported by the triple layered business model canvas and the levelised cost were used for four differents scenarios : Scenario 1 using an alkaline electrolyser, Scenario 2 employing an alkaline electrolyser and batteries, Scenario 3 utilising polymer membrane electrolyser (PME), and Scenario 4 using Solid Oxide Electrolyse SOE electrolyser. These scenarios were constituted base on the eclectrolyser type and storage option. by incorporating data from the literature review. The results of this work showed that the success sustainable business model depend on the government partnering . Scenario 1 had the lowest Levelised cost of methanol (LCOM) at $812/t due to the low cost of the alkaline electrolyser. The highest LCOM of $1797/t was observed in Scenario 2, where battery storage was incorporated. Among different electrolyser types, Scenario 4, which used SOE electrolyser, had the highest LCOM at $1206/t. Furthermore, the sensitivity analysis show it is possible to have an optimal LCOM at $612/t by reducing the taxes at 75% and scaling up the plant to 1500ton of methanol per year.

Key words: E-methanol, e-fuel, hydrogen electrolyser, business model, levelise cost, Cote d'Ivoire.

RESUME

L'impact du changement climatique sur la sécurité de l'eau dans les régions arides est évident à travers la hausse des températures. La cause profonde, l'augmentation des niveaux de dioxyde de carbone dans l'atmosphère, nécessite une réduction urgente des émissions anthropiques des secteurs industriel et des transports. Le e-méthanol apparaît comme une solution prometteuse en raison de sa compatibilité avec les infrastructures existantes et de son bilan carbone négatif. Cette étude vise à proposer un modèle économique durable et une analyse complète des pertes dans la création de valeur d' une usine de production de e-méthanol en Côte d'Ivoire. Pour y parvenir , une méthode d'étude de cas soutenue par le triple couches de « business model canevas » et le coût actualisé ete utilisés pour quatre scénarios différents : Scénario 1 utilisant un électrolyseur alcalin, scénario 2 utilisant un électrolyseur alcalin et des batteries, scénario 3 utilisant un polymer membrane électrolyseur (PME) et scénario 4 utilisant un solide oxide électrolyseur (SOE). Ces scénarios ont été constitués en fonction du type d'électrolyseur et de l'option de stockage. En intégrant les données de la revue de la littérature. Les résultats de ce travail ont montré que le succès du modèle économique durable dépend du partenariat gouvernemental . Le scénario 1 présente le coût actualisé le plus bas, à 812 $/t, en raison du faible coût de l'électrolyseur alcalin. Le coût actualisé le plus élevé de 1 797 $/t a été observé dans le scénario 2, dans lequel le stockage par batterie était intégré. Parmi les différents types d'électrolyseurs, le scénario 4, qui utilisait un électrolyseur SOE, avait le coût actualisé le plus élevé, à 1 206 $/t. En outre, l'analyse de sensibilité montre qu'il est possible d'avoir un coût actualisé optimal à 612 $/t en réduisant les taxes à 75 % et en augmentant la capacite de l'usine à 1 500 tonnes de méthanol par an.

Mots clés : E-méthanol, e-carburant, électrolyseur d'hydrogène, business model, nivellement des coûts, Côte d'Ivoire.

ACRONYMS AND ABBREVIATIONS

CAPEX : Capital expense

CO_2 : Carbon dioxid

$Cu/ZnO/Al_2O_3$: copper, zinc oxide, aluminum oxide

DAC : Direct Air Capture

DPM : Direct Policy Method

H2 : Hydrogen

IEA : International Energy Agency

IPCC : Intergovernmental Panel on Climate Change

KW : Kilowatt

LCOM : Levelised Cost of Methanol

LCA : Life Cycle Assessment

MW : Megawatt

MWh : Megawatt hour

NGO : Non-Governmental Organization

O2 : Oxygen

OPEX : Operational expenses

PEM : Proton Exchange Membrane

PV : Photovoltaic

PVGIS : Photovoltaic Geographical Information System

QSPM : Quantitative Strategy Planning Matrix

SWOP : Strength, Weakness, Opportunity, and Threat

SOE : Solid Oxid Electrolyser

TLBMC : Triple Layered Business Model Canvas

WASCAL : West African Science Service Center on Climate Change and Adapted Land Use

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INTRODUCTION

In recent decades our planet is facing climatic disturbances, floods and temperature increases, which are the direct effects of greenhouse gas emissions (IPCC, 2023). In arid and vulnerable regions, these effects are characterized by reduced rainfall, increased evaporation and limited water resources. Climate change is one of the most challenging environmental concerns for development because of its impact on water security, especially in arid and semi-arid regions (Stringer et al., 2021). The root cause of this issue is the increase of Carbone dioxide (CO_2) in the atmosphere. These anthropogenic emissions, largely coming from the industrial and transport sector, must be reduced to mitigate climate change. To achieve this goal, several alternatives have been considered for decarbonizing these sectors: electric cars, agro fuels, electro fuels (e-methanol) and many others. Among these alternatives, e-methanol stands out as one of the most promising options since it allows to utilise existing infrastructures and energy systems without requiring significant modification (Sankaran, 2023).

E-methanol is a liquid product easily obtainable from CO_2 and green hydrogen via a one-step catalytic process and produced through a Power-to-X technology (Irena, 2021).The production of e-methanol requires a substantial amount of renewable energy through the process of electrolysis for green hydrogen. This fuel is considered environmental friendly because its production process absorbs more carbon dioxide than it emits during its use. Every one ton of e-methanol used prevents emission of 2 tons of CO_2 (Mondal and Yadav, 2021). Therefore, when considering its entire life cycle, e-methanol has a negative carbon footprint. Compared to conventional fuels, renewable methanol reduces carbon dioxide emissions by up to 95%, reduces nitrogen oxide (NOx) emissions by up to 80%, and completely eliminates sulfur oxide (SOx) emissions and emissions of particulate matter (Rufer, 2022). The integration of e-methanol as one of the fuels in the energy transition has been a topic of significant discussion. Recently, Germany and Italy have successfully get an agreement to recognise synthetic fuels (e-methanol) as a zero-emission technology within the European union[1]. E-methanol emerges as a promising solution, garnering significant research interest. Previous investigations into e-methanol have primarily emphasized the CO_2 source, and neglecting the consideration of water sourcing. Rufer (2022) proposed an e-methanol design reliant on seawater, necessitating energy-intensive desalination and pumping. Meanwhile, Van-Dal and Bouallou (2013)

[1] https://europe.autonews.com/environmentemissions/eu-germany-reach-car-emissions-deal-includes-e-fuels

explored CO_2 hydrogenation from flue gas but did not specify the water source for electrolysis. Limited attention has been given to e-methanol processes combining water and CO_2 captured by Direct Air Capture (DAC). Bos et al. (2020) studied e-methanol production using DAC-captured water, their approach employed a PME electrolyser in a specific case. The particularity of this master thesis is to focus on e-methanol synthesis using DAC-derived water in a broader context, encompassing various scenarios of diverse electrolyser types. This study is especially advantageous in arid regions with ample renewable energy potential but limited water resources. In the Sahara and Sahel area, solar irradiance is at its highest, with daily average values reaching up to 300 W/m², as indicated by the SARAH-2.1 dataset (Neher et al., 2020). By employing this system, hydrogen and methanol can be produced in arid environments without creating water conflicts. This new technology not only reduces carbon emission and water conflict, but also plays a significant role in decreasing reliance on fossil fuel in transportation sector. Moreover, It will help create an international trade by promoting the export of e-fuels to countries committed to reducing their carbon footprint. Consequently, it contributes to economic growth while generating new jobs opportunities.

However, in order to fully harness the benefits of this innovative solution for fuel production in arid environments, it is crucial to effectively integrate it into the existing energy business. The establishment of a solid business model becomes imperative to ensure its economic, social and environmental viability. Therefore, the general objective of the master's thesis is to propose a suitable business model and a comprehensive analysis of the losses in the creation of value.

To develop this master's thesis, the different research questions were formulated:

- What is an appropriate business model for e-methanol production using the DAC technology?
- What efficiency losses in the value creation of e-methanol production using the DAC technology can be expected during the ramp-up phase?
- How can the identified efficiency losses be managed?
- What are the consequences of the mitigation of efficiency losses for the business model?

To address the research questions in this master's thesis, a case study method is used, supported by the Triple Layered Business Model Canvas (TLBMC) and the levelized cost. Our specific case study focus on the design of a methanol plant in Cote d'ivoire because it potential in primary energy source and relative humidity. Data were collected through a literature review.

This master's thesis is composed of three (3) chapters: the first chapter present a detailed literature review on DAC technology, business models and losses in the value chain. The second chapter explains the different methods and approaches used to address the research questions. Finally The third chapter presents the results and discussion.

CHAPTER 1: LITERATURE REVIEW

The transition towards sustainable energy solutions has gained significant interest for e-methanol as a substitute of fossil fuel . This emerging field not only addresses the need for cleaner energy alternatives but also presents opportunities for optimizing value chains and reducing losses. By analyzing some relevant articles, this literature review will explore various circular and sustainable business model, some business model case studies and different strategies for minimizing losses in the e-methanol value creation.

1.1.Sustainable and Circular Business Model

The business model framework has experienced significant advancement through the contribution of various research to refine the existing framework and accommodate the sustainability and circularity concept. Numerous studies have refined the Osterwalder model to incoporate innovation that can address the sustainability and the circularity concepts.

Osterwalder and Pigneur (2010) offered an flexible framework for designing a business model. This framework is composed of nine (9) elements, which describe how the company operate to capture value. These elements include customer segments, value propositions, channel, customer relationship, revenue streams, key resources, key activities, key partnerships, and cost structure. By effectively connecting these elements, the business can offer a unique value proposition that meet with the customer need, and optimize the cost structure. This tool has become the foundation for several circular and sustainable business model widely used today.
Scholtysik et al. (2023) conducted research on designing a circular business model. They identified 45 criteria, which influence the model's design and most of them could be assign to the 9 elements of the Osterwalder business model canvas. Only 17 criteria could not be directly be assigned, and these were grouped into five (5) new elements to complement the canvas. Their proposed framework is composed of 14 elements: 9 from Osterwader canvas and 5 newly introduced elements.
Lewandowski, (2016) developed a framework for designing business model for the circular economy. The original Osterwalder business model canvas was analysed to redefine its components in the context of circular economy. Two new components were added, which are indispensable for the circular economy: Take-back system, which involve the reverse logistic for taking back to product from the customer after use, and Adaptation factor, which deal with the organization capacity to shift toward circular economy.

Foxon et al. (2015) extended the Osterwalder original business model canvas by incorporating the social and environmental aspects. For that, the value proposition was divided into four (4) parts: Direct consumption, social value proposition, economic value proposition and ecological value proposition. The revenue stream was changed to the value stream, which is further divided into four (4) parts: fiscal, social, development and ecological. The developed framework was applied in two case studies: smart grid electricity distribution and district heat network. It facilitated decision-making for infrastructure investments and the achievement of environmental and social objectives.
Joyce and Paquin, (2016) propose the tree layer business model, which lies on the tree bottom lines approach. This innovative tool contributes to the design of a holistic and sustainable business model that take into account of economic value, environmental issue through the environmental life cycle assessment (LCA) and the social value through the stakeholder management. The tree layers business model is the extension of Osterwalder business model canvas by adding two (2) layers: environmental and social layer. Each of these additional layers contains nine (9) blocks where are some similarities with the Osterwalder's original archetype and some difference that was extrapoled in environment or social context. This new tool helps to evaluate and validate the existing business model. It can conceptualize a new model with a broad vision where we can identify an unexpected value. Despite its importance, this tool has some limits it cannot be used to assess a new technology.

Fichter and Tiemann, (2015) built a new framework to support the sustainability for business modeling. By analyzing the existing approach in the literature, the Osterwalder business model canvas has been modified. The customer's segment and the relationship have been combined to one element, which is customer, and two (2) elements have been added. The first element is business model vision, which define the future in the next five (5) years and depict the central value of the company. The second element that is competitor and relevant stakeholders focus on the strategy management for internal and external stakeholders. This framework is advantageous for teaching, business plan competition.

There is a convergence between the circular and sustainable business model. A circular model can be a specific strategy of a sustainable business model.

1.2.Case Studies

The application of these business model concepts is exemplified by various case studies:

Vaishnavi et al. (2023) designed a biofuel business model for a biofuel startup named Bioclaion, by using Osterwerder business model canvas. The resulting business model lies on pay-per-use to lower the entry barrier for certain categories of clients. Some potential sources of funding have been identified for the investment method. Environmental and social goal was assigned to the business model to make it more sustainable. Their long-term vision is to substitute all the fossil fuel in India by 2030. For the market survey, some customer was not aware about the pollution problem and most of them want to shift toward the sustainable fuel.

Similarly Mustika et al. (2017) proposed a business model and strategies aligned with the Indonesia government's policies for developing a palm oil company. The methods used to conduct this research were Osterwalder business model canvas BMC, SWOT and Quantitative Strategic Planning Matrix QSPM. Within the business model, the study identified two customer segments: domestic and international, fostering a co-creation relationship. The value proposition was centered around biodiesel and the key resources identified were human resources and raw materials. The key activities were the biodiesel production and the marketing while the value channel was shipping. Revenue is created by selling the biodiesel and the glycerol. The main cost is the factory operational cost: raw material, workers' salaries. The analysis conducted using SWOT and QSPM demonstrates that increasing of production led to lower cost.

Beside the biofuel case others studies have been conducted Xu et al. (2023) did the Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis of the current state of the china grid company. The analysis revealed several findings: high grid management cost, lower electricity price, fewer customers and many other opportunities. Based on these results the authors formulated four (4) business strategies that require the integration of green hydrogen into their business model. To implement these strategies, a business model energy (as a service) is designed for the company, where hydrogen is part of the created value. The hydrogen produced by the excess of electricity is sold as raw material to the end consumer.

Additionaly Riester et al. (2022) used direct policy method (DPM) to analyses the hydrogen opportunity in different segment of market. The study identified grid service, refinery and power to liquid as the most attractive segment. The authors found that among the four (4) segments, power to liquid stand out as the most suitable for solid oxide electrolyser because its functionality for co-electrolysis which is beneficial for methanol and ammonia production in high efficiency. Base on this outcome, a business model for methanol an ammonia production using solid oxide electrolyser was designed. The business model follows a bottom-up – approach and is characterized by high capex because of maturity level of SOE.

1.3. Methanol value optimisation

Efforts to optimize methanol value creation have been explored through technical innovations: Lacerda De Oliveira Campos et al. (2022) demonstrated how the addition of two (2) intermediate condensation units between the reaction step can be beneficial for the methanol synthesis. It can boost the carbon dioxide single pass conversion from 28.5% to 53.9%, while simultaneously reducing reactant losses and compression work. Despite of the additional unit of condensation, the investment cost is reduced by 22.7% by minimizing the size of the main equipment and increasing the reaction rate.

In the similar manner Bos et al. (2020) explored a study of methanol production from wind power, water electrolysis and DAC. It is one of the few study that focus on the DAC for co-capturing water and carbon dioxide. In this process it was demonstrated that the heat generated during the electrolysis process can fulfil the heat demand needed for the CO_2 desorption. Moreover, this energy optimization and sorbent mass reduction can significantly improve the cost efficiency of methanol production. The resulting levelized cost of methanol is 800 e/t and the energy efficiency of the plant is around 50%.

In the same way Kotowicz and Brzęczek, (2021) proposed three methods to increase the electro-methanol production efficiency: the CO_2 compression on the side of the Carbon Capture Storage (CCS), the replacement of the throttle valve with an expander, and the replacement of the heat exchanger with an organic Rankine cycle ORC for co-generation of electricity. The installation for the methanol synthesis was complemented by 8 MW of wind farm, 2MW of photovoltaic, and a water electrolyser. The CO_2 is provided by a separate CCS plant. The optimal energy efficiency obtained through these enhancements was 52.41%, corresponding to 3.5% increase compare to the reference case.

Those technical innovations enable a reduction in losses by enhancing the energy efficiency of the plant and reducing the quantity of feedstock. In addition to these technological approaches, another group of research studies explores economic and policy aspects to improve the e-methanol value creation. These approaches involve the integration of co-selling oxygen byproducts, implementing carbon emission taxes, and measures aimed at decreasing hydrogen costs.

Sollai et al. (2023) conducted a technico-economic assessment for e-methanol in Sardinia, Italy. They examined several options to assess the cost competitiveness of e-methanol. Firstly, they evaluated the cost of e-methanol production when the plant operates only during periods of excess renewable energy, resulting in an operational time of 2000 hours and a levelized cost of 2000 €/ton. The second option involved an operational time of 8000 hours, with the option of selling oxygen byproducts and saving costs from carbon credits. The resulting LCOM was 950 €/ton, which is double the market price of fossil methanol. The LCOM is highly impacted by inefficiencies related to the price of electricity, the capital cost of the electrolyzer, and the capacity factor of the plant. The authors concluded that to make e-methanol competitive with conventional methanol, policies should be established to increase carbon credits. In the mid-term future, they expect e-methanol to become cost-effective as electrolyzer prices decrease in the market, and electricity prices decrease due to the widespread deployment of renewable energy.

Belloti et al. (2017) examined the economic viability of e-methanol produced from excess electricity from the grid. They investigated the influence of oxygen selling, methanol selling prices, and the capital cost of the electrolyzer on the viability of three different e-methanol plant capacities (4000, 10000, and 50000 tons/year). Their results showed that none of the three (3) plants are viable if oxygen is not sold, and the electrolyzer cost accounts for more than 75% of the total capital cost. With the current market price of electrolyzers, the project can become viable if the selling price of e-methanol is set at a minimum of 600 €/ton. The larger plant size also allows for high carbon capture, which is advantageous for carbon tax considerations and can reduce the production cost of e-fuel.

Nyari et al. (2020) investigated an e-methanol plant with a daily capacity of 5,000 tons, incorporating a heat exchange network. The success of their project depended on the price of feedstock. To mitigate economic losses, they proposed: co-selling oxygen byproducts, a 50% reduction in current hydrogen costs, and the integration of carbon taxes, meaning that CO_2 consumers are compensated for capturing CO_2.

In most of the studies, electricity and the hydrogen production process are identified as the bottlenecks for the cost competitiveness of e-methanol. In this context, Nizami et al. (2022) examined the levelized cost for two different scenarios of e-methanol plants with different power supply configurations: PV electrolysis with batteries and PV electrolysis with grid electricity. From an economic perspective, the results showed LCOM values of 1040.17 and 1669.56 $/ton, respectively, for PV-grid and PV-battery scenarios. However, from an environmental standpoint, the CO_2 emissions were 0.244 kg-CO2/MJ-MeOH for PV-grid and 0.016 kg-CO2/MJ-MeOH for the PV-Battery scenario. Therefore, coupling the production of e-methanol with a non-renewable electricity grid can reduce LCOM but increase the environmental impact of the e-fuel.

In summary the design of business model and losses optimization of e-methanol has been extensively studied in the past. There's been growing attention towards transitioning these models sustainably, especially in the context of climate change. Researchers have developed frameworks for adapting business models to address climate challenges. However, only a few have explored how e-methanol fits into this new landscape.

Existing literature predominantly emphasizes circular business models rather than sustainability-focused ones. Further, the sustainable business framework is relatively recent, with few studies available, and in our knowledge, none have specifically applied the sustainable business model to e-methanol. Additionally regarding the technology, there is limited studies focusing on e-methanol production throught CO_2 and water co-harvesting from direct air capture. Bos et al. (2020) investigated this aspect in Netherlands, but they focused on a specific case involving polymer membrane electrolyser (PME).

The present study aims to shed light on the broader context of e-methanol production through direct air capture of CO_2 and water. It proposes a sustainable business model and conducts an analysis of losses in four scenarios based on different types of electrolyzers and storage options.

CHAPTER 2: METHODOLOGY

This chapter explains the procedure and research approach employed to accomplish this project. It covers the description of the e-methanol production process, details about data collection, and the techniques used for data analysis.

2.1. Process Description

Fig. 1 describe the process of e-methanol production. The principal activities of the startup is to produce and sell e-methanol. The production facility is mainly composed of four (4) sub-units: a PV plant, an electrolyser, a direct air capture and a methanol unit. The pv plant generates electricity to power the facility, with a portion of this energy being used to produce hydrogen from electrolysis of water sourced from the direct air capture (DAC) and the methanol reactor. The DAC utilizes solar power and recovered heat to capture CO_2 and water from the air. The hydrogen is compressed at 20bar to a temporary stored before being sent to the methanol reactor. The carbon dioxide is also compressed to a temporary storage in form of liquid at 20bar and pumped to the methanol reactor. The methanol section unit is composed of a reactor for the direct hydrogenation of carbon dioxide, a compressor to recycle the unreacted gas, a purification system to separate methanol from water and unreacted gas, and a storage to store the methanol before it distribution. The different steps of the process are as following:

- **Electrolysis**

An electrolyzer is a device that uses electricity to split water or other components into their constituent elements through electrolysis. This study utilizes three distinct variations of electrolyzers: alkaline, polymer membrane, and solid oxide electrolyzers.

- **CO_2 Capture**

In this study, the DAC is used for harvesting water and CO_2 from the air capture. Among the solid DAC technologies, the solid amine stand out as the most popular nowadays. The direct air capture system has been sized based on the stoichiometric mass of CO_2 required for the methanol synthesis and the operational time. The DAC is powered by the PV electricity and the recovered heat for the CO2 desorption. The share of the heat in it energy consumption is around 75% (IEA, 2022). The capture efficiency is reported around 90%. In this process the carbon dioxide is absorbed when the ambient air contacts the sorbent and the heat facilitate the desorption by separating the CO_2 from the sorbent. The sorbent is regenerated for a new absorption. This process is accompanied by water capture based on the relative humidity of the place (0 – 2 ton of water / CO_2 captured) (IEA, 2022).

❖ **Methanol Synthesis Unit**

An isothermal-fixed-bed reactor has been selected because of the heat recovery. The catalyst choosed is $Cu/Zn/Al_2O_3$. The hydrogen and the carbon dioxide are compressed in the reactor at 65 bar to ensure the chemical reaction. After the hydrogenation process, the unreacted gas made up of hydrogen and carbon dioxide are recirculated back to the reactor through a recycling compressor while 1% of it of are purged to diminish the accumulation of inert gas (Sollai et al., 2023). In the distillation column arrive the raw methanol containing water and trace of carbon dioxide. The mixture is heated , where water is condensed and collected.

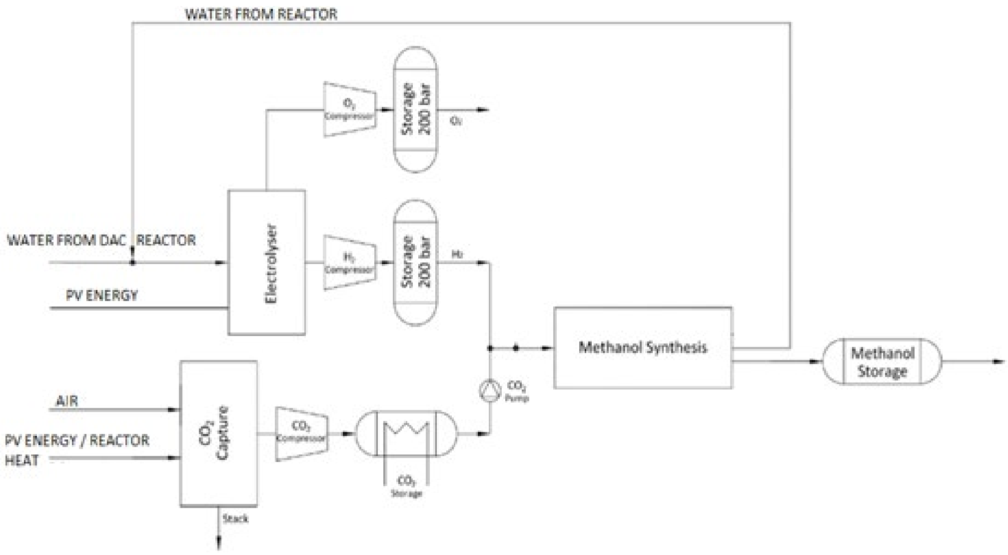

Figure 1. Chart flow of the e-methanol production

Source : adapted from (Sollai et al., 2023)

2.2.Method

The main method used in this master's thesis is the case study method, supported by the triple-layered Business Model Canvas and the levelized cost. The utilization of a case study allows for broad data collection and its application within a sustainable business framework, specifically within the real-life context of West Africa, particularly in Cote d'Ivoire.

The case study enables a deep analysis of the topic in the context of the selected case. By examining the unique socio-economic factors in Cote d'Ivoire, the use of a case study will help identify the challenges of introducing e-methanol into the business landscape while optimizing value creation and minimizing losses.

To accomplish this objective, the case study relies on two auxiliary tools: the TLBM and the levelized cost. The TLBM framework serves to design a sustainable business model, providing a holistic view of the business model in terms of its environmental, social, and economic aspects. It facilitates an examination of the environmental and social layers, enabling the identification of inefficiencies in these dimensions.

The levelized cost on the other hand, serves as a metric tool that quantifies the economic value and identifies potential economic losses. It allows for the comparison of the costs of different scenarios for the production of e-methanol, facilitating the selection of the most cost-effective approach.

2.2.1. Case Study Method

According to Bromley (1896), the case study is an in-depth, detailed examination of a particular case (or cases) within a real-world context. The selected case is an e-methanol plant in Cote Ivoire, because it potential in primary energy energies resources like solar and relative humidity. A sustainable business model of the startup is designed by using the triple layered business model canvas. Through the analysis of this model, the environment and social losses are identified. To have a comprehensive understanding of the economic losses, the plant is designed with multiples scenarios based on the electrolyser technologies and the PV storage with batteries, without batteries, Alkaline, PEM and SOE. A levelised cost calculation is conducted for each scenario to identify how the LCOM variate based on the choice of the configuration of the plant and the technical losses. The base scenario is e-methanol with alkaline electrolyser without batterie.

2.2.3 Data Collection:

To gather data a literature review was conducted using academics databases: google scholar, elicit and Scopus. Several article relative to the topic were found. To facilitate the data gathering, the process was divided into three (3) parts:

The first part focused on researching article relative to the business model data matrix: this included topics such as value design, sustainable and circular business model design, the three bottom line approach, the life cycle assessment and the stakeholder analysis.

The second part was researching data for the e-methanol technico-economic assessment: this group of articles covered areas like the feasibility study of renewable methanol, the levelized cost of e-methanol, green hydrogen technico economic assessment, the direct air capture cost analysis. This part makes possible to get the cost of the entire e-methanol plant components.

The third part was the collection of climatic data specific to the methanol plant (Cote ivoire). For that, some data bases have been consulted like photovoltaic geographical information (PVGIS) for the solar potential assessment and Power larc Nasa for the relative humidity.

2.2.4 Data Analysis

To address the research questions, data is analysed with different tools:

- ❖ Triple layered business model canvas for designing a sustainable business model for the e-methanol production. The analysis of the resulted model helps to identify the environmental and social losses.
- ❖ Levelised Cost of Methanol (LCOM) for quantifying the economic value and the losses influencing it.

➢ **Triple Layered Business Model Canvas (TLBMC)**

The Triple Layered Business Model Canvas is a tool that helps businesses explore sustainability-oriented business model innovation. It extend the original Business Model Canvas by adding two additional layers: an environmental layer that takes a lifecycle perspective and a social layer that takes a stakeholder perspective (Joyce and Paquin, 2016).

✓ Economic Layer

This layer is typically the original archetype of Osterwalder business model canvas. It has nine (9) blocks or elements that have to be filled based on the collected data relative to the market, customer, competitor and the industrial trend. The first step consists of the value proposition design, where it has been checked if the proposed value match with the costumer profile or if the proposed solution fit with the customers problems. From the secondary data and individual brainstorming, valuable insights have obtained about the pricing strategy, cost structure, costumer segment, manufacturing technique and revenue stream, which help to fill out the nine (9) blocks of the canvas.

✓ Enviromental Layer

To build this layer, the life cycle of e-methanol conducted by Carlo Hamelinck (2022), has been utilized. From their study, the emission factors of each process are extracted and applied to this project. The functional value is identified first, followed by assessing the environmental impact during the production phase, the use phase, the distribution and the end-of-life. The summary of the environmental impacts and benefits reveals the sustainability level of the product. The indicator used in this study is the carbon footprint.

✓ Social Layer

This layer lies on the stakeholders management and measure the social dimension of the project. The first step is identiying the stakeholders have and understanding their different relationships. The mission of the project has been a reference to identify the social value. The structure and the organization are defined by the governance element. The societal culture and the outreach scale are respectively used to describe the potential impact on the society as whole and the intensity of stakeholder's relationship. For the end-user element, the improvement in quality of life is explained. The social impact and social benefit components illustrate respectively the negative impact and the social advantage.

➢ Levelised Cost Calculation

The aim of this section is to calculate and analyse the levelised cost by following this approach.

Case → Sizing → LCOM

The levelised cost of methanol is simulated trough an excel sheet for four the (4) scenarios. From the literature review, it was found that the bottlenecks in e-methanol cost are electricity costs and the hydrogen production process. A significant portion of the high cost of e-methanol is attributed to electricity and hydrogen production. Therefore, the scenarios were selected based on electrolyzer technology and power supply configuration to identify the most cost-efficient option. These scenarios are :

- Scenario 1 : use alkaline electrolyser and PV without batteries to produce hydrogen;
- Scenario 2 : use alkaline electrolyser and PV with batteries storage to produce hydrogen;
- Scenario 3 : utilise PME electrolyser and PV without batteries to produce hydrogen;
- Scenario 4 : use the SOE electrolyser and PV without batteries to produce hydrogen.

✓ Sizing

The sizing is composed of determination of quantity of matter that are going to be use for one (1) year and the size of the production equipment. In this study, all the sizing is based on a methanol capacity of 500 tons per year. This capacity was chosen because it is more realistic, and most implemented methanol plants have capacities of around 500 to 1000 tons of methanol per year.

- **Quantity Of Matter**

The main chemical reaction 1 in the methanol reactor is used to determine the relationship between the different mass of the components (Rufer, 2022) :

$$CO_2 + 3H_2 \quad \leftrightarrow \quad CH_3OH \ + \ H_2 \qquad (1)$$

$$44 \quad + \quad 6 \quad \leftrightarrow \quad 32 \quad + \quad 18 \tag{2}$$

From reaction 1 and equation 2, the mass of carbon dioxide m_{CO2}, hydrogen m_{H2} and water produced mH_20 in the reactor are deducted in function of the methanol mass m_{CH3OH} by:

$$m_{H2} = \frac{6}{32} \cdot m_{CH3OH} \tag{3}$$

$$m_{CO2} = \frac{44}{32} \cdot m_{CH3OH} \tag{4}$$

$$m_{H20} = \frac{18}{32} \cdot m_{CH3OH} \tag{5}$$

Reaction 6 is used for calculating the necessary mass of water required for electrolysis, as well as the mass of oxygen produced (Rufer, 2022).

$$2H_20 \quad \leftrightarrow \quad 2H_2 \; + \; O_2 \tag{6}$$

$$36 \quad \leftrightarrow \quad 4 \quad + 32 \tag{7}$$

From reaction 6 and equation 7, we can deduct the mass oxygen m_{O2} and the water m_{H20} in function of the hydrogen mass m_{H2}:

$$m_{O2} = \frac{32}{4} \; x \; m_{H2} \tag{8}$$

$$m_{H20} = \frac{36}{4} x \; m_{H2} \tag{9}$$

The equation 10 is used to determine the thermal energy (Eth) in kilo joule, that can be recovered to supply the DAC in order to reduce the energy consumption (Rufer, 2022).

$$Eth = 49.5 \frac{kj}{mol} \; x \; mole \; number \; of \; produced \; methanol \tag{10}$$

Through the equation 11, the plant electricity consumption (E_{elec}) in MWh has been determined by summing the consumption the tree sub-unit: electrolyser, DAC and methanol synthetiser. The values of those consumption are find in the literature (IEA, 2022 ; (Soler et al., 2021).

$$\text{Eelec} = \frac{58.37\text{kWh}}{\text{kg}} \text{ x } m_{H2} + \frac{2333.33\text{kWh}}{\text{t}} \text{ x } m_{CO2} + \frac{276.11\text{kWh}}{\text{t}} \text{ x } m_{CH3OH} \tag{11}$$

The efficiency of the e-methanol plant is defined as the ratio of the heat value of the produced fuel divided by the renewable energy fed into the process (Rufer, 2022).

- **Equipment Size**

For the sizing of the PV plant, the PVGIS database was utilized to identify a location with excellent solar potential. The chosen site is situated in northern Cote d'Ivoire at the coordinates

(10.105; -5.610). Its annual global irradiation for 2020 amounts to Eg $= 2187.42\ \mathrm{kWh.m^{-2}}/$ year. (see appendix A2 for more detail)

Equation 12, is utilized to determine the capacity of the photovoltaic panel (Bhandari, 2022).

$$Ppeak = \frac{El\ x\ Istc}{Eg\ x\ Q} \tag{12}$$

Where Ppeak is the power of the PV (kWp); El is the output energy of the system (kWh/a); Istc is the incident solar radiation (1kW/m^2); Eg annual global solar radiation; Q the quality factor of the system.

The equation 13 is employed to determine batteries storage capacity. Where B is battery capacity (kWh); Da is number of autonomous days; D is number of electricity demand per year (kWh); DoD is the depth of discharge rate of the battery (%); n is battery energy conversion (%) (Bhandari, 2022).

$$B = \frac{Ed\ .\ Da}{DoD\ .\ n\ .\ D} \tag{13}$$

Equation 14 defines the capacity of the electrolyzer (C) in kW as the ratio of the hydrogen energy equivalent (EH_2) in kWh produced to the operational time (t) in hours.

$$C = \frac{EH_2}{t} \tag{14}$$

Equation 15 expresses the capacity of the methanol reactor (P_{CH3OH}) in kW as the energy equivalent of the methanol produced in kWh divided by the operational time (t) in hours

$$P_{CH3OH} = \frac{Energy\ equivalent\ of\ the\ produced\ methanol}{t} \tag{15}$$

Equation 16 determines the Direct Air Capture capacity (DAC) as the mass of carbon dioxide (mCO2) produced in tons over the operational time (t) in hours.

$$DAC = \frac{m_{CO2}}{t} \tag{16}$$

✓ **Levelised Cost of Methanol**

The purpose here is to calculate the levelized cost of methanol and identify the different losses that can affect it. To achieve this, it is essential to know in advance the capital and operational cost, and some financial parameter of project.

- **Financial Assumption**

The project life time has been estimated to 25 years (Nizami et al., 2022), while the yearly operational time for the base scenario is determined based on the solar factor capacity factor of the location (1749.9h). The discount rate is 4.25% [2] and all the cost is in US Dollar ($). To convert certain cost euro to dollar, the exchange rate used is 1.09$/€.

- **Capital Cost**

Most of the capital cost come mainly from the literature (see appendix Table A1). For the compressors and pump, their capital cost has been estimated in equation 17, according to (Sollai et al 2023). Where C is the cost of the compressor, Co the base parameter depends on the type of the fluid compressed (equal to 36856; 2651 and 2327 for H_2, CO_2 and O_2 respectively), ṁ is the rate flow of the fluid (kg/h).

$$C = Co\ x\ (\dot{m}\ x\ ln\beta)^{0.5} \tag{17}$$

For the pump which has to pump the CO_2 from 20bar to 65bar, it cost is estimated by the equation 18 according to (Sollai et al 2023). Where C is the cost pump and Wp is the pump power (kW).

$$C = 1.417\ x\ 10^6\ x\ \left(\frac{Wp}{1000}\right) + 0.09\ x\ 10^6 \tag{18}$$

Some investment during the operational phase has been considered like the replacement stack of the electrolyser, the batteries replacement and the compressor and pump replacement according to their life time given by the literature.

Finally some indirect capital cost have been estimated as done by Sollai et al. (2023) :
Procurement and engineering account 15% of the bare erected cost, land preparation is 2% of the bare erected cost and permit fees constitutes 15% of the bare erected cost.

- **Operation And Maintenance Cost**

The operationl expenditure (OPEX) cost is generally given per year. For this study most of the variables OPEX are taken from the literature (see appendix Table A1).

The labor cost is estimated at 15000 $/person, based on the Africa salary scale (World Bank, 2023). There are a total of 8 operators: 3 operators for the plant without the PV plant (Sollai et al., 2023), and 5 operators for the 4 megawatt PV (solairworld, n.d.). Additionally certain indirect operational costs have been estimated according to Sollai et al. (2023) : property tax and insurance is 2% of the capex and general administration is 2% of the labor.

[2] https://www.exchangerate.com/statistics-data/central-bank-discount-rate/What-is-the-central-bank-discount-rate-of-Cote-d-Ivoire.html

- **Levelised Cost**

According Poluzzi et al. (2022) the levelized cost of the methanol can be defined as the breakeven selling price that, at the end of the plant lifetime (LT), repays the total cost by producing a certain amount of methanol. it considers the capital cost, the operational cost (OPEX), the capital charge factor (CCF) and the produced mass of methanol (m_{MeOH}) as shows in the equation 19.

$$LCOM = \frac{CAPEX\ .\ CCF + OPEX}{mMeOH} \tag{19}$$

CCF is determined according to equation 20, where α is the discount rate and L is the operational life time .

$$CCF = \frac{\alpha\ .\ (1+\alpha)^{L}}{(1+\alpha)^{L}-1} \tag{20}$$

CHAPTER 3: RESULTS AND DISCUSSION

This chapter present the different results obtained from the implemented methodology, accompanied by a comprehensive discussion.

3.1 Results

This section presents the findings of the sustainable business model, followed by an identification and optimization of losses for a 500-ton/year e-methanol plant in Côte d'Ivoire.

3.1.1. Business Model design

This subsection show the sustainable business model designed for the production of 500 ton of e-methanol per year in Cote ivoire. The resulting business model obtained trough the TLBM canvas is composed of three (3) layers as presented below :

❖ **Economic Layer**

The economic layer in (Table 1) examine the entire necessary component to capture the value and determine the viability of the power-to-methanol system.

The value proposition:

The proposed value of the e-methanol plant in cote ivoire is an eco-friendly fuel which can adapt to the existing energy system and infrastructure that will help to protect the environment.

Customer segment:

The potential customer identified are the transport companies and industries, which want to reduce their emission. The second group is the population after having a awareness campaign about climate change.

Channel:

To distribute the fuel, an option of truck is envisaged to deliver the product to the companies, industries and retailer fuel station.

Customer relationship:

The customer relationship that the business is going to develop is co-creation. Through a strong communication with the customer, value is co-created which solve the customers need.

Revenue stream:

Revenue is created by selling directly the e-fuel to the customers.

Cost structure:

The cost structure is mainly composed of the cost of the plant (capex), the worker's salary, the taxes and the maintenance cost. For this case the production cost is dominated by the operational cost , which is majorly composed of the taxes, workers salary and some equipment maintenance cost.

Key Activity:

The development of the business require some activities which are: the energy production, the hydrogen production, the direct air capture, the methanol synthesis, the distribution, the selling and the awareness campaign.

Key resources:

the natural resources are the solar potential which is 2187.42 kwh/m^2/year (“JRC Photovoltaic Geographical Information System (PVGIS) - European Commission,” n.d.) and the relative humidity of the location. The human and financial resource are indispensable for the business.

Key partnership :

They identified partnership are: the government for establishing policies favorable for the sustainability, the NGO for awareness campaigns on climate change, the local community, suppliers of energy equipment and solution, and the transport companies and industries.

Table 1: Economic Busines model Layer

KEY PARTNERS	KEY ACTIVITIES	VALUE PROPOSITION	CUSTOMER RELATIONSHIP	CUSTOMER SEGMENT
Government Local community NGO: GIZ, AFD CVCI	Hydrogen production Carbon capture Methanol production Shipping Local distribution Marketing Selling	E-methanol is more ecofriendly E-methanol can adapt to the existing energy system and infrastructure	Co-creation	SIAT CITRANS ISS-CI BITTCT SODEMI
	KEY RESOURCES Human resource Primary energy source Humid air Financial resource		**CHANNELS** Truck Refueling station	
COST STRUCTURE Plant operational cost Worker's salary Raw material cost		**REVENUE STREAM** Selling Methanol		

Source: Author

❖ **Environmental Layer**

The environmemtal layer in (table 2) is obtained based on the environmental life cycle assessment of e-methanol. It assess the environmental impact of the e-fuel across all the stages of it life. The indicator used for tracking the environmental impact is the carbon footprint.

Functional value:

The functional value represent the environmental value generated by the business model. In this projet it is the pollution avoided per mega joule of e-methanol multiplied by the quantity of e-fuel consumed over one year.

Material :

The pollution during the convervion of the feedstock to methanol depends on the quality of the catalyst material.

Production:

The impact for the production activities in this project are : Electricity generation and the methanol synthesis.

Supplies and outsourcing:

The supplies and outsourcing is the material, which are not directly linked to the functional value, but needed for a holistic assessment of the sustainability of the business model. In this case it represent the solar panel, the direct air capture unit, the electrolyser and the methanol reactor.

Distribution:

The distribution represent the environmental impact of the delivering mode which is choose to deliver the good to the customers. In this, project a truck option is selected and it emission for 100 km is 13.1t $_{CO2}$eq/year.

Use phase:

the impact during the usage is caracterise by the emission rejected by the combustion of the e-methanol.

End of life :

There is no end-of-life emissions because, after the combustion of the e-fuel, the emission is released into the air, where it's captured for producing new e-fuel. The cycle is circular.

Environmental impact:

The highest impact is observed during the usage phase, and the synthesis process. The efficiency of the carbon dioxide conversion and the transport of the product to the customer contribute to the increase of the carbon footprint of the business. The overall impact of this e-methanol project is : 44.9t $_{CO2}$eq/year.

Environmental benefits :

Compare to the conventional methanol (natural gas), the e-methanol can achieve the reduction of carbon dioxide up to 90%.

Table 2 Environmental life cycle layer

<table>
<tr>
<td rowspan="2">SUPPLIES AND OUT-SOURCING

Production of solar panel, electrolyser, DAC and catalytic reactor.</td>
<td>PRODUCTION

.PV-energy ($25tCO_{2eq}$/year)

.Methanol synthesis (6.87t CO_2eq/year)</td>
<td rowspan="2">FUNCTIONAL VALUE

Pollution avoided per one ton of fuel multiplied by the quantity of methanol consumed over one year</td>
<td>END-OF-LIFE

.No end of life emission for e-methanol</td>
<td rowspan="2">USE PHASE

Combustion of methanol</td>
</tr>
<tr>
<td>MATERIALS

Catalyst</td>
<td>DISTRIBUTION

Truck on diesel for 100km
(13.1t CO_2eq/year)</td>
</tr>
<tr>
<td colspan="2">ENVIRONMENTAL IMPACT
Carbon dioxide
(44.9t CO_2eq/year)</td>
<td colspan="3">ENVIRONMENTAL BENEFITS
Reduction of CO_2emission by 90% compare to the methanol from natural gas</td>
</tr>
</table>

Source: Author

❖ **Social Layer**

The social layer in (Table 3) is constructed based on the stakeholders management. It investigates the social impact of the project by exploring the interaction and the influence between the different stakeholders.

Social value:

The social value refers to the project's mission which create benefits for the stakeholders. In this case, it correspond to improving the health of the community by reducing the pollution and reducing the fossil energy dependence.

Employee:

For the employment, priority will be given to the local community workforce and a training program will be offered to develop their existing skill.

Governance:

The governance define the structure and the decision-making policies for the organization. The structure of the startup is privately owned for profit and the decision-making will be in transparency.

Communities:

The community component describes how the organization collaborates with the local community to create mutual benefits. In this project, the local community will receive excess water for irrigation, and they will be involved in a climate change awareness campaign.

Societal culture:

The societal culture refers to the potential impact of the projects on society in a broader cultural context. This project develop a culture of environment protection and the efficient use of the natural resource.

Scale of outreach:

The scale of outreach describe how the relationship with stakeholders is going to be extended over the time. The project intend to cooperate with some organization which promote green energy in west Africa and participate to international energy cooperation between EU and Africa.

End-users:

The end-user component describe how the value proposition is going to improve the quality life of the end-users. For this case its improving the health and reducing the carbon footprint while conserving the existing energy and transport infrastructure.

Social impact:

The identified social impact are : displacement of some community because of the land required by the pv plant and the increase of the energy poverty because of the e-fuel price is higher than the conventional fuel price.

Social benefits:

The expected social benefits of the start-up are: reducing the respiratory deseases Increasing the employment rate reducing reliance on fossil fuel importation.

Table 3 Social layer

<table>
<tr>
<td rowspan="2">LOCAL COMMUNITIES

The excess of water will be used by the local community for their irrigation or water use.

The local community will participate to the campaign of climate change.</td>
<td>GOVERNANCE

.Privately owned for profit
. Transparency in decision making</td>
<td rowspan="2">SOCIAL VALUE

. Improve the health of the community by reducing the pollution

. Reduce the energy dependence</td>
<td>SOCIETAL CULTURE

. culture of environmental protection
. culture of efficient use of natural resource</td>
<td rowspan="2">END-USER

.clean transport
. reduced carbon footprint</td>
</tr>
<tr>
<td>EMPLOYEES
. More than 70% of employees will come from Cote ivoire.
.The local community will be prioritized for the employment.
. Offer of training program to develop the existing skill</td>
<td>SCALE OF OUTREACH
Cooperate with some organization which promote green energy in west Africa
.Participate to international energy cooperation between EU and Africa</td>
</tr>
<tr>
<td colspan="2">SOCIAL IMPACT
. Displacement of community because of the required land of pv.
. Increase of the energy poverty.</td>
<td colspan="3">SOCIAL BENEFITS
. Improve the quality of air and reduce the respiratory deseases
. Increase the employement rate
. reduce reliance on fossil fuel importation</td>
</tr>
</table>

Source: Author

3.1.2. Losses Identification

This subsection provide the different losses that are expected during the ramp-up phase of the project. The analysis of the sustainable business model provide the environmental and social losses while the technico-economic assessment trough the levelised cost presente the economic efficiency losses.

- **Environmental and Social Losses**

The environmental and social losses are identified trough the analysis of the environmental and social layer of the sustainable business model.

Environmental value losses: Certain components of the environmental layer exhibit some inefficiencies that can impact the sustainability of the created value, such as: the management of waste materials used, product distribution, carbon dioxide conversion in the methanol reactor during the production phase, and nitrous oxide rejection during fuel combustion.

Social losses: In the social layer of the business model, certain inefficiencies have an impact on the social value created, such as community displacement and concerns related to energy poverty.

- **Economic Losses**

The sizing and the levelised cost calculation for 4 differents scenarios of production of e-methanol identify the economic losses which affect the production cost and identify the most cost-effective scenario suitable for this project.

As outlined in chapter 2, the four scenarios are as follow: scenario1 employs alkaline, scenario 2 incorporate both alkaline electrolyser and batterie, scenario 3 use PME electrolyser and scenario 4 utilise SOE electrolyser. For the sizing result, all the scenario studied have in common the same quantity of matter required to produce the 500 ton of methanol per year. These values are presented in the table 4.

Table 4 Quantity of matter for all the scenario

Quantity of matter	Value	Unit
Methanol	500	ton/year
Hydrogen	93.75	ton/year
Carbon dioxide	687.5	ton/year
Water needed	843.75	ton/year

Source : author calculation

- **SCENARIO 1 : Alkaline**
  - **Sizing**

Table 5 shows the result of the sizing for scenario 1. Notably, it demonstrates that, the operational time in of the plant in this scenario is limited and depend of the solar capacity in the location. This constraint leads to an augmentation in the dimensions of the production equipment, like the electrolyser capacity reaching up to 2.6 MW. The utilization of heat recovered from the methanol reactor to fuel the DAC has contributed to achieving an efficiency up to 50%. This facility need a vast land area, a superficies of 14313.7 m^2 is required. The Fig.2 shows, the share of the energy consumption. Its observed that, the electrolysis technology is by far the most energy intensive of the e-methanol plant, with 76% of the totoal energy consumption . then followed by the DAC unit which is 22% of the total energy consumption.

Table 5 Sizing result for scenario 1

Variables	Value	Unit
Energy recovered	214.57	MWh/y
Energy electrolyser	4734.37	MWh/y
Energy DAC	1389.59	MWh/y
Energy of reactor	138.05	MWh/y
Total energy of plant	6262.02	MWh/y
Capacity of Electrolyser	2.6	MW
Capacity of DAC	0.39	(tco2/h)
Capacity of Reactor	1800.06	kW
Capacity of PV plant	3.57	MW
Operational time	1749.9	hours/year
Land needed	14313.7	m^2
Plant efficiency	0.5	

Source: Author calculation

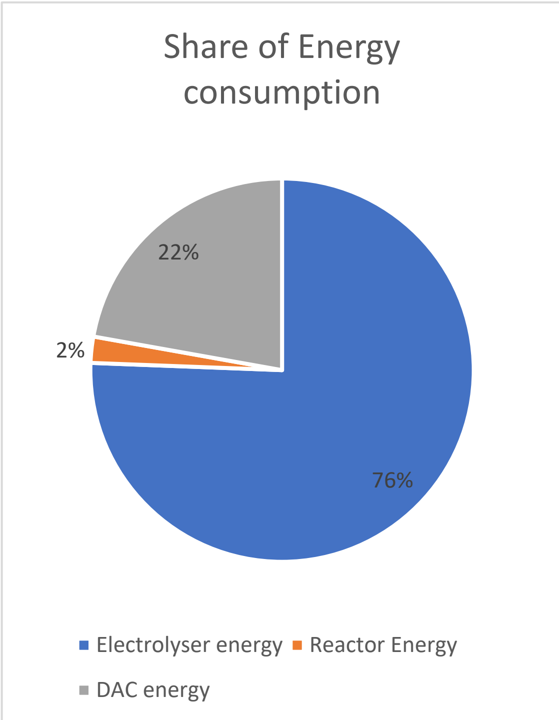

Figure 2. Scenario 1 Energy Share

Source: Author

- **Economic analysis**

Table 6 summarise the differents parameter used to calculed the levelised cost. The resulting LCOM is calculated to be 812 $/ton. To identify which parameter affect the most the levelised cost, a break down of the LCOM was done where it was found the capex is 6% of LCOM and the opex is 94% of LCOM . This significant portion of the OPEX necessitates its decomposition. Figure 3 illustrates the breakdown of operational expenses, indicating that labor constitutes 32%, taxes and insurance contribute 26%, direct air capture makes up 13%, electrolyser accounts for 10%, and the PV plant contributes 8%

Table 6 LCOM for Scenario 1

Variables	OPEX ($)	CAPEX ($)
DAC	48181.76	1204544.05
Electrolyser	39287.15	1964357.55
Methanol reactor	13770.50	688525.18
Pv plant	32205.88	2147058.53
CO2 compression & storage	6149.90	364223.17
H2 compression & storage	16085.46	803851.70
Land		429411.71
Procuremt & Eng		1140295.78
Study & land preparation		152039.44
Permis Fees		1140295.78
property tax & insuance	100346.03	
Labour	120000.00	
General administratn	2400.00	
LCOM ($/t)	812.17	

Source: Author calculation

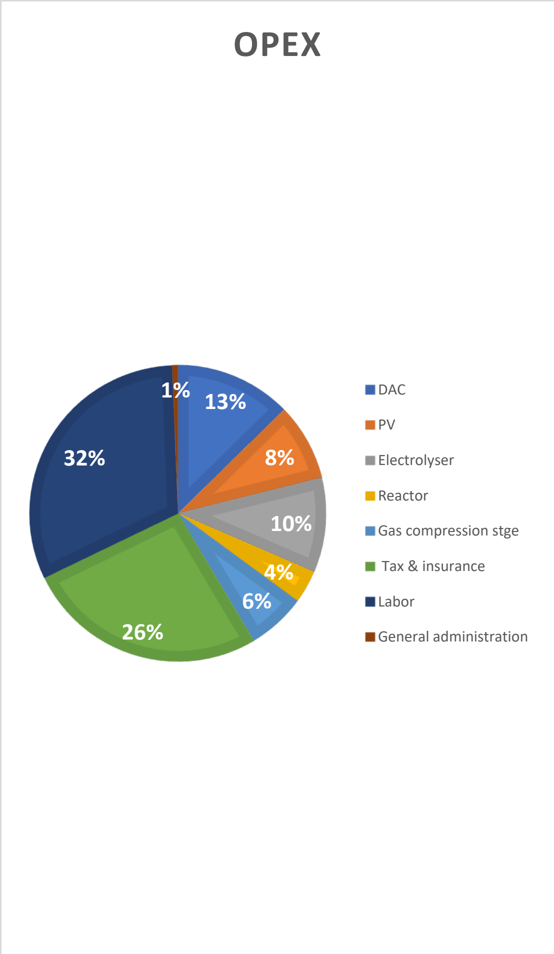

Figure 3. Opex breakdown scenario 1
Source: Author

- **Scenario 2 : Alkaline electrolyser with batteries**
  - **Sizing**

In scenario 2, the system operates for 8000 hours per year due to the incorporation of batteries. This extended operational period allows for a reduction in the size of production equipment, such as the electrolyser capacity which decreases to 0.57 MW. Importantly, the inclusion of batteries has no impact on the size of the photovoltaic (PV) plant, the required land area, or the energy efficiency of the overall plant, which remains at 50%.

As depicted in the fig 4, the distribution of energy shares remains consistent. Notably, the electrolysis process remains the most energy-intensive, accounting for 76% of the total energy consumption, followed by direct air capture which contributes 22% of the total energy usage.

Table 7 Sizing result for scenario 2

Variables	Value	Unit
Energy recovered	214.57	MWh/y
Energy electrolyser	4734.37	MWh/y
Energy DAC	1389.59	MWh/y
Energy of reactor	138.05	MWh/y
Total energy of plant	6262.02	MWh/y
Capacity of Electrolyser	0.57	MW
Capacity of DAC	0.085	(tco2/h)
Capacity of Reactor	393.75	kW
Capacity of PV plant	3.57	MW
Operational time	8000	hours/year
Land needed	14313.7	m^2
Plant efficiency	0.5	
Capacity of Batteries	28834.0	kWh

Source: Author calculation

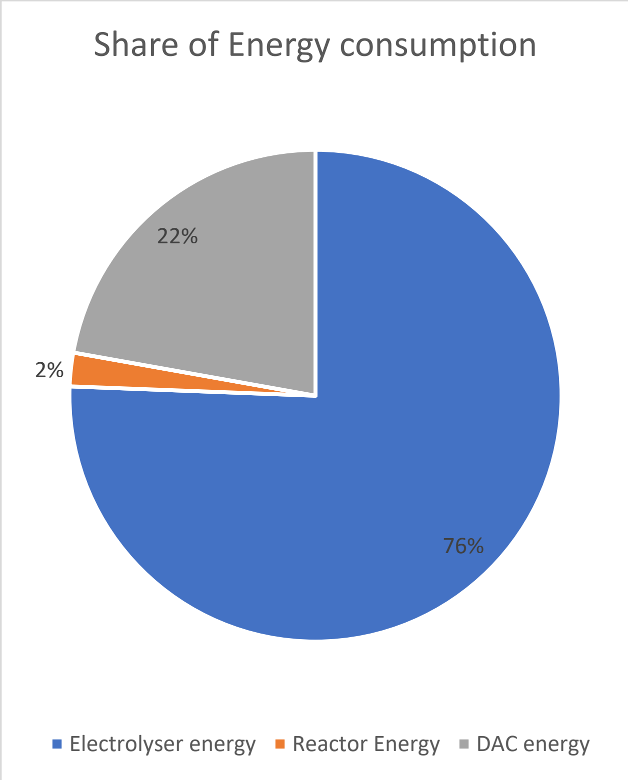

Figure 4. Scenario 2 Energy Share
Source: Author

- **Economic analysis**

Table 8 provide a summary of different variable cost for determining the levelised cost of e-methanol. Diverging from scenario 1, the introduction of the batteries to the system leads to a significant increases of the capex and opex. As a result, the levelized cost of e-methanol (LCOM) experiences an elevation, reaching 2220.2$/ton . The distribution of capex and opex components within the levelized cost structure remains consistent, with corresponding proportions of 6% and 94%, respectively. Further a detail of the opex breakdown is presented in Figure 5, illustrating that batteries constitutes 52% of the total, taxes and insurance collectively contribute 26%, labor for 14%, pv plant represents 4%, and and the remaining portion is allocated to other equipment.

Table 8 Levelised cost for scenario 2

Variables	OPEX ($)	CAPEX ($)
DAC	10539.38	263484.38
Electrolyser	8593.75	880859.38
Methanol reactor	3012.19	150609.38
Pv plant	32205.88	2147058.53
CO2 compression & storage	5828.44	416074.093
H2 compression & storage	6005.34	598849.70
BATTERIES	432510.07	11533601.96
Land		429411.71
Procuremt & Eng		2462992.37
Study & land preparation		328398.98
Permis Fees	2462992.37	
property tax & insuance	216743.33	
Labour	120000.00	
General administratn		2400.00
LCOM ($/t)	1786.6	

Source: Author calculation

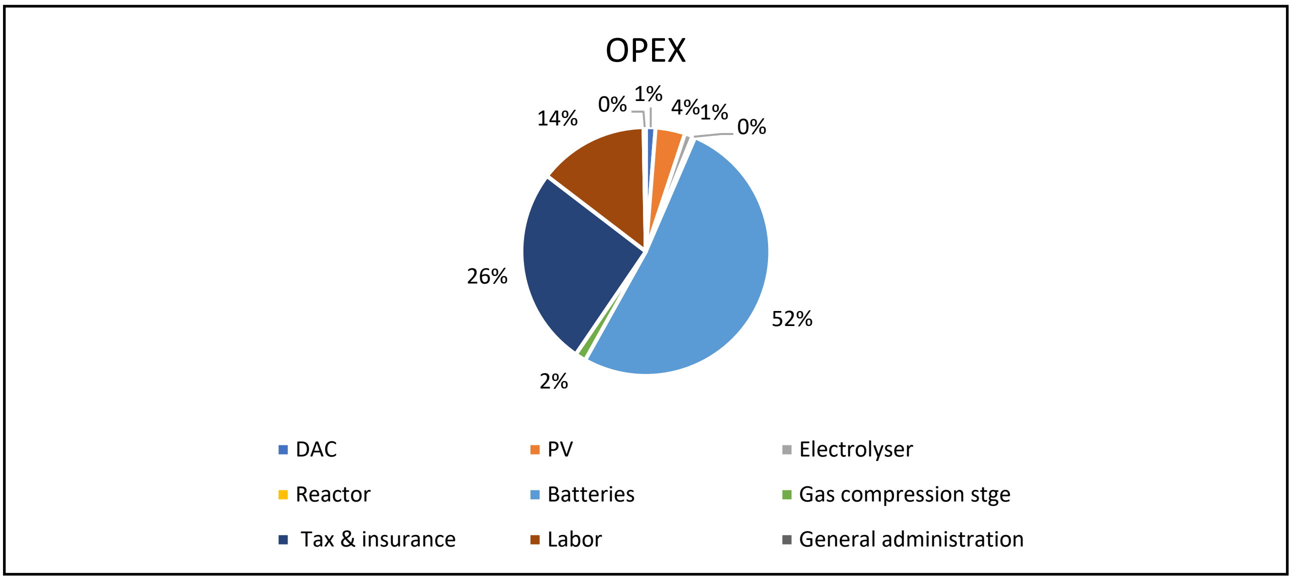

Figure 5. Share of energy consumption for scenario 2
Source: Author

❖ **Scenario 3 : PME electrolyser**

Sizing

In scenario 3, As indicate in table 9, the operation time is limited similarly to scenario 1 and depend to the solar capacity factor of the plant geographical location. this constraint has an impact on the scale of the production equipment, such as the electrolyser, which is designed for a capacity of 2.62 MW. In spite of the recuperation of heat from the methanol reactor, the overall energy efficiency of the plant is 45% due to the lower energy efficiency of PME electrolyser compare to the alkaline. Consequently, this leads to an increase of land requirement up to 1600 m^2.

As demonstrated by figure 6, the electrolysis process has the largest energy consumption, accounting for 78% of the total energy usage. Direct air capture follows closely, constituting 20% of the overall energy consumption.

Table 9 Sizing result for scenario 3

Variables	Value	Unit
Energy recovered	214.57	MWh/y
Energy electrolyser	5472.19	MWh/y
Energy DAC	1389.59	MWh/y
Energy of reactor	138.05	MWh/y
Total energy of plant	6999.84	MWh/y
Capacity of Electrolyser	2.62	MW
Capacity of DAC	0.39	(tco2/h)
Capacity of Reactor	1800.07	kW
Capacity of PV plant	4.00	MW
Operational time	1749.9	hours/year
Land needed	16000.21	m^2
Plant efficiency	0.45	

Source: Author calculation

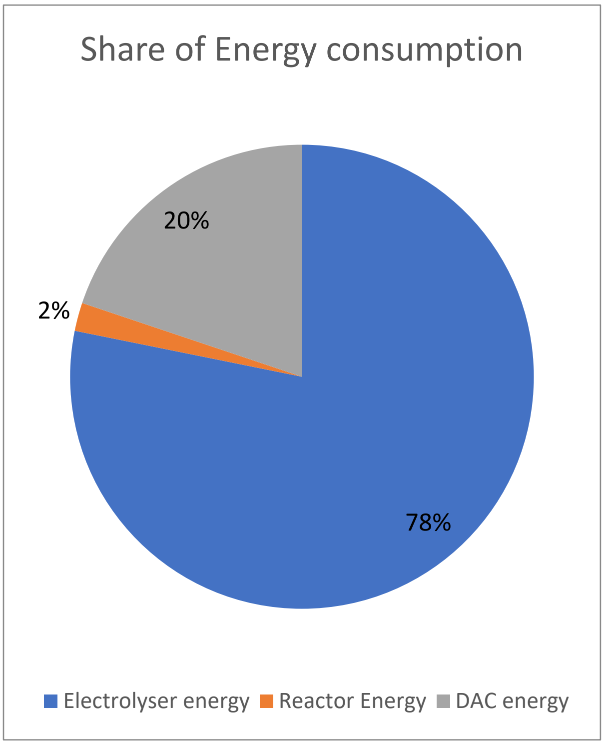

Figure 6. Scenario 3 Energy Share
Source: Author

Economic analysis

Table 10 présent a comprehensive overview of the calculations for the levelised cost of e-methanol. The resulted levelised cost is $1090.6 per ton. In oder to determine the parameter driving the levelised cost, a detailed breakdown of the LCOM was conducted. This breakdown revealed that the CAPEX account for 7% of the LCOM, while the OPEX represent the remaining of 93%. Seeing this significant portion of the OPEX, a further analysis of its components was necessary. Figure 3 show the breakdown of the operational expenses, indicating the share: labor at 30%, taxes and insurance at 29%, direct air capture at 12%, electrolyser 10%, and the pv plant at 9% of the total operational expenses.

Table 10: Levelised cost for scenario 3

Variables	OPEX ($)	CAPEX ($)
DAC	48181.8	1204544.1
Electrolyser	38030.0	2881057.7
Methanol reactor	13770.5	688525.2
Pv plant	36000.5	2400032.1
CO2 compression & storage	8118.3	364223.2
H2 compression & storage	16085.5	803851.7
Land		480006.4
Procuremt & Eng		1323336.0
Study & land preparation		176444.8
Permis Fees		1323336.0
property tax & insuance	119885.86	
Labour	120000.0	
General administratn	2400.0	
LCOM ($/t)	877	

Source: Author calculation

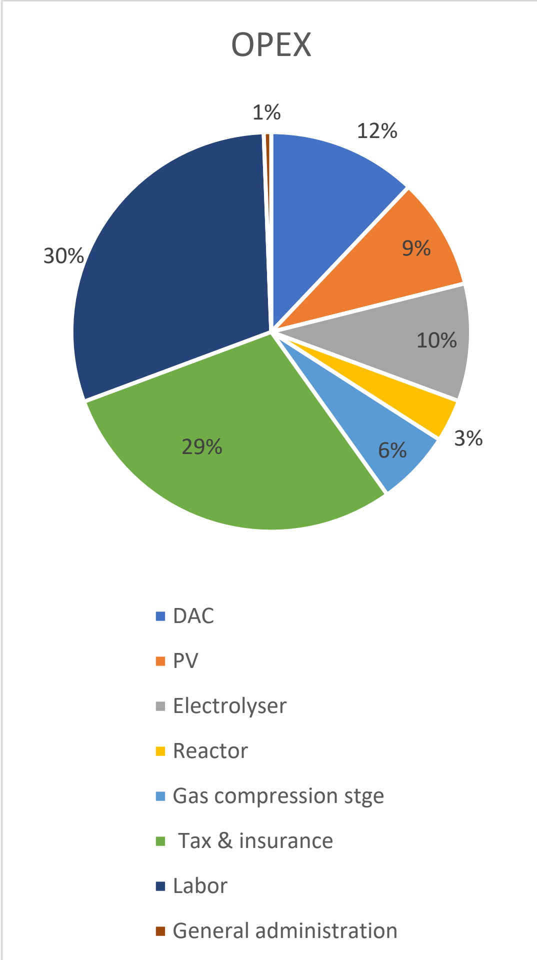

Figure 7. Opex breakdown for scenario 3
Source: Author

❖ **SCENARIO 4 : SOE electrolyser**

➢ **Sizing**

In scenario 4, as illustrated in table 11, the use of the SOE provide some particularity to the power-to-methanol system . Among various electrolyzer technologies, SOE exhibits the highest energy efficiency. Consequently, this leads to a modest reduction in the size of the production equipment, despite the operational time limitation by the solar capacity factor. The heat recovery combine to the high efficiency of the SOE, contributes to achieving an optimal energy efficiency of 57% for the entire plant. This optimization, in turn, impacts the sizing of the PV system, which is determined to be 3.15 MW, and the required land area of 12599.3 m².

As showed by in Fig 8 , the electrolysis technology stands out the most energy intensive of the e-methanol plant, accounting for 72% of the total energy consumption . The following is the DAC unit, contributing 25% of the total energy consumption.

Table 11 Sizing result for scenario 4

Variables	Value	Unit
Energy recovered	214.57	MWh/y
Energy electrolyser	3984.38	MWh/y
Energy DAC	1389.59	MWh/y
Energy of reactor	138.05	MWh/y
Total energy of plant	5512.03	MWh/y
Capacity of Electrolyser	2.08	MW
Capacity of DAC	0.39	(tco2/h)
Capacity of Reactor	1800.07	kW
Capacity of PV plant	3.15	MW
Operational time	1749.9	hours/year
Land needed	12599.38	m^2
Plant efficiency	0.57	

Source: Author calculation

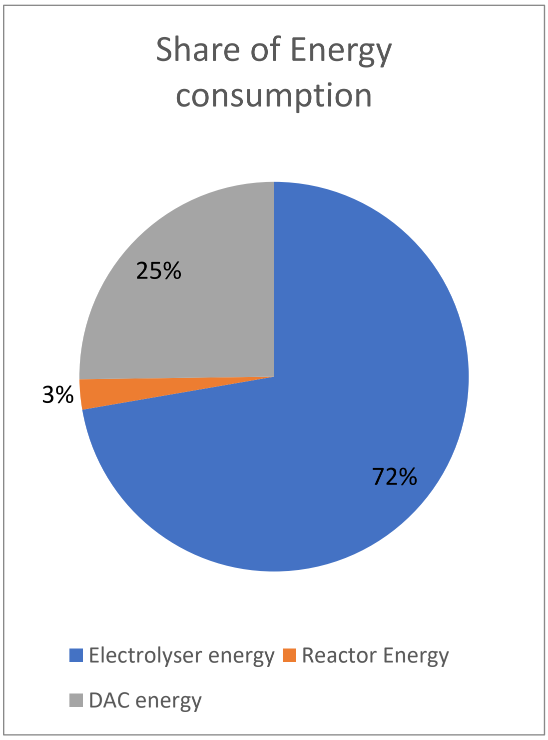

Figure 8. Scenario 4 Energy Share
Source: Author

- **Economic analysis**

Table 11 present detailed information regarding the determination of the levelized cost of e-methanol. Despite the high efficiency of SOE, which reduce the required size of the pv plant , the levelised cost remains high at $1187.45 per ton, due to the maturity of the SOE technology. The breakdown of this LCOM show a greater influence of OPEX which account for 93% of the LCOM. To have a further insight, a decomposition of the opex was conducted to identify the key contributors. Figure 9 highlight the breakdown of the operational expenses with electrolyser at 30%, taxes and insurance at 27%, labor at 22%, direct air capture at 9%, and the pv plant at 5% of the total OPEX.

Table 12 Levelised cost for scenario 4

Variables	OPEX ($)	CAPEX ($)
DAC	48181.8	1204544.1
Electrolyser	166392.6	6156527.7
Methanol reactor	13770.5	688525.2
Pv plant	28348.6	1889906.3
CO2 compression & storage	8118.3	364223.2
H2 compression & storage	16085.46	803851.7035
Land		377981.3
Procuremt & Eng		1722833.9
Study & land preparation		229711.2
Permis Fees		1722833.9
property tax & insuance	151609.38	
Labour	120000.0	
General administratn	2400.0	
LCOM ($/t)	1187.452	

Source : Author calculation

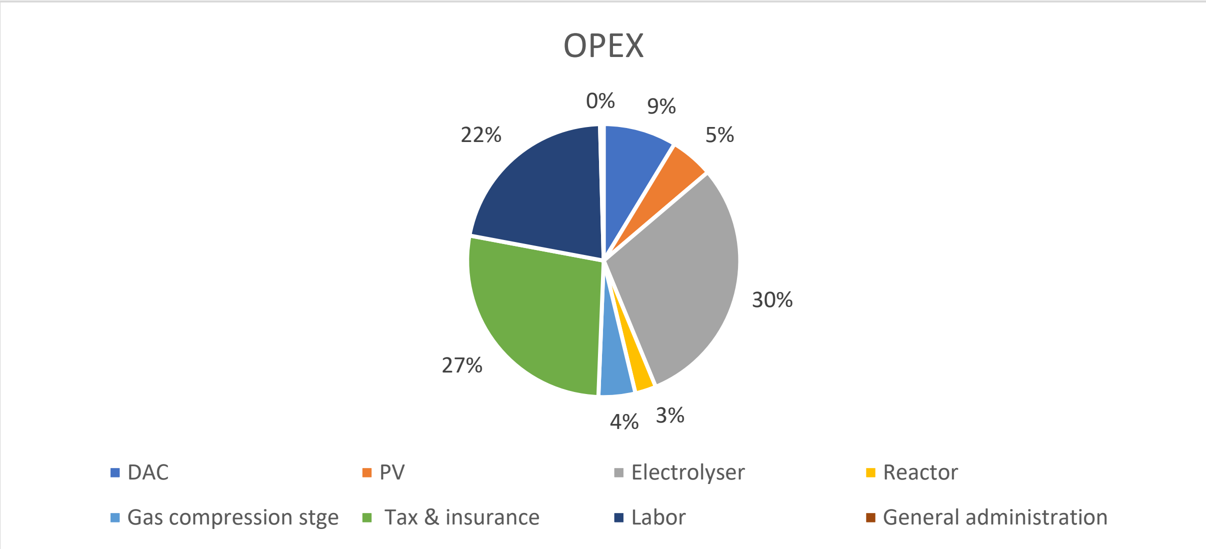

Figure 9. Opex breakdown for scenario 4
Source: Author

3.1.3 Losses Optimisation

This sub-section present the optimization of the economic losses identified previously. A sensitivity analysis is permormed on all the scenarios to obtain the optimal levelised cost of e-methanol for the project.

Sensitivity Analysis

A sensitivity analysis is performed in oder to see how the levelised cost of the e-methanol behave by variating some parameters. Three parameters are selected to see their influence on the LCOM..Those parameter are : tax and insurance, capacity of methanol production and the sale of oxygen.

❖ **Tax and Insurance**

In the previous result it can seen that for the scenario 1 and 2, the tax and insurance have the largest share of the opex. Fig 10 shows how the levelised cost change when tax and insurance is reduced gradually. It can be noticed a decrease of the levelised cost for all the scenario. The lower levelised cost is observed in scenario 1 whith 75% of tax reduction 661 $/ton.

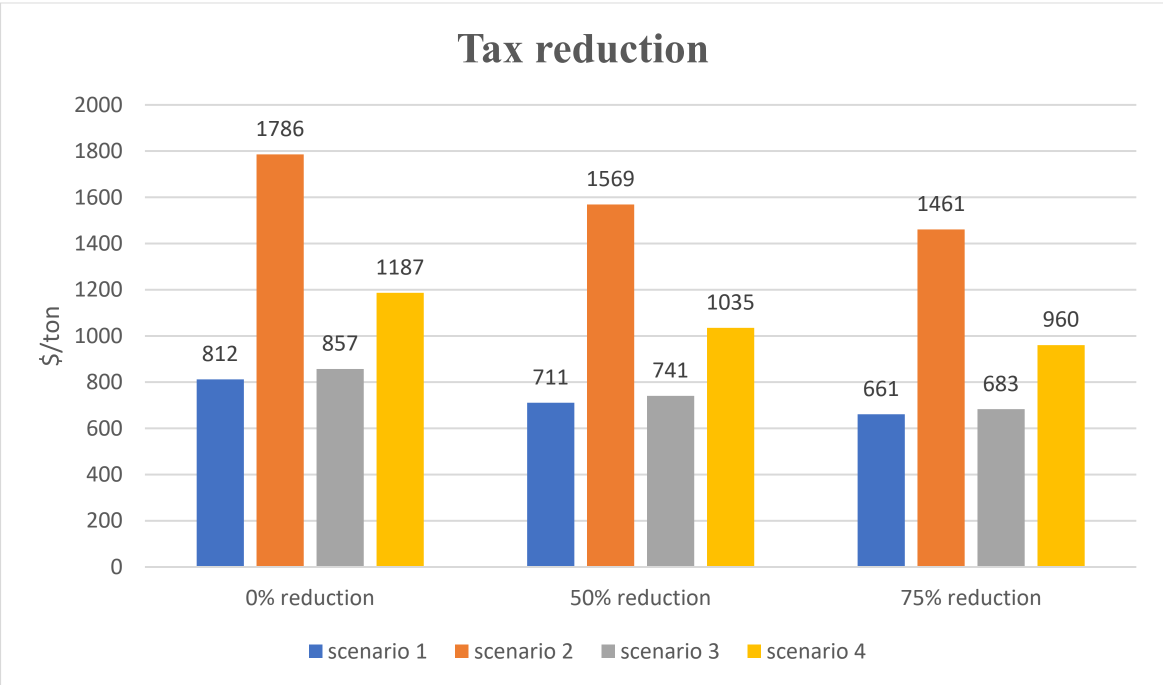

Figure 10. LCOM with different tax reduction
Source: Author

- **Capacity of e-methanol production**

The mass of the methanol produced annually is going to be variate base on two (2) value : 1000 ton and 1500 ton . in the sensitivity analysis it was assume that the labor is directly proportional to the capacity of the plant . Fig 11 show that the increase of the methanol mass decrease slightly the levelised cost for all the scenario. The lowest levelised cost is observe in scenario 1 with 1500 ton of e- methanol.

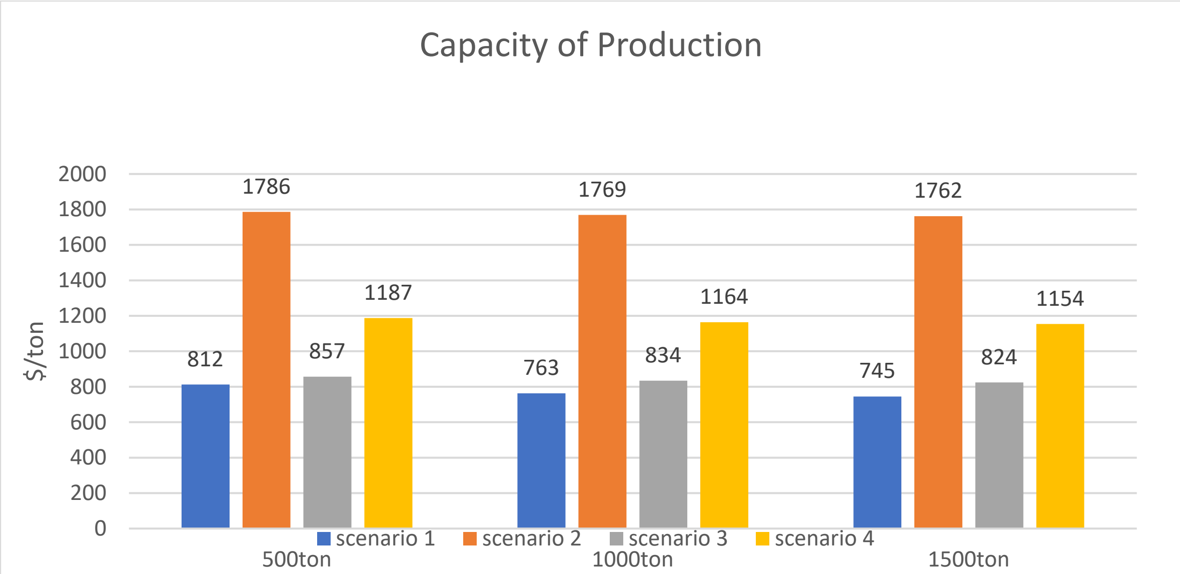

Figure 11. LCOM when scaling up the production capacity
Source: Author

- **Sale of oxygen**

The levelized cost of e-methanol is simulated with the consideration of selling the oxygen byproduct to assess its influence. As depicted in Fig. 12, the LCOM of all scenarios slightly increases when oxygen is sold. However, this option of selling oxygen is not viable for the project.

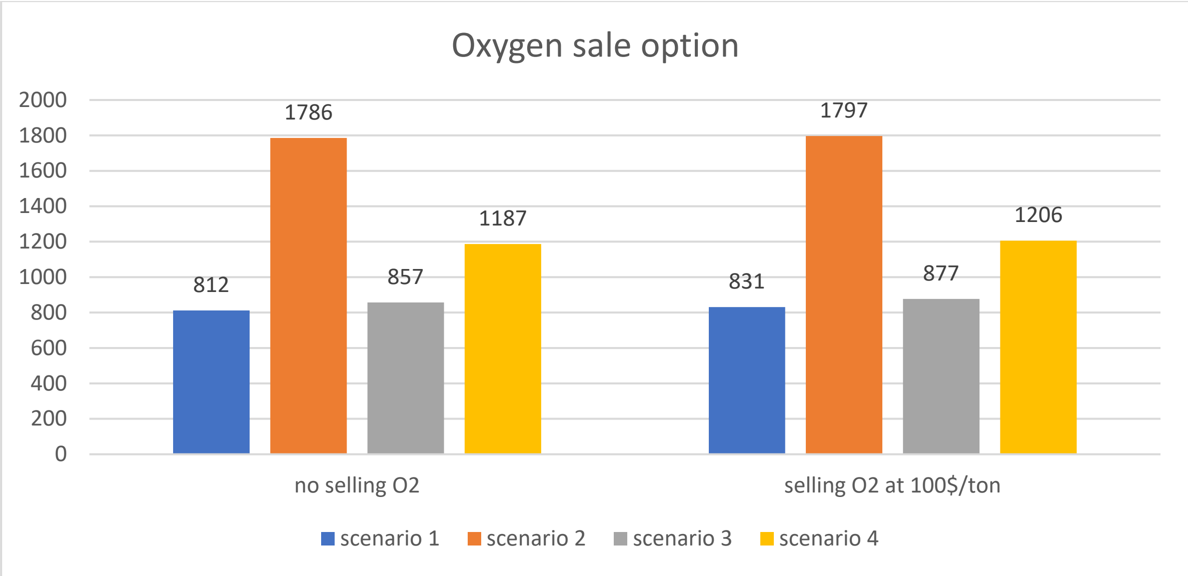

Figure 12. Influence of selling oxygen on the LCOM
Source: Author

In summary as outlined in the previous subsection the scenario 1 is the most cost effective option. In this sensitivity analysis the reduction in tax and the increase of the plant's capacity prove advantageous for achieving a lower levelised cost. When we apply a 75% tax reduction and increase the plant's capacity to 1500 tons, we can perform an optimal levelised cost of 612 $/ton.

3.2. Discusion

3.2.1 Business Model

In the economic layer, the value proposition primarily addresses the environmental concerns of customers. Those who are particularly concerned about reducing their carbon footprint will be interested to the product. From an economic aspect, e-methanol is more cost-effective compared to alternative solutions like electric cars and biofuel. (Siemens Energy, 2021). The cost of avoiding greenhouse gas emissions with e-fuels varies from under €200/tCO2 to €450/tCO2, while it can reach €700/tCO2 for bio-ethanol. Additionally, it's more sustainable than biofuel as it doesn't compete with food resources. However, a significant affordability challenge exists when comparing it to fossil fuel. To make e-methanol economically preferable for customers over fossil fuel, great improvements are needed. In this economic layer, a connection exists between two components: key partners and customer segments. Key partners include government, NGOs, and some suppliers. Government involvement can greatly incentivize companies to reduce pollution. Especially in the transportation and industrial sectors, this can increase the interest for e-methanol fuel and augment the customer. NGOs can contribute by raising awareness about climate change through various projects of sensibilisation. . Some study, emphasize the need of the government involvement to foster their business model. For instance Mustika et al. (2017), develop a business model with align with the government policy in Indonesia. Aligning with this, partnering with the government can impact the project's viability by influencing the cost structure. Government policies can reduce taxes on e-fuel and increase taxes on fossil fuel, ultimately lowering the production cost of e-methanol. Further, another link is observed between key resources and the cost structure. E-fuel production is energy-intensive. The availability of primary energy sources resource, such as solar can improve the quantity of the e-methanol produced and lower costs.

The interactions between these components demonstrate how each element contributes to the economic viability of an e-methanol plant.

In the environmental side, e-methanol offers a higher level of sustainability. Analyzing its lifecycle, e-methanol can reduce 95% of carbon emissions compared to fossil fuels (Jong et al.,2022). However, it has some environmental imapact, which are indicated in these elements : material, distribution, production, and usage phases. For the material impact, the efficiency of the carbon conversion to methanol depends on the quality of the catalysts material used. In the methanol synthetiser each unreacted mass of carbon deliver 44/12 of mass in the form of CO_2 (Carlo Hamelinck, 2022). For the distribution, emissions come from CO_2 rejection by the truck during the product delivering to the customer. According to (Marle de Jong et al., 2022), the emission factor for diesel truck transport is 263 gCO_2eq/tonne/km, whereas for pipelines, it is 15.74 gCO2eq/tonne/km. The distribution plays a significant role in the sustainability of e-methanol. The choice of the delivery mode is crucial and depends on the distance. In this project, trucks are used for short distances due to their convenience, but for longer distances, the preferred option is a pipeline to minimize distribution emissions. For the use-phase, the emission are from the combustion of e-fuel during the usage. For the production, the emission are provocated by the lower rate of the CO_2 conversion in the methanol reactor and the electricity generation process. It's important to note that, in the environmental LCA only the emissions during the usage phase are considered for the production equipment: solar panels, electrolyzers, and reactors.

At the social level, the mission of the e-methanol business is to improve the health of community and to reduce their reliance on fossil fuel. To achieve this, the startup must collaborate with stakeholders to develop a societal culture centered around environment protection, and efficient use of natural resource. The startup have a vision to extend it social impact by partnering with some green organization at a continental and international scale. The local community will be prioritized for the employment and training program will be offered to develop their existing skill. Contrarily there are negative impacts caused by the startup like the displacement of some community for the pv land requirement and the energy affordability if they want to shift from the fossil to the sustainable fuel.

In general there is a connection between the component of the tree layer. All the different type of value are linked. The improvement of the inefficiency in the environmental and social layer can impact the economic value positively.

3.2.2 Losses Identification and Analysis

In this study, the diverse results confirm the research hypothese regarding losses in the value creation of e-methanol. The identified losses are categorised base on the type of created value: environmental, social and economic losses.

Environmental value losses: in the environment layer of the business model, some inefficiencies have been identified in the management of waste of the materiel used, product distribution, carbon dioxide conversion in the methanol reactor during the production phase, and nitrous oxide and sulfur rejection during the fuel combustion.

Social losses: In the social layer of the business model, certain inefficiencies impact the social value created like the displacement of the community and energy poverty concern.
Economic losses : In all four (4) scenarios of e-methanol production, losses were observed including energy losses and cost efficiency losses.
Cost efficiency losses: high cost of certain of certain equipment such as the batteries and SOE were identified. The higher cost of SOE it is attributed to its technology maturity level. Energy losses are frequently caused by heat management and electrolyser efficiency.
For heat management, in the production lines, some equipment rejects heat while other consumes it in the form of energy. Equipment like isothermal reactor, alkaline and the PME electrolyser generate heat during operation whereas DAC and SOE require heat. If this rejected heat is not recovered, it would constitute an energy losses. This heat could have been used to reduce the energy consumption of certain equipment and minimise the size of the PV plant. Notably in all the four scenarios, around 858 MWh of heat from the e-methanol reactor was annually wasted, and not recovering this energy constituted an energy loss. For the hydrogen electrolyser efficiency, it was demonstrated in the result section that, it consumes more than 70% of the total energy. The choice of electrolyzer type that corresponds to the configuration of the e-methanol plant can affect the overall energy efficiency and the cost of producing e-methanol. Fig. 11 suggest how the different losses interact with the levelised cost and the plant configuration across all the scenarios.
In terms of storage, the utilization of batteries offers an extension of the operational time of the e-methanol plant, and a reduction in the size of production equipment apart from photovoltaics. However, from an economic perspective, the levelised Cost of the system with batteries significantly higher than the a system without batteries. This can be observed when comparing Scenario 1, which employs an alkaline system without batteries, with a levelized cost of $812 per ton, to Scenario 2, which utilizes an alkaline system with batteries and exhibits a levelized cost of $1786 per ton.
In term of type of electrolyser technology, the alkaline has best advantage to lower the levelised cost of methanol due to its intermediary energy efficiency and lower associated costs CAPEX. This is observed in Scenario 1, where the utilization of an alkaline electrolyzer results in the lowest levelized cost. On the other hand, Solid Oxide Electrolyzer SOE technology excels in terms of energy efficiency, boosting overall plant efficiency up to 57%. However, due to its relatively low maturity level, it carries a higher cost levelised cost with a significant capital

expenditure CAPEX. This is evident in Scenario 4, where the employment of SOE as the electrolyzer leads to the highest levelized cost of $1186 per ton.

The PME electrolyser is inbetween of the two (2) others technologies. Its cost and energy efficiency is slightly higher than the alkaline electrolyser. The levelised cost in scenario 3, which is $857 per ton, is not too far from the levelised cost of scenario 1.

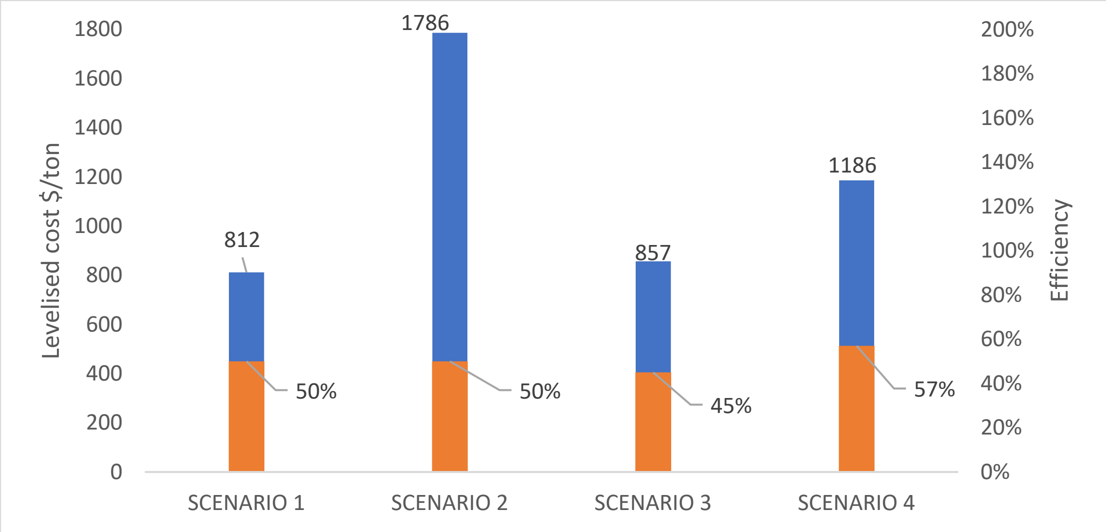

Figure 13. Scenarios comparison
Source: Author

3.2.3 Strategy of Losses Management

Recent research highlights the significance of effective heat management in achieving cost optimization. (Bos et al., 2020) conducted a study where they utilized the heat generated by the electrolyzer to meet the energy requirements of DAC, thereby enhancing the optimization of LCOM to 800 e/ton. Similarly, Lombardelli et al. (2021) undertook simulations for e-methanol production across three scenarios, incorporating heat integration and a purge stream. This yielded a range of LCOM values, with the best-case scenario achieving 1361 euros per ton.

In our current study, we combine various methods to minimize losses and optimize costs. Technically, we utilize heat recovery to enhance efficiency. We selected the electrolyzer which carry the lowest LCOM. Additionally, in a sensitivity analysis, we increase the production scale to 1500 tons per year and reduce taxes by 75%. This cumulative effort results in an optimal LCOM of 612 $/ton. This cost is notably close to the market price of conventional methanol, which stands at 450 euros per ton (Methanex, 2021). This achievement of 612 $/ton reflects a significant reduction from previously reported costs. Despite the advancement of various technical strategies such as heat recovery and scaling up, tax incentives play a crucial role in the cost-effectiveness of e-methanol. Therefore, government initiatives to decrease taxes on e-methanol can enhance its competitiveness against fossil fuels and encourage investment in this sustainable solution. However the impact of this losses optimation will lead to increase the increase the investment cost and a solid collaboration with differents stakeholders.

Summing up the comprehensive loss analysis derived from the results, we propose a holistic strategy for loss management, considering both environmental and social factors:

- Waste management : recycle of the waste of the sorben and catalyst;
- Distribution of the fuel by pipe line;
- Use the good catalyst to increase the CO_2 conversion in the methanol reactor;
- Research and development to eliminate the sulfur and nitroxide during the combustion of the fuel;
- Heat management : recovering waste heat for reuse;
- Choice of the electolyser type which fit the system;
- Increase the scale of production;
- Reduction of tax on the methanol.

CONCLUSION

Climate change's impact on water security in arid regions is evident through rising temperatures, and reducing rainfall. The root cause, increased carbon dioxide levels in the atmosphere, necessitates the urgent reduction of anthropogenic emissions from industrial and transport sectors. E-methanol emerges as a promising solution due to its compatibility with existing infrastructure, and carbon-negative attributes, preventing 2 tons of CO2 emissions per ton used. This work aimed to propose a suitable business model and conduct a comprehensive analysis of the value losses in e-methanol production. To achieve that, a case study method supported by TLMC and levelized cost was used. The selected case is an e-methanol plant in Cote d'Ivoire. By incorporating data from the literature review, a sustainable business model was designed to integrate e-methanol into the energy business landscape. To identify the losses, an analysis of the designed business model was conducted to highlight environmental and social losses. For economic loss determination, the levelized cost of methanol was calculated for four scenarios of e-methanol production: Scenario 1 using an alkaline electrolyser, Scenario 2 employing an alkaline electrolyser and batteries, Scenario 3 using PME electrolyser, and Scenario 4 using SOE electrolyser. The results of this study present a sustainable business model with three layers. The viability of the model is highly dependent on partnering with the government to establish policies that incentivize the use of e-fuel and improve cost effectiveness through tax reduction to 75%. Furthermore, social and environmental losses were identified, including waste from materials used, product delivery methods, CO_2 conversion inefficiencies, and emissions during combustion. Social losses were community displacement and energy poverty concerns. Economic losses were observed after analyzing the LCOM of the four scenarios, revealing challenges related to energy efficiency, heat management, and the high cost of specific equipment. Scenario 1 had the lowest LCOM at $812/t due to the low cost of the alkaline electrolyser. The highest LCOM of $1797/ton was observed in Scenario 2, where battery storage was incorporated. Among different electrolyser types, Scenario 4, which used SOE electrolyser, had the highest LCOM at $1206/t.

Through a sensitivity analysis involving varying the e-methanol plant capacity and tax rates, an optimal levelized cost of $612/t was achieved in Scenario 1 by scaling up the plant capacity to 1500 tons and reducing taxes by 75%.

In this study, a strategy to address value losses is proposed. In the short term, losses can be managed through recycling sorbents and catalysts, fuel distribution via pipelines, enhancing CO_2 conversion using effective catalysts in methanol reactors, heat recovery for reuse, selecting appropriate electrolyzers, reducing methanol-related taxes, and scaling up production. In the long term, losses can be managed by conducting study research on mitigation of sulfur and nitroxide emissions during fuel combustion and reducing the cost of certain technologically immature equipment.

In summary, the business development of e-methanol is highly dependent on government contributions to incentivize investment and energy transition. The cost competitiveness of e-methanol relies on plant configuration (type of electrolyser) and the policy framework established by the government.

LIMITATIONS AND FUTURE WORK

One limitation in the exploration of e-methanol business models and losses reduction is the lack of real-time and updated data due to its current developmental stage. As e-methanol is still in the emergent phases as a solution, there exists a scarcity of practical implementation and operational data that can be used to accurately model its economic and environmental performance. Relying on outdated data and certain assumptions may introduce potential inaccuracies and diminish the credibility of the study's findings.

The finding of this study underscore the paramount significance of collaborative efforts between the government and stakeholders to ensure the prosperity of the proposed business model. To comprehensively assess the adaptability and resilience required for effective energy transition, a socio-economic research study becomes essential. This future study will delve into the engagement of stakeholders, gauge public acceptance levels, and examine the fluctuations in market demand. This comprehensive approach will contribute to a more informed and strategic implementation of the e-methanol business model, aligning it with the evolving energy landscape.

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Appendix

Table A 1 : VARIABLES COSTS

VARIABLES		VALUES	UNITS	SOURCES
DAC	capex	350	$/t	(International Energy Agency, 2022)
	opex	4% of capex	$/t	(Nizami et al., 2022)
PV	capex	600	$/kW	(Nizami et al., 2022)
	opex	9	$/kW	(Nizami et al., 2022)
PEM ELECTROLYSER	capex	1100	$/kW	(Nizami et al., 2022)
	opex	14.52	$/kW	(Nizami et al., 2022)
	Stake replcmt	35	%capex	(Monitor Deloitte, 2021)
	Life time	80 000	hours	(IRENA, 2020)
ALKALINE ELECTROLYSER	capex	750	$/kW	(IRENA, 2020)
	opex	15	$/kW	(Monitor Deloitte, 2021)
	Stake replcmt	35	%capex	(Monitor Deloitte, 2021)
	Life time	60 000	hours	(IRENA, 2020)
SOE ELECTROLYSER	capex	1600	$/kW	(Monitor Deloitte, 2021)
	opex	80	$/kW	(Monitor Deloitte, 2021)
	Stake replcmt	50	%capex	(Monitor Deloitte, 2021)
	Life time	25 000	hours	(Monitor Deloitte, 2021)
MeOH Synthetiser	capex	275	$/t	(Nizami et al., 2022)
	opex	2	%capex	(Nizami et al., 2022)
BATTERY	capex	200	$/kWh	(Nizami et al., 2022)
	opex	7.5% capex	$/kWh	(Nizami et al., 2022)
	Life time	15	Years	(Nizami et al., 2022)
CO2 Compressor	capex			
	opex	2%capex		(Sollai et al., 2023)
	Life time	80000	hours	(Sollai et al., 2023)
H2 Compressor	capex			
	opex	2%capex		(Sollai et al., 2023)
	Life time	80000	hours	(Sollai et al., 2023)
O2 Compressor	capex			
	opex	2%capex		(Sollai et al., 2023)
	Life time	8000	hours	(Sollai et al., 2023)
CO2 Storage	capex	9265	$/m^3	(Sollai et al., 2023)
	opex	3%capex	$/m^3	(Sollai et al., 2023)
H2 , O2 Storage	capex	49.09	$/m^3	(Sollai et al., 2023)
	opex	3%capex	$/m^3	(Sollai et al., 2023)
LAND	capex	30	$/m^2	Asumption from World Bank

Table A 2 Solar irradition for Cote ivoire. Coordonates (10.105; -5.610)

Months	**Values**	**Units**
January	190.64	kWh/m^2/month
February	198.54	kWh/m^2/month
March	193.23	kWh/m^2/month
April	198.14	kWh/m^2/month
May	201.1	kWh/m^2/month
June	182.17	kWh/m^2/month
July	158.8	kWh/m^2/month
August	149.88	kWh/m^2/month
September	152.73	kWh/m^2/month
October	188.42	kWh/m^2/month
November	189.12	kWh/m^2/month
December	184.65	kWh/m^2/month

Source: PVGIS Database