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 :

Modelling cost structures of green hydrogen production through Direct Air Capture (DAC) in Senegal.

Presented the 20/09/2023 by :

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Date: September 15th, 2023 Signature: **Pingwinde Prephina Rouamba**

DEDICATION

This thesis is dedicated to Francois Dapelgo and Aline Dapelgo

To my family

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ABSTRACT

This paper presents a modelling cost structure of the stand-alone system of green hydrogen production coupled with a direct air capture (DAC) over a period of one year, having a daily production of 1 ton of hydrogen(H_2) and 7 tons of carbon dioxide (CO2). The electricity source for the facility is solar photovoltaic (PV) systems, while concentrated solar power (CSP) is harnessed to provide heat. Additionally, the water necessary for the electrolysis process is sourced from Direct Air Capture (DAC). A keen attention is paid to the DAC component to understand the operating principles and interplay with other components. The research is conducted in Senegal, focusing on specific subcases located in Saint-Louis, Touba, Tambacounda, Kolda, and Ziguinchor. Each of these locations represents the different climatic zones of Senegal. The primary aim is to identify the best weather conditions for a competitive stand-alone system and to determine the cost drivers of such a system. The data used are secondary data extracted from the literature and official websites. We perform calculations through a Python-based algorithm to determine the economical parameters of each case and then determine the optimum scenario. We determine the annualised cost and the levelized cost of the different commodity using weather data from the year 2019. Hydrogen can be produced in Senegal at a levelized cost ranging from 6.88-7,57 €/kg_{H2} and a carbon dioxide capture cost ranging from 6,88 to 7,57 €/kgH2. the conclusion of this study is that humid regions with good potential for renewable energy are favourable to such a system. The cost of heat acts as a primary cost driver.

Key words: DAC; SOEC; Adsorption capacity; Regeneration heat; LCOC

RESUME

Cet article présente une structure de coûts de modélisation du système autonome de production d'hydrogène vert couplé à un système de capture directe de l'air (DAC) sur une période d'un an, avec une production quotidienne d'une tonne d'hydrogène (H2) et de 7 tonnes de dioxyde de carbone (CO2). La source d'électricité de l'installation est constituée de systèmes solaires photovoltaïques (PV), tandis que l'énergie solaire concentrée (CSP) est exploitée pour fournir de la chaleur. En outre, l'eau nécessaire au processus d'électrolyse provient du captage direct de l'air (DAC). Une attention particulière est accordée au composant DAC afin de comprendre les principes de fonctionnement et l'interaction avec les autres composants. La recherche est menée au Sénégal, en se concentrant sur des sous-cas spécifiques situés à Saint-Louis, Touba, Tambacounda, Kolda, et Ziguinchor. Chacune de ces localités représente les différentes zones climatiques du Sénégal. L'objectif principal est d'identifier les meilleures conditions climatiques pour un système autonome compétitif et de déterminer les facteurs de coût d'un tel système. Les données utilisées sont des données secondaires extraites de la littérature et des sites web officiels. Nous effectuons des calculs à l'aide d'un algorithme basé sur Python afin de déterminer les paramètres économiques de chaque cas, puis le scénario optimal. Nous déterminons le coût annualisé et le coût nivelé des différents produits en utilisant les données météorologiques de l'année 2019. L'hydrogène peut être produit au Sénégal à un coût levé allant de 6,88 à 7,57 €/kgH2 et un coût de capture du dioxyde de carbone allant de 6,88 à 7,57 €/kgH2. La conclusion de cette étude est que les régions humides avec un bon potentiel pour les énergies renouvelables sont favorables à un tel système. Le coût de la chaleur est le principal facteur de coût.

Mots cles : DAC; SOEC; Capacité d'adsorption; Chaleur de régénération; LCOC.

ACRONYMS AND ABBREVIATIONS

- **ACC**: Annual Capital Charge
- **ACCR**: Annual Capital Charge ratio
- **BAU**: Business As Usual
- **BECCS**: Bioenergy with Carbone Capture and Storage
- **BET**: Brunauer–Emmett–Teller
- **Capex**: Capital Expenditures
- **CDR**: Carbon Dioxide Removal
- **CO2**: Carbone Dioxide
- **CSP**: Concentrated Solar Power
- **DAC**: Direct Air Capture
- **GAB** : Guggenheim–Anderson–de Boer
- **H2**: Hydrogen
- I**RENA**: International Renewables Energy Agency
- **JETP**: Just Energy Transition Partnership
- **LCA**: Life Cycle Assessment
- **LCOC**: Levelized Cost of Carbon
- **LCOC**: Levelized Cost of Carbon
- **LCOH**: Levelized Cost of Heat
- **LCOH**$_{2}$: Levelized Cost of Hydrogen
- **L-DAC**: Liquid Direct Air Capture
- **LNG**: Liquefied Natural Gas
- **LOHC**: liquid organic hydrogen carriers
- **LT- DAC**: Low Temperature DAC
- **MILP**: Mix Integer Linear Programming
- **NDCs**: Nationally Determined Contributions
- **NET**: Negative Emissions technology
- **O2**: Oxygen
- **PEM**: Proton Exchange Membrane
- **PV**: Photovoltaic
- **RE**: Renewable Energy
- **S-DAC**: Solid Direct Air Capture
- **SOEC**: Solid Oxide Electrolysis Cell
- **SOFCs**: solid oxide fuel cells#
- **TAC**: Total Annualised cost
- **TRL**: Technological Readiness Level
- **UK**: United Kingdom
- **WAPP**: West Africa Power Pool
- **WASCAL:** West African Science Service Center on Climate Change and Adapted Land Use

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1. Introduction

1.1 background

"The only way to prevent catastrophic climate change is to phase out fossil fuels and transition to clean, renewable energy sources as quickly as possible." Said once the Environmentalist and Author Bill McKibben. As response to Paris Agreement new pathways and new technologies are developed for a greener world. It is in this context that Direct Air Capture (DAC) and green hydrogen are being explored individually or together for the production of green e-methanol. Hydrogen, as an energy vector, holds promise in enabling the integration of renewable energy sources and increasing their penetration levels. Moreover, hydrogen flexibility, versatility, and portability open the door for sector coupling. DAC is receiving queen attention among Carbon Dioxide Removal (CDR) technologies. Qualities such as location flexibility, space efficiency, productivity, and modularity give DAC a competitive edge over other technologies.

Senegal, a country located in West Africa on the Atlantic coastline has a good potential in solar and wind energy. However the energy supply relies mainly on imported oil with a share of 54% (EITI, 2021) and the electricity access rate is 68%(World Bank, 2023a). Nevertheless, Senegal has shown a strong commitment for energy transition and Greenhouse Gases Emissions reduction, which has led to the implementation of several strategies at national, community and international levels. Deploying green hydrogen and DAC in Senegal could be part of the country's dynamic and could boost the energy transition, even though Senegal does not yet have a policy or agenda for implementing these technologies.

The energy transition is not only about shifting from fossil fuel to renewable energies but involves cost efficiency and socio-economic impacts. The high cost of green hydrogen and DAC is a barrier their expansion, with a high part of the cost due to the capital investment in and energy cost. A pile of research has been done and is still going on the different ways to reduce cost. It is in this context that Sendi et al., (2022) shows the importance of understanding how regional differences affect DAC techno-economic performance. Indeed, relative humidity and temperature has an influence on DAC performance. Most studies neglected this aspect and those that consider made the assumption to operates in dry conditions. This situation has given rise to concern, so the aim of the studies on CO_2/H_2O co-adsorption was to propose solutions to reduce the energy penalty that comes with water desorption. To the best of our knowledge there is no study available on DAC as a water cooperative model.

This paper Models the cost structures of green hydrogen production through Direct Air Capture (DAC) in Senegal and answer the following research questions: What is the impact of the temperature and humidity on DAC efficiency? What the cost drivers?

1.2 Scope and objectives

The aim of DAC technology is to capture CO2 with water release as a byproduct, which could be used to supply the electrolyser's demand in water. The scope of this thesis encompasses an in-depth exploration of the synergistic relationship between carbon capture approached as a water cooperative model and hydrogen production within the context of sustainable energy solutions. This study will investigate the technological and economic aspects of integrating carbon capture techniques with hydrogen generation processes in Senegal.

The performance of DAC plants will be highly dependent on the climate and weather fluctuations of their location; therefore, we will choose 5 study cases based on the 5 climatic zones of Senegal. Then we will develop a framework to determine the levelized cost of hydrogen (LCOH) and levelized cost of carbon (LCOC) of a plant integrating solar PV and solar thermal power as energy sources. The results will shed light on the interplay between the plant performance and the different climates conditions and determine the optimal case. Additionally, the optimal case will undergo a sensitivity analysis to determine the cost drivers.

The structure of the thesis will be delineated into three distinct sections. The initial segment will encompass a comprehensive literature review that furnishes an overarching perspective of prior research endeavours within this domain. Subsequently, the second section will expound upon the intricate methodology employed in this study. Lastly, the concluding segment will be dedicated to presenting the findings, engaging in analytical discussions, and undertaking a meticulous examination.

2. Concept of DAC and SOEC

2.1 Theoretical Framework

2.1.1 Carbon Removal and Green hydrogen in climate change mitigation

The first objective of the Paris Agreement is to limit global warming by keeping the global average temperature rise well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 degrees Celsius. This target is crucial to avoid the most severe impacts of climate change. However, some scientists like (Beuttler et al., 2019) showed that such a goal either requires extremely ambitious reductions of carbon emissions within the next decade (energy transition), or extensive use of technologies and management techniques to remove carbon dioxide from the atmosphere. The achievement of a goal of limiting warming below 1.5 ° C by the end of the century is now almost impossible without the removal of carbon dioxide from the atmosphere (Meckling & Biber, 2021). Negative Emissions Technologies (NETs) also referred to as Carbone Dioxide Removal (CDR) are technologies that encompass a diverse range of processes and systems designed to actively extract CO2 from the atmosphere. The ultimate goals of these technologies include the permanent storage of CO2 or its utilization for various purposes (Young et al., 2021). The scientific literature discusses a number of prominent CDR strategies such as increased weathering, carbon capture and storage, afforestation, Bioenergy with Carbon Capture and Storage (BECCS), agricultural practices, and changes in land use. CDR is part of a comprehensive strategy for “net” zero, where emissions being released are ultimately balanced with emissions removed, resulting in a net reduction of greenhouse gas concentrations, particularly CO2, and contributing to efforts in achieving climate goals(IEA, 2022).

Among CDR, DAC (Direct Air Capture is receiving a queen attention. Direct Air Capture (DAC) refers to the extraction of CO2 from the air through an artificial contractor. DAC offers the benefit of effectively tackling emissions from distributed and mobile sources, such as those originating from the transportation sector, by addressing both current and historical emissions (Wurzbacher et al., 2012). In general, the primary advantage of DAC technology is its space efficiency and adaptability to non-arable land, thus avoiding additional strain on ecosystems and food systems(Beuttler et al., 2019). Thanks to all these benefits DAC has a significant appeal for climate change mitigation. Few evaluations of DAC's potential role in climate mitigation have been conducted, and those that exist highlight its significant influence on mitigation alternatives. DAC scenarios show net negative emissions, resulting in substantial carbon removal (Marcucci et al., 2017). By comparing scenarios with and without DAC, it becomes clear that DAC plays a crucial role in shaping the form of the mitigation pathway and the timing of peak emissions (Realmonte et al., 2019). DAC offers possibilities for meeting the Paris Agreement's temperature targets of 1.5 °C or 2 °C.

Hydrogen is a highly prized gas due to hits numerous applications. As of 2018, there was a 70 million of ton global demand for pure hydrogen (Bhandari & Shah, 2021). Depending on the source of production, hydrogen is classified into several categories. Steam reforming is the most commonly used process for hydrogen production due to a cheaper cost of production 1.5-2€/kg(Gerloff, 2023). However, this contributes to large emissions. As the world focuses more on sustainable energy solutions and reducing carbon emissions, green hydrogen has gained increased attention as a versatile and eco-friendly energy carrier with the potential to revolutionize various industries and contribute to a cleaner and more sustainable future. There is various pathway to produce green hydrogen as shown in figure 1. However, the cost remains a limiting factor. Biomass-based hydrogen production is more affordable and environmentally friendly than other renewable energy-based hydrogen production processes(Wang et al., 2019).

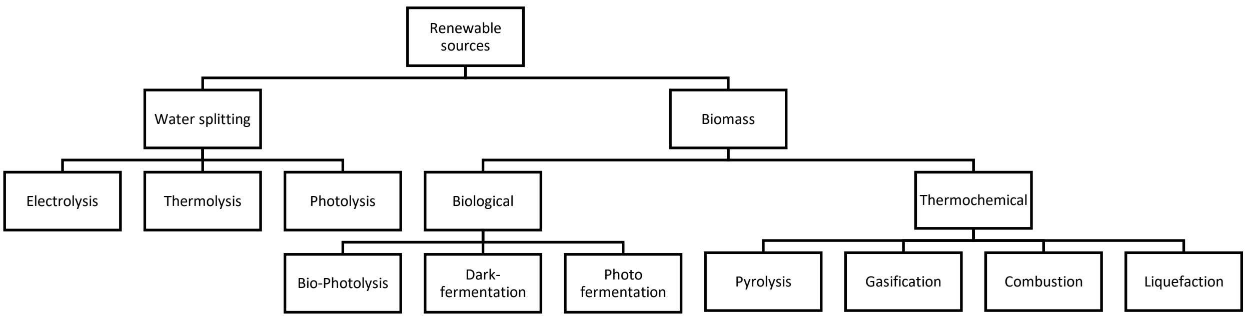


Figure 1:Hydrogen production method base on renewable (Nikolaidis & Poullikkas, 2017)

As part of the energy transition, electrolytic hydrogen holds great promise due to the numerous advantages its presents. Green hydrogen trough electrolysis is offering a viable solution for the renewable energy to be stored on a long term base, carried and converted to the suitable form when needed (Bhandari & Shah, 2021). A way to finally unleash the deployment of renewable energies and making energy transition a reality. In addition to meeting the existing electricity need, the renewable energy potential from wind, solar, and hydro can also meet the increased electricity requirement for electrolytic hydrogen (Bhandari & Shah, 2021),(Yates et al., 2020).

As a storage and flexibility alternative, as well as carbon capture and utilization (CCU) technology, the conversion of electrolytic H2 and CO2 into liquid fuels (Power-to-Liquid, PtL) is gaining increasing interest (Dieterich et al., 2020). This process is particularly appealing because it offers the possibility of sector coupling between electricity sector and transport , moreover it will allow the decarbonization of hard-to-abate sectors(Dieterich et al., 2020). Furthermore, when atmospheric CO2 is utilized, the resulting fuels can become almost carbon-neutral since the CO2 emitted during their combustion was previously captured from the atmosphere. This capability allows DAC technology to support the establishment of a circular economy free from fossil hydrocarbons and contribute to conventional climate change mitigation efforts as well (Beuttler et al., 2019).

2.1.2 West Africa and Senegal framework for Climate mitigation

Achieving Sustainable Development Goal (SDG) 7: Ensure universal access to affordable, dependable, and modern energy services is a long-term issue for the energy sector in the ECOWAS area (ECREEE, 2022). According the World Bank 220 million people live without access to power in West Africa, which also has one of the lowest electrification rates and some of the most expensive electricity prices in Sub-Saharan Africa(World Bank, 2023b), with one of the challenges being the lack of distribution infrastructures. To alleviate this problem, initiatives have been taken at regional level, such as the creation of the West Africa Power Pool (WAPP). However, it has to be said that energy supply is essentially based on fossil fuels, the vast majority of which are imported. As part of the climate change mitigation, and given the region's huge potential in renewable energies an energy transition is envisaged.

This led to the adoption of the ECOWAS renewable energy policy in July 2013 (ECREEE, 2013), with the aim is to promote renewable energies and increase the energy mix. One of the main points of this agreement is to reach a grid connected RE mix of 23% in 2020 and 31% in 2030(including medium and large hydro) and a blending ratios for Ethanol/Bio-diesel in transport by 5% in 2020 and 10% in 2030(ECREEE, 2013). Alle stakeholder of ECOWAS committed to regional sustainable energy initiatives, but have different starting points and different RE agendas. The creation of a strategy for renewable energy and an implementation plan for it has already advanced in Member States(ECREEE, 2013), which is the case of Senegal.

The government of Senegal adopted a new development strategy named Emerging Senegal Plan which gave a new dynamic and ambitious target for energy transition. In the nationally determined contributions (NDCs) in accordance with Paris Agreement , two primary goals are outlined: using more natural gas to replace fuel oil and coal-fired power plants, and increasing the share of renewable energy in the country's energy mix to 40 percent by 2035 (EITI, 2021). Moreover, Senegal wants to conditionally cut its greenhouse gas (GHG) emissions by at least 23% by 2030. To the best of our knowledge neither ECOWAS nor Senegal has an available policy or roadmap related to carbon capture and green hydrogen.

In June 2023, the EU and the International Partners Group announced the creation of a partnership for a just energy transition (JETP) with Senegal, combining climate and development objectives. This partnership which is the first of its kind in Africa, heralds a new dynamic in terms of the political and financial aspects of the energy transition in Senegal. This partnership will support both the publication by COP28 of a vision for a long-term low greenhouse gas emission development strategy (LTS) due to be finalized in 2024 and the acceleration of the deployment of renewable energies, increasing the share of renewable energies in installed capacity to 40% of Senegal's electricity mix by 2030(EU, 2023). New climate ambition is expected to be published at COP30.

2.2 Technical review of the technology

2.2.1 Different technology of DAC and water co-adsorption

There are two primary DAC technology pathways available, depending on the material used to capture CO_2, which can either be an aqueous solvent or a solid sorbent. The solid sorbent t type uses amine materials bonded to a porous solid support operating through an adsorption/desorption cycling process. A wider range of solid sorbents are being investigated (e.g. ionic membranes24, zeolites25, solid oxides (Realmonte et al., 2019). While the adsorption takes place at ambient temperature and pressure, the desorption happens through a temperature–vacuum swing process, where CO_2 is released at low pressure7 and medium temperature (80-100°C)(IEA, 2022). Both processes have their respective advantages and drawbacks.

Solid DAC and Liquid DAC had both the capacity to remove CO_2 from the air while S-DAC can produce water by extracting it from the air, L-DAC needs water for its continuous operation.(IEA, 2022). Hydroxide solutions require high-temperature heat to be regenerated (T > 800 °C), which can be provided by burning natural gas, while amine adsorbents require only approximately 85–120 °C, meaning that waste heat can be used(Realmonte et al., 2019), beside regeneration is carried in the same unit. Waste heat could be found in waste incinerators, electrolyzers, or Fischer-Tropsch synthesis plants, as well as in combined heat and power plants like geothermal or solar thermal power plants(Breyer et al., 2019). Liquid DAC technology is more mature, it employs equipment already developed and adopted in other industry, the major expenditure is related to capital investment for building plant facilities, with limited potential for future cost reduction(Realmonte et al., 2019). Due to the inclusion of more widely used components, such as calcination, the liquid DAC method might experience faster industrial scalability. The S-DAC route's new technologies, on the other hand, may have a greater learning rate, which could hasten the industrial scaling (Breyer et al., 2019). However, both technologies are still in their early stages of development and commercialisation. According to IEA the technology is still at a Technological Readiness Level (TRL) of 6. In this paper we will focus on S-DAC , mainly because it releases water.

S-DAC technology, in addition to capturing CO_2, has the potential to coextract water from ambient air. This water coextraction can be valuable, especially in solar fuel production plants located in regions with vast solar irradiation but limited fresh water resources(Wurzbacher et al., 2012). The water co-adsorbed during the DAC process could be used for various purposes, including drinking water, which aligns with several Sustainable Development Goals (SDGs) such as 13 (Climate Action), 9 (Industry, Innovation, and Infrastructure), and 6 (Clean Water and Sanitation) (Beuttler et al., 2019). While water co-adsorption has potential benefits, it also increases the energy demand, which poses challenges for DAC technology (Breyer et al., 2019). The heat requirements for water desorption during sorbent regeneration can be substantial and will typically be of the same order of magnitude as the heat of evaporation of the co-adsorbed water (Wurzbacher et al., 2012). A process based approach to reduce the energy penalty of water co-adsorption is the humidity swing adsorption concept(Drechsler & Agar, 2020). DAC performance, including capital and operational costs, is sensitive to temperature and humidity. Different climate conditions can influence the productivity and energy requirements of DAC plants, impacting their cost and efficiency(Sendi et al., 2022). With this in mind, particular attention is paid to amine-functionalized solid sorbents because of their tolerance to air moisture, in contrast to physical sorbents such as zeolites, an increase of the CO2 adsorption capacity was observed under humid conditions compared to dry conditions(Wurzbacher et al., 2012). Understanding the co-adsorption of CO2 and H2O is crucial for optimizing DAC processes.

Novel mechanistic co-adsorption isotherm models have been developed to describe the interaction between CO2 and H2O in DAC sorbents(Young et al., 2021). CO2 adsorption is described by Toth Isotherm model (Drechsler & Agar, 2020) and H20 adsorption is described by Brunauer–Emmett–Teller (BET) isotherm model (Drechsler & Agar, 2020) or Guggenheim–Anderson–de Boer(GAB) isotherm model(Young et al., 2021) which is an extension of BET model. The role of humidity in enhancing CO2 adsorption on amine-functionalized adsorbents has been demonstrated by (Wurzbacher et al., 2012) and(Young et al., 2021). Relative Humidity has boosting influence during adsorption on both CO2 and H2O capacities; compared to CO2 adsorption, the influence on H2O adsorption is greater(Wurzbacher et al., 2012). According to (Sendi et al., 2022) within a temperature range of 1C to 30C , Relative Humidity has an observable effect on both electricity requirement and productivity, while temperature change only has a noticeable effect on productivity However, as temperature increases to 40C and 50C, the effect of temperature on electricity requirement becomes more apparent. Colder and drier regions, where the temperature remains above the DAC operating temperature of 15°C for most of the year, are highly suitable for DAC, disregarding capital costs. However, these regions might not offer the most economical Levelized Cost of Direct air capture (LCOD) due to energy costs(Sendi et al., 2022). The worse performance of the DAC unit can be counterbalanced by the abundant and cost-effective availability of renewable energy(Wiegner et al., 2022).

2.2.2 Hydrogen production via electrolysis

Water electrolysis, driven by renewable electricity, is a clean and effective method of hydrogen production. The process involves breaking down water molecules into hydrogen and oxygen gases, it occurs in an electrolytic cell consisting of a positively charged anode and a negatively charged cathode. Overall, the electrolysis of water results in the production of oxygen gas (O2) at the anode and hydrogen gas (H2) at the cathode. There are different technologies for the electrolysis of water: alkaline, proton exchange membrane (PEM) and solid oxide electrolysis (SOE).

Alkaline electrolyser, also referred as low-temperature electrolysis cell is a well-established technology. KOH or NaOH aqueous solution serves as the electrolyte in alkaline water electrolysis, which operates at a temperature (60–80 °C)(Chi & Yu, 2018). Alkaline electrolyzers have a maximum working current density of less than 400 mA/cm2, and the power needed to produce H2 is roughly 4.5–5.5 kWh/Nm3 with an efficiency of 60–70%(Chi & Yu, 2018). Alkaline electrolysis does, however, have drawbacks, such as its inability to produce current densities greater than 400 mA/cm2(Shiva Kumar & Himabindu, 2019). Moreover, its slow starting process and slow loading response, makes it difficult to cope with the fluctuation of renewables energies.

PEM electrolyser, also known as a polymer electrolyte membrane electrolysis, is a device that uses a solid polymer electrolyte membrane to conduct protons and separate product gases during the process of water electrolysis. The current density is above 2 $A.cm^{-2}$ and energy efficiency is the range of 80–90%(Shiva Kumar & Himabindu, 2019). PEM electrolysis facilities are more easier to balance, making them more appealing for industrial applications(Chi & Yu, 2018). They can operate with more flexibility and is therefore more suitable for renewables energies. However, the cost of PEM electrolysis was high since expensive materials were used(Naeini et al., 2022). PEM is advantageous over alkaline with a smaller footprint(LAZARD, 2021)

Solid Oxide is the less mature technology among the electrolysers. The principle of operation SOEC is the reverse of that of solid oxide fuel cells (SOFCs). Steam is produced from water during solid oxide electrolysis, which runs at high pressures and temperatures (500–850 °C)(Shiva Kumar & Himabindu, 2019), these high temperatures are necessary to thermally activate oxide ion migration and facilitate electrochemical reactions on both electrodes. O2 conductors used in the solid oxide electrolysis technique are mostly made of nickel/yttria stabilized zirconia(Liang et al., 2009). The operating principle is depicted on figure 4. At the anode, the water reduction reaction takes place. Oxygen ions (O2-) migrate from the cathode to the anode and release electrons to the external circuit. At the cathode, the water oxidation reaction occurs. Steam is fed into the porous cathode, and when a voltage is applied, the steam moves to the cathode-electrolyte interface and is reduced to form pure hydrogen (H2) and oxygen ions. The halves equations at the anode and cathode and the overall reaction of the cell are as follows respectively:

$$2\ O2- \rightarrow O2 + 4\ e- \qquad (1)$$

$$H2O + 2\ e- \rightarrow H2 + O2- \qquad (2)$$

$$H2O \rightarrow H2 + \tfrac{1}{2}\ O2- \qquad (3)$$

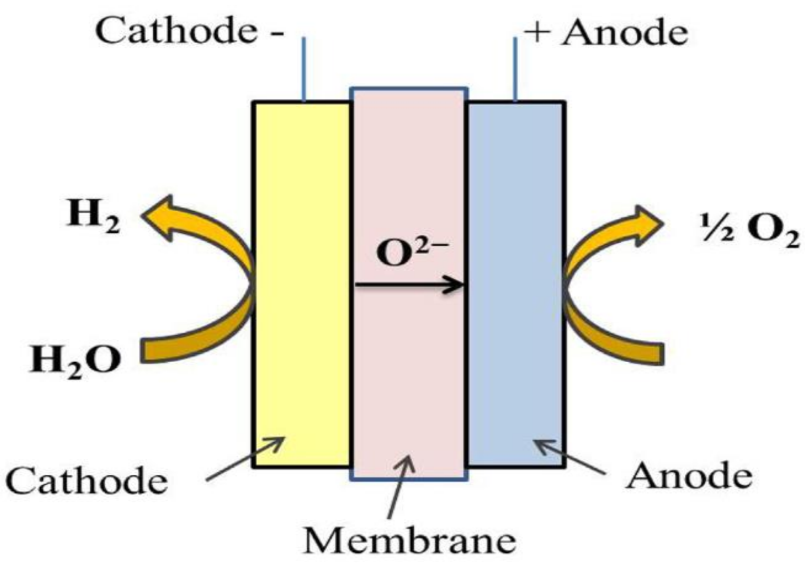


Figure 2:SOEC operating principle (Shiva Kumar & Himabindu, 2019)

Thermoneutral, endothermal, and exothermal are the three operating modes that are compatible with SOEC according to (Gerloff, 2023) . He asserts that for the thermoneutral operational state, the energy input aligns with the energy demand, resulting in a 100% efficiency for converting electrical energy to hydrogen. Conversely, the exothermal mode yields an efficiency below 100% due to an energy input surpassing the reaction enthalpy. Conversely, the endothermal mode demands external heat input, like process heat, to maintain temperature since the electrical energy input falls below the reaction enthalpy. Due to their high working temperatures, SOECs are more effective at producing hydrogen per unit of power used than low-temperature electrolysers(Sanz-Bermejo et al., 2015). Indeed the efficiency is the range of 90-100%(Shiva Kumar & Himabindu, 2019), which is due to an thermodynamic efficiency and a faster kinetics. Moreover, SOEC can be integrated with downstream industrial processes, enabling the production of synthetic fuels, methanol, ammonia, and carbon dioxide recycling. However, due to the high amount of deterioration these cells frequently encounter, the large-scale commercialization of solid oxide electrolysis cells (SOECs) has not yet been accomplished(Naeini et al., 2022). Temperature, current density, and fuel gas humidity have the greatest effects on SOEC degradation(Hoerlein et al., 2018). 14 years is longest period of time known for the functioning of solid oxide cells before a catastrophic failure(Naeini et al., 2022).

2.3 Techno-economic review of the technology

2.3.1 Hydrogen production

Cost effectivity remains a barrier for the expansion of green hydrogen based on electrolysis. In regards to this situation numerous analyses have been done, and the literature body continue to grow. For hydrogen to be cost efficient the cost of production has to be competitive with hydrogen from fossil fuel. The main components entering in the calculation of the Hydrogen levelized cost of hydrogen ($LCOH_2$) are the Capex of the Electrolyser and Bop, the operational and maintenance (O&M) cost, the cost of electricity and the cost of water and finally the discount rate. From the literature we have various results due to the different methodology and different energy source adopted by the authors, which makes it difficult to not to do biased-comparison.

In order to reduce the $LCOH_2$, (Seitz et al., 2017) did an economic optimization on a solar-thermal-powered SOEC that had been combined with thermal energy storage. They assert that the fact of combining SOEC to CSP power plant can reduce the electricity consumption to less than 5% of its yearly working time. The results obtained is an $LCOH_2$ of 6.25€/kg (0.11€/kWh) without thermal energy storage and 4.30€/kg (0.16€/kWh) with thermal energy storage. A similar analyses was done by Joshi et al, an electrolyser paired with a CSP system will attain a better overall efficiency and sustainability index compared to a photovoltaic system(Joshi et al., 2011).

The lifetime of the electrolyser can have a significant impact on the $LCOH_2$ and a maximum of lifetime of 14 years for the SOEC has been recorded(Naeini et al., 2022). The findings indicated a levelized cost of hydrogen ($LCOH_2$) produced by SOECs (ranging from 2.78 to 11.67 \$/kg H2). The results of a sensitivity analysis also revealed that the capital cost has less of an impact on the $LCOH_2$ than the energy price does (Naeini et al., 2022).

The accessibility of cheap renewable energy is essential because the price of electricity is a major factor in the price of green hydrogen. This point was proven by (Gerloff, 2023) , when an $LCOH_2$ of 5.96€/kg was found for a renewable energy cost at 50€/MWh against and $LCOH_2$ of 13.66 €/kg for a grid electricity of 232 €/MWh. Both $LCOH_2$ were calculated in the same conditions.

When the electrolyser is operating on a stand-alone system, the capacity can influence the levelized cost. Shaner et al. reported an $LCOH_2$ of $12.1/kg using PV-coupled electrolyzers, albeit at a low capacity factor of 20% and with a high electrolyzer CAPEX of $900/kW(Shaner et al., 2016). When using Renewable electricity the Capex can account for more than 45% of the LCOH(Gerloff, 2023). Taking into account the novelty of the SOEC technology no much data is available, the highest value was recorded is 2000 €/kW(Dieterich et al., 2020) , medium value of 1750 €/kW(Gerloff, 2023) .

2.3.2 Business model, policy perspectives and challenges of DAC

DAC has attracted significant interest and development, and commercial entities are now actively operating in the market. Investments in DAC technologies are primarily motivated by two commercial objectives: 1) the sale of high-quality carbon removal services when DAC is combined with CO2 storage; and 2) the sale of climate-neutral CO2 as a feedstock for a variety of products, such as aviation fuels and beverage carbonation.(IEA, 2022).

Over the past four decades, it has become apparent how difficult it is to agree on, and implement, appropriate policies that result in the mitigation pathways so urgently needed(Beuttler et al., 2019). In the current economic context, the externalities associated with greenhouse gas emissions have not been adequately accounted for, presenting a viable opportunity for DAC companies to operate in niche markets, producing CO2-based fuels and materials(Beuttler et al., 2019). However, achieving substantial scale in DAC operations necessitates the incorporation of these externalities through pricing mechanisms or regulations, prompting the need for well-designed policies to facilitate the required scale-up (Beuttler et al., 2019) .The development of DAC markets is heavily reliant on policy support, surpassing the level required for other low-carbon technologies(Meckling & Biber, 2021) . To this end, the key policy formula appears to be a combination of "financial incentives + deployment or performance mandates" (Meckling & Biber, 2021) .

The efficacy of financial incentives, such as subsidies or tax rebates, has been demonstrated in advancing the deployment of renewable energy technologies and electric vehicles, thus presenting an applicable model for fostering DAC adoption (Meckling & Biber, 2021). Governments have already taken significant strides in providing initial investments to support DAC and other greenhouse gas removal technologies. For instance, the UK Government has allocated £100 million for DAC initiatives, signalling its commitment to addressing climate change (Erans et al., 2022). Various national governments have also implemented schemes to incentivize CO2 storage, exemplified by the 45Q tax credit in the US, while others, such as Norway and the UK, have shifted their focus towards supporting transportation and storage infrastructure (Erans et al., 2022). As DAC transitions from its research and development phase, policymakers will possess an array of policy levers to encourage its adoption and cost reduction(Erans et al., 2022). Technology mandates offer a means of ensuring DAC deployment in crucial sectors like energy and transport. However, careful consideration must be given to prevent the prolongation of old, high-carbon plants through such mandates (Erans et al., 2022). Furthermore, tax breaks and capital grants, which have proven instrumental in supporting other low-carbon technologies like offshore wind and solar PV, represent alternative avenues for mitigating the risks associated with large-scale DAC demonstrations (Erans et al., 2022). The commitment of governments to DAC development and deployment is evident in the substantial funding commitments, which have already surpassed USD 4 billion(IEA, 2022). This highlights the recognition of DAC's potential as a crucial tool in addressing climate change and advancing sustainable technologies.

2.3.3 Research gap

The energy transition toward clean and sustainable energy sources requires effective energy storage technologies. Hydrogen, as an energy vector, offers a promising solution to integrate renewable energy sources and mitigate their intermittency. Solid oxide electrolysis cells (SOEC) stand out as a viable and efficient hydrogen production technology, operating at intermediate temperatures and eliminating the need for hydrogen gas purification. SOEC's role in the energy transition can be significant, especially with advancements in scale and efficiency, paving the way for a hydrogen-based energy economy. However, even if the cost of water is negligible in LCOH, it remains an essential element of the system. But the majority of studies do not include an assessment of water availability. Therefore, for some regions with good potential, fresh water scarcity remains a barrier for hydrogen production deployment.

DAC's potential impact on climate mitigation, policy costs, and global temperature targets is significant. While it offers advantages in reducing costs and achieving climate goals, there are challenges related to scaling, costs, and potential feedback cycles. Government support and market ramp-up are crucial for the successful deployment of DAC as a key technology in the energy transition and climate change mitigation efforts.

According to Sabatino et al. (2021) the behaviour of DAC with regard to water adsorption is a crucial factor that requires attention. H2O can influence the adsorption of CO2 and, consequently, the process productivity and energy needs, depending on the ambient conditions and the solid properties. However, most researches neglected the impact the temperature and humidity on DAC efficiency. Additionally, few research on CO_2/H_20 adsorptions have the objective of proposing measures to reduced water penalty, e.g.: the implementation of water swing adsorption process or environmental constraint (operating in dry regions). DAC component as water-cooperative or competitive model is an unexplored path. Even though it is not yet explored, some researchers suggested the idea. Wurzbacher et al. (2012) mention that the coextraction of water could have benefit in the production of synthetic fuel using solar power in region with high potential and limited resources of fresh water. However, for countries having access to sea water, desalinisation will be a solution much cheaper. To the best of our knowledge no techno-economic studies were published about such system, and detailed data of DAC component to conduct such study remains scarce

2.4 Overview on Senegal

2.4.1 Current energy situation

Senegal has a population of is an interesting country to research since its energy industry is going through significant transformation right now. As shown on figure 3, the energy system of the country relying majority on imported oil.

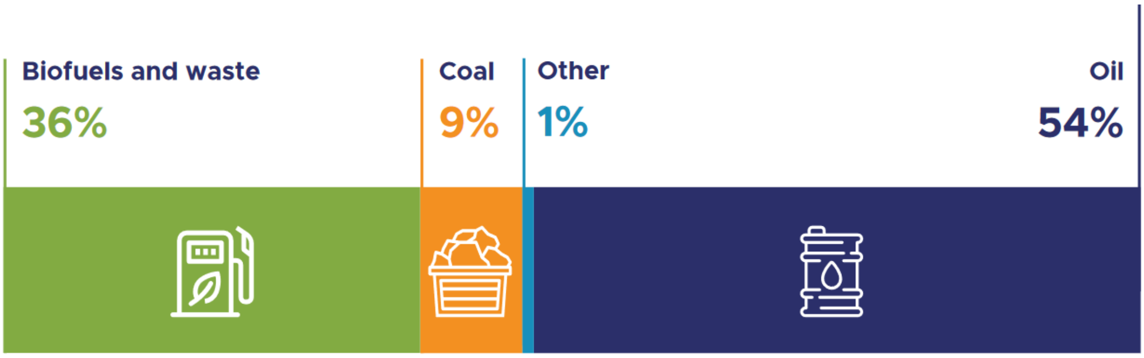


Figure 3:Hydrogen production method base on renewable (Nikolaidis & Poullikkas, 2017)

In 2021 Senegal had an electricity access 68% (World Bank, 2023a), which is higher than most than the electricity access rate of most countries in ECOWAS community. However, Senegal has recorded most of the highest generations cost 34-38 cents per kilowatt hour due to reliance on imported fuels. Figure 4 depicts the electricity generation by source. We can observe the rapid deployment of renewable energy sources, with the introduction of Solar in 2017 and wind in 2020. The RE capacity connected to the grid is estimated to 168 MW for solar, 51MW for wind and 75MW for hydro, which represent 22% of the country electricity generation(ANER, 2020a). This is reflecting the efficiency of RE politic and strategy .The discovery and exploitation of natural gas in 2015 start to raised concerns could act as a brake on the prioritisation of renewable energy.

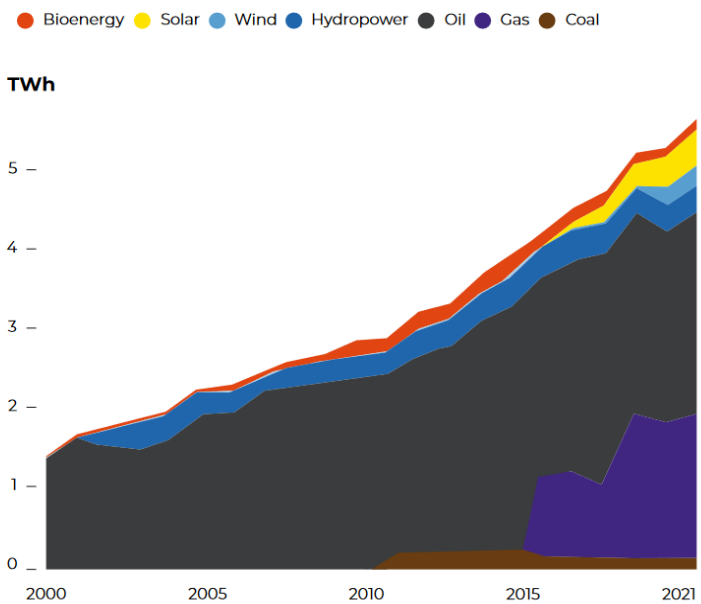


Figure 4: Electricity generation by source (Kachi et al., 2023)

2.4.2 Opportunities of Senegal

Senegal has been chosen as a study country for the opportunities it offers on the energy sector. Senegal is a country in West Africa located between 12°5 and 16°5 north latitude on the Atlantic coastline and benefits from a ray of good sunshine. Senegal has an average daily irradiance of 5.7 kWh/m^2 for an average duration of 3,000 hours(ANER, 2020b). The breakdown is shown below, see figure 5. We observe a reduction of potential from the South-West to the North-East. According to IRENA's estimates, the photovoltaic (PV) potential is projected at 37,233 MW, while concentrated solar power (CSP) holds a potential of 5,424 MW. This places CSP as the second most abundant renewable resource, trailing behind solar PV(IRENA, 2018)

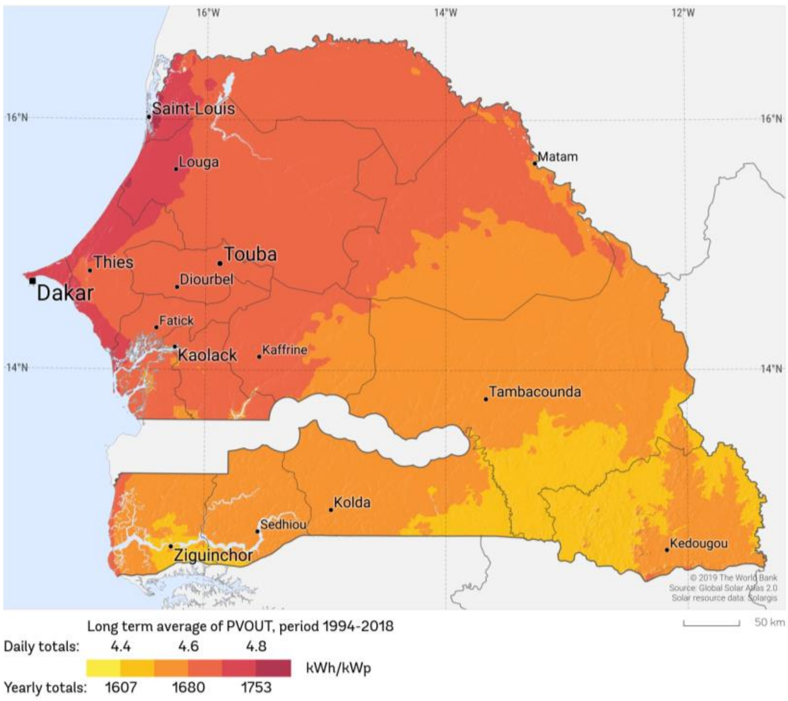


Figure 5:Photovoltaic potential of Senegal, sources: Solargis

The climate diversity, which implies a variation in vegetation and climatic conditions such as temperature, humidity, wind and even the potential of resources. The year into two main seasons: from November to May is the dry season, with an average temperature of 25°C, followed by the rainy season from June to October, which is longer in the south than in the north. The west of the country has cooler temperatures than the east, which, along with the centre, remains the hottest part of the country. From north to south, there are 5 main zones where the tropical climate varies: the Sahelian zone, the Sahelo-Sudanian zone, the Sudanian zone, the Sudano-Guinean zone, the Guinean zone tropical rainforest. These are the 5 climates met in West Africa. Operating the carbon Capture plant and Hydrogen generation process in the 5 zones will gives us an overview of the performance of the plant anywhere in West Africa.

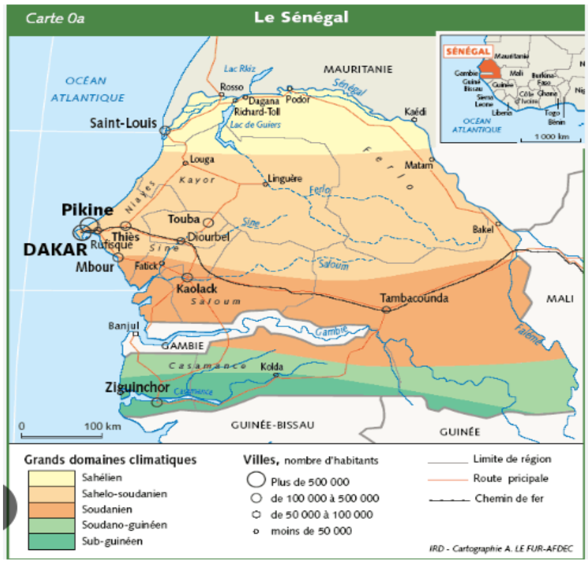


Figure 6: Climatic zones of Sénégal, sources: Cartographie A. LE FUR-AFDEC

Last but not least a prosperous economy and political stability. Senegal has one of sub-Saharan Africa's most successful economies. The economy has been experiencing consistent growth above 6% for several years now, which makes. The GDP of the country was estimated to USD 27.68 billion. Since gaining independence in 1960, Senegal has seen three peaceful political changes, making it one of the most stable nations in all of Africa(World Bank, 2023a).Unlike many African nations, Senegal never had military coup, civil war, ethnic conflict, or religious conflict, with the exception of an independentist conflict in its southern region in the 1980s. The nation has a long history of social and political stability and its constantly improving business environment make it a safe place for investments.

3. Methods and Materials

3.1 Boundaries and methodology framework

Definition of the system boundaries is an essential step of the methodology. Our model will only take in account the system including power generation, carbon capture and hydrogen production. Methanol production can be a downstream application of such a system but won't be included.

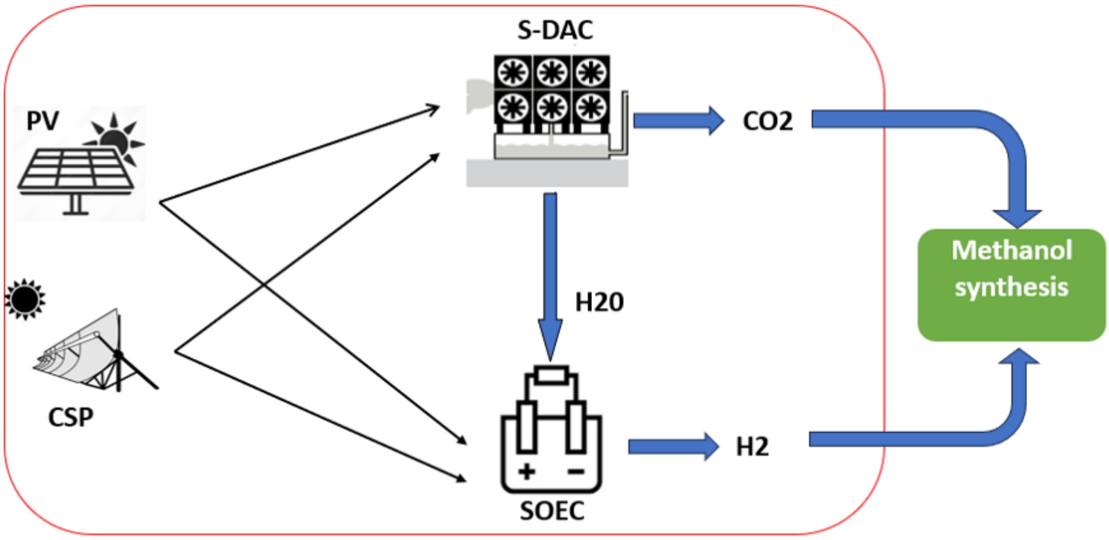


Figure 7:System Boundaries

The aim of this research paper is to model the cost structure of a cohesive system involving the production of green hydrogen via electrolysis in conjunction with Direct Air Capture (DAC) technology. We intend to reveal the cost drivers associated with the operational mode of DAC technology using a micro-costing approach, with the ultimate goal of identifying optimal environmental conditions for green hydrogen production and DAC technology integration. We propose a framework built on three pillars to answer our research questions. 1-Location filters, 2-Project design, hydrogen production simulation, and cost evaluation tool, 3-Sensitivity analysis.

First and foremost, it is important to emphasize that our focus region is WEST AFRICA and 1 country out of 15 has to be chosen. We, therefore, propose a set of criteria that will allow us to select a specific country in the West Africa region for our study case. These criteria include, among others solar PV potential, Variety of Climate zones, Socio-economic impact of Green Hydrogen, access to seawater and groundwater for further technology comparisons, and last but not least economic and political environment. The chosen country is SENEGAL, based on Figure 6 we identified one location in every climate zone, which gives us five unique combinations of solar potential and weather conditions (temperature and humidity). The locations are presented in Table 1 based on their location ordered from the North to the South.

Table 1:Geographical coordinates of the study cases sources: google

Location name	**Geographical coordinates**
Saint Louis	16.0326° N, 16.4818° W
Touba	14.8666° N, 15.8995° W
Tambacounda	13.7726° N, 13.6710° W
Kolda	12.9002° N, 14.9425° W
Ziguinchor	12.5641° N, 16.2640° W

The design of the power starts by fixing the hydrogen demand hydrogen and the carbon demand on a daily based which respectively is 1t/day and 7t/day. According IRENA, (2021) producing 250 Mt of e-methanol will require about 350 Mt of CO_2 and 48 Mt of hydrogen, which highlight a ratio of 7.29 between the quantity of CO_2 and hydrogen needed. Nevertheless, for reasons of calculation fluidity we assume a ratio of 7. DAC technology is then sized to be able to provide the amount of necessary water to the electrolyzer each day of the year. Solar PV generators and Concentrated solar power are designed to provide respectively electricity and heat to the whole plant. Based on these requirements, the optimum energy system is determined using a Python Algorithm-based package called COMANDO.

COMANDO is a modelling framework for Component-Oriented Modelling and Optimization for Nonlinear Design and Operation of integrated energy systems. The software considers our energy system, and models specific components' cost, efficiency, and other parameters to represent the energy system as a MILP (Mix Integer Linear Programming) problem. It then uses the GLPK solver to solve the optimization problem and obtain the optimal sizing and operation of the components. In our case it establishes a capacity mix of the solar PV and CSP power plant, the electrolyzers, DAC and eventually a battery storage capacity to achieve a cost-optimum target based on the user's define techno-economic parameters.

This paper focus on the operating principle and DAC performance based on environmental conditions is important to emphasize that our energy system is focused on the DAC. The energy requirement of DAC technology is divided into 2 components: electricity and heat. Electricity demand will be defined as a fixed value while heat that is needed during the regeneration process is subject to variations due to weather fluctuations. So, costs are allocated based on energy requirements during every cycle. All cost generated from DAC is allocated to C02 capture, while Water is considered a byproduct of the process.

The output of the simulation is the size of the different components in the systems and the and the net production of the system that is calculated based on annualized cost approach method. Then economic variables such as variables; the levelized cost of electricity (LOCE), levelized cost of heat (LOCH) the levelized cost of carbon (LCOD), and finally the levelized of hydrogen ($LCOH_2$) are determined. The annual energy generation and energy demand are clustered into 3 typical days. Senegal's climate is divided into 2 seasons; the rainy season and the dry season. However, there are variations in the dry season: hot and cold. The three typical days correspond to sunny days, cloudy dry days, and cloudy wet days. Upon all the results a best scenario case will be chosen according to the cheapest total annualised cost. We will identify the patterns of cost variation and then compare them to the literature to verify the accuracy of our results.

3.2 Economic Assessment

The economic assessment was done by using the annualised cost investment method. This method is more appropriate to our research for 2 reasons. First the diversity of components in the system which imply varying life spans, thus illustrating all cost over a period of one year encompasses all differences. Secondly, our study is a comparative study, different projects are evaluated in different conditions to choose the optimum projects. By transforming the capital cost into a future annual capital charge, the annualized cost approach contrasts the size of a capital investment in current currency with a future revenue stream(Towler & Sinnott, 2008). The total annualised cost (TAC) is given by the equation 3. Annual Capital Charge (ACC) is calculated by multiplying the capex by the annual capital charge ratio(ACCR), shown in equation 5.

$$TAC = AAC + Opex, fix + Opex, var \tag{3}$$

$$ACC = Capex * ACCR \tag{4}$$

When a capital investment is being amortized, the annuity (A) is the consistent annual payment that must be made to produce the same amount of money over n years as will be produced by investing P at i% interest for n years(Towler & Sinnott, 2008). The capital charge ratio (ACCR) can be calculated with the equation 9 (Vega Puga et al., 2022)

$$ACCR = \frac{A}{P} = \frac{\mathrm{r} \times (1 + \mathrm{r})^{N}}{(1 + \mathrm{r})^{N} - 1} \tag{5}$$

Finally, optimal study case will go through a sensitivity analysis to determine the cost drivers.

Scenario 1: Usage of waste heat from SOEC

In this scenario, assumptions are made that heat requirement from DAC component is supplied by a wasted heat source. Thus, there is no expenses linked to the DAC heat requirement. The only energy cost accounted is the cost of electricity.

Scenario 2: Reduction of the capital cost of 10%

The cost of DAC is distributed between the Capex, the operating and maintenance cost and the replacement cost. The capex is assumed to have a value 10% lower than the initial case.

3.3 Technical assessment

The sorbent used in our model use Lewatits VP OC 1065(LANXESS, 2011) as an example of a typical primary amine-functionalised. A key reason to select this sorbent is its commercial availability (Young et al., 2021) and adaptability to air moisture(Wurzbacher et al., 2012)

.Additionally, several authors such as (Veneman et al., 2014) have carried out research on this sorbent, finally leading companies in DAC field like CLIMEWORKS are using Lewatits VP OC 1065 for their products(CLIMEWORKS, 2018).

S-DAC operates as a cyclic system comprising an adsorption stage and a desorption stage as depicted in figure 8. We assume in this study that a cycle comprising one adsorption step and one desorption step last one hour. (Wurzbacher et al., 2012) demonstrated in his experiment that at 1h, H_2O adsorption reaches equilibrium while CO2 While CO2 adsorption takes longer than 5 hours to achieve equilibrium. The first priority of DAC component is to provide water to the electrolyser.

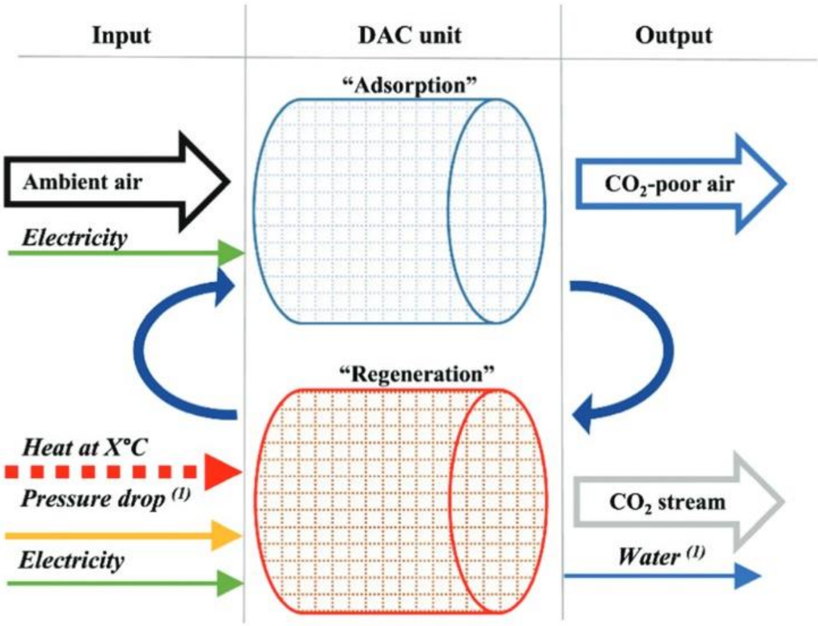


Figure 8:Representation of low-temperature DAC by Global Thermostat and Climework

The experimental data provided by (Veneman et al., 2014), followed by (Drechsler & Agar, 2020) indicate that water loading during adsorption, at equilibrium on Lewatits VP OC 1065 can described by BET isotherm model (equation 6).

$$\frac{qH2O,eq}{qH2O,eq,mono} = \frac{CBET*rH}{1-rH} * \frac{1-(nBET+1)*rH^{nBET}+nBET*rH^{nBET+1}}{1+(CBET-1)*rH+CBET*rH^{nBET+1}} \quad (6)(\text{Drechsler \& Agar, 2020})$$

$q_{H2O,eq}$ is the quantity of water adsorb at equilibrium, $q_{H2O,eq,mono}$ monolayer loading with a value of 2.933 mol. Kg^{-1} of sorbent. The number of layers nBET is 7.680 and an affinity cBET of 6.257 indicating Lewatit to be hydrophilic(Drechsler & Agar, 2020), rh is the relative humidity .

Carbone dioxide adsorption at equilibrium on Lewatits VP OC 1065 is described by Toth isotherm model, expressed by the following equations.

$$qC02,eq = \frac{qsbsPco2}{(1+(bsPco2)^{th})^{\frac{1}{th}}} \quad \text{(7.a) (Bos et al., 2019)}$$

$$bs = b0\exp\left[\frac{\Delta H}{RT0}\left(\frac{T0}{T}-1\right)\right] \quad \text{(7.b)}$$

$$th = t0 + \alpha\left(1-\frac{T0}{T}\right) \quad \text{(7.c)}$$

$$qs = qso\exp\left[\chi\left(1-\frac{T0}{T}\right)\right] \quad \text{(7.d)}$$

where qCO2 is the loading of CO2 on the adsorbent ($mol.kg^{-1}$) , qs is maximum loading CO2 capacity, bs is the affinity of CO2 to the adsorbent, P_{CO2} [Pa], is the partial pressure of CO2, and th is an exponential factor to account for surface heterogeneity. bs is the affinity of the sorbent to CO2 is defined b, t0 is t at the reference temperature, and a is a factor used to describe the temperature dependency.

Table 2:The parameters set of the Toth equations are given in the

Parameter	**Value**	**Sources**
qs0	3.40 mol/kg,	(Bos et al., 2019)
χ	0	(Bos et al., 2019)
T_0	353.15 K	(Bos et al., 2019)
B_0	93 bar^{-1}	(Bos et al., 2019)
ΔH_0	95.3 kJ mol^{-1}	(Bos et al., 2019)
T_{h0}	0.37	(Bos et al., 2019)
α	0.33	(Bos et al., 2019)
R	8.3144598 $J.mol^{-1}.K^{-1}$	Constant value

The DAC system needs heat for regeneration in addition to electricity, which is mostly used for fans and control systems (Fasihi et al., 2019). In terms of total energy needs heat consumption represent 80 to 85% while electricity represent 20 to 25%(IEA, 2022). Since the energy penalty occurs mainly during the regeneration phase, we assume that the demand is a fixed value for electricity and heat requirements will be dependent on climatic conditions. The regeneration heat is the sum of heat required to bring the sorbent material up to the desorption temperature (equation 8.a), as well as the heat input required to account for the CO2 and H2O desorption enthalpies (equation 8.b)(Wurzbacher et al., 2012).

$$Qsen = \left(\frac{1}{\Delta qCO2,des} * Cp,sorb + Cp,CO2 + \frac{\Delta qH2O,des}{\Delta qCO2,des} * CpH2O\right) * (Tdes - Tads) \quad (8.a)$$

$$Qdes = hdes,CO2 + \frac{\Delta qH2O,des}{\Delta qCO2,des} * hdes,H2O \quad (8.b)$$

$$Qreg = Qsen + Qdes \quad (8.c)$$

Q_{sens} represents the specific sensible heat, Q_{sens} the heat of desorption and Q_{reg} the total heat required for regeneration in kJ.mol^{-1} of CO2 captured. We assume that the quantity of carbon dioxide and water desorbed (ΔqCO2,des and ΔqH20,des) equal to the quantity of carbon dioxide and water adsorbed at equilibrium (qCO2,eq and qCO2,eq); there is no losses. Additionally Parasitic losses including pressure dips across pipes, heat losses, and irreversible heat transfer are not taken into account.

Table 3:Assumption for heat requirement generations

Parameter	Value	Sources
Tads	Ambient Temperature	-
Tdes	373.15 K (100 C)	(Young et al., 2021)
$Cp,_{sorb}$	1.4 kJ.kg^{-1}.K^{-1}	(Moran & Shapiro, 2006)
Cp_{CO2}	37 J.mol^{-1}.K^{-1}	(Moran & Shapiro, 2006)
Cp_{H2O}	76 J.mol^{-1}.K^{-1}	(Moran & Shapiro, 2006)

hdes,$_{CO2}$	~90 $kJ.mol^{-1}$	(Wurzbacher et al., 2012)
Hdes$_{,H2O}$	~47 $kJ.mol^{-1}$	(Wurzbacher et al., 2012)

3.3 Data sources

In this paper secondary data was due to the unavailability of primary data. The data was then extracted and synthesized from public sources like journals, articles, books official websites such as World Bank database, ANER (Renewables Energy National Agency Senegal). Renewable potential and weather data were taken from the following websites: NASA database, Renewable Ninja, and H2 Atlas, the base year of the weather data is 2019.

- **Technical data**

The lifetime of the plant is assume to be 20 years which correspond to the lifetime of solar PV.

Table 4:Technical assumptions of DAC the system

Parameter	Value	sources
Cycle duration	1h	This work
DAC Lifetime	20 years	(Fasihi et al., 2019)
Electricity requirement	250 $kWel.tCO2^{-1}$	(Fasihi et al., 2019)
Sorbent lifetime	1 years	(McQueen et al., 2021)

Table 5:Technical parameters of SOEC

Parameter	Value	source
Efficiency	0.8	This work
Electricity consumption	42.3 kWhel/Kg	(Gerloff, 2023)
Heat consumption	30% of electricity consumption	This work
lifetime	20 years	(Gerloff, 2023)
Stack lifetime	27,500 hrs	(Gerloff, 2023)

The SOEC system is run in its thermoneutral operational mode, which prevents the chemical reaction and energy demand of the SOEC from changing the input and outlet temperatures of the cathode and anode streams(Seitz et al., 2017).

- **Economical data**

A discount rate of 6 % is assume in this paper, in most studies of power-to-gas system the discount rate varies between 6-8%(Gerloff, 2023).

Table 6:Economic data of the different components

Component	parameter	value	sources	Estimation year
DAC	$Capex_{DAC}$	730 €/tCO2^{-1}	(Fasihi et al., 2019)	2020
	$Opex_{fix}$	4% (Capex.a)	(Fasihi et al., 2019)	2020
	$Opex_{var}$	11-38 €/tCO2^{-1}	(IEA, 2022)	-
SOEC	$Capex_{SOEC}$	1750 €/tCO2^{-1}	(Gerloff, 2023)	2023
	Additional for installation	28% ($Capex_{SOEC}$)	(Gerloff, 2023)	2023
	Additional cost for design, planning	140,000 €	(Gerloff, 2023)	2023
	$Opex_{fix}$	4%(CapexSOEC)	(Gerloff, 2023)	2023
	Stack replacement cost	24%(CapexSOEC)	(Gerloff, 2023)	2023
H2_storage	$Capex_{H2storage}$	490,000 €/tH2	(Gerloff, 2023)	2023
	$Opex_{H2storage}$	1%($Opex_{H2storag}$)	(Gerloff, 2023)	2023
PV	$Capex_{PV}$	800 €/kW^{-1}	(Bhandari & Shah, 2021)	-
	Opex	1% (Capex)	(Bhandari & Shah, 2021)	-
CSP	$Capex_{CSP}$	833 €/m^2	(Wiegner et al., 2022)	-
	Opex	4.7% ($Capex_{CSP}$)	(Wiegner et al., 2022)	-

Battery	$Capex_{Bat}$	560 €/kWh	(Bhandari & Shah, 2021)	-
	Opex	2.5% ($Capex_{Bat}$)	(Fasihi et al., 2019)	-
	Replacements cost	200 €/kWh	(Bhandari & Shah, 2021)	-

4 Results and discussions

4.1 Results and interpretation

4.1.1 Technical analysis

The following section present the result of the 5 different case study of and hydrogen production plant coupled with a DAC, with a daily demand of 1ton of hydrogen and 7 tons of carbon dioxide. Table 8 shows a summary of the design variables of different components of the plant.

Table 7:Summary of design variables

Design variables	**Saint Louis**	**Touba**	**Tambacounda**	**Kolda**	**Ziguinchor**
Range of RH (%)	7-100	3-100	3-99	7-100	8-100
Yearly Average RH (%)	53	40	41	56	64
Range of Temperature(°C)	11-42	12-45	13-46	12-44	14-42
Yearly average temperature(°C)	26	28	29	27	26
PV size(kW)	42 550	46 610	41 710	41 400	44 400

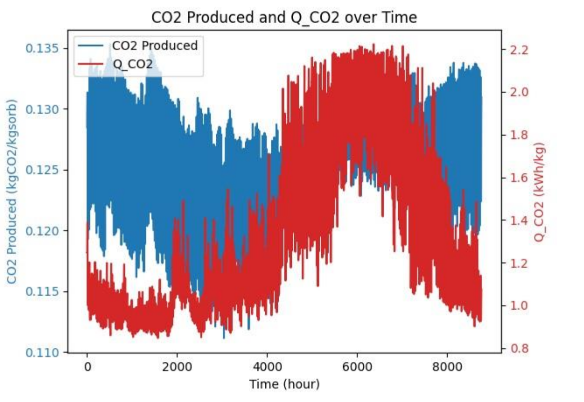
Battery size(kWh)	0	0	0	0	0
CSP size(kW)	17 080	17 890	18 620	16 230	16 380
DAC size(kgCO2)	8 000	7 237	7 626	8 049	7 326
CO2 storage(kg)	8 119	3 952	6 050	7 442	5 333
SOEC (kW)	22 550	20 480	22 380	21 690	20 460
H2 size (kg)	469.8	554.7	373.8	429.3	500.2
Total Annual investment(€.a)	13 693 071	13 258 947	13 784 222	13 156 707	12 890 414

- **Productivity and performance of DAC**

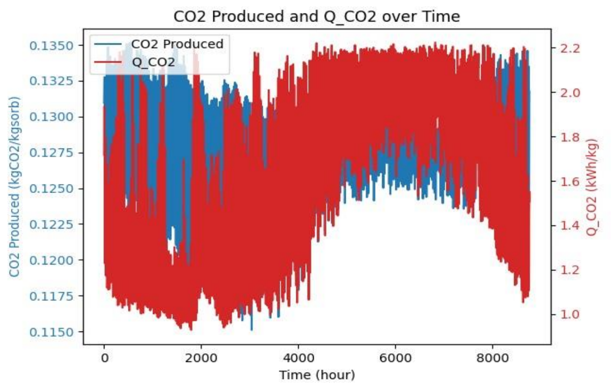
As result of the simulation of the thermodynamic model of DAC, we were able to quantify the capacity of adsorption of CO2 which allows to evaluate the productivity and the thermal energy requirement for the regeneration process which can allow to evaluate the performance along the year, see figure 9.

Concerning the adsorption capacity of the sorbent, for the case of Tambacounda it varies between 0.110-0.135 kg_{CO2}/kg_{sorb}(2.5mol/kg-3.06mol/kg) and for Ziguinchor 0.115-0.135 kg_{CO2}/kg_{sorb} (2.61mol/kg-3.06mol/kg). We can observe that the lowest values occurred between 2000-4000h which correspond to the dry-hot period (mid-February to mid-May).The temperature has a strong effect on the CO2 adsorption capacity; higher temperature results in lower productivity while the presence of water (higher RH) has a boosting effect on the adsorption capacity of the sorbent(Wurzbacher et al., 2012)&(Wiegner et al., 2022). Consequently, the highest productivity occurred at the beginning and the end of the year that correspond to the cold season. The difference of minimum values between the two cases is due to the fact that Tambacounda locality is hotter and dryer (yearly average temperature 29°C and RH 41%) than Ziguinchor (yearly average temperature 26°C and RH 64%).

(Bos et al., 2019) shown similar results in his experiments, an average adsorption capacity of 2.75mol/kg at a temperature of 20°C and a CO2 partial pressure of 0.2 bar was recorded. Veneman et al. (2014) obtained a maximum value of 2.5mol/kg at temperature of 33°C. This difference in results can be explained by the fact that he used different reference parameters in the Toth isotherm equation.



a) Tambacounda



b) Ziguinchor

Figure 9:CO2 productivity and heat requirement during the regeneration step

In terms of heat requirement for the regeneration process, the results for all five cases vary between 0.9 - 2.2kWh/tCO2, this wide range of values is explained by the fact that climatic conditions have a wide range of variation. In the case study of Tambacounda, the commencement of the annual cycle corresponds to a phase characterized by cold and arid climatic conditions, indicative of both moderate low temperatures and diminished relative humidity levels. Air humidity affects the performance of solid amine sorbents; higher humidity level results in increase adsorption capacity leading to larger capturing capacity by cycle but at the same time increases energy demand, since greater quantities of water have to be desorbed(Wiegner et al., 2022). Consequently, this climatic disposition gives rise to a constricted capacity for water loading alongside with a reduction in thermal energy requirement. Subsequently, a progressive decrease in productivity becomes manifest, attributed to the progressive elevation of the average ambient temperature, which marks the transition into the hot and arid phase of the year. The acme of energy demand throughout the annual period aligns with the rainy season, characterized by an elevated relative humidity profile. This augmented humidity content directly leads to a proportional augmentation in both the quantity of adsorbed water and the volume subjected to the regeneration process. Ziguinchor location is the most humid region with a longer rainy season, we can therefore observe the difference of performance between the two case studies. The graph shed light on the interplay and susceptibility of DAC systems to fluctuations stemming from seasonal variations.

Our results are similar to the characteristics of CLIMEWORKS products, they have a thermal energy demand of 1500-2000 kWh/t_{CO2}. However, this range is only valid for a restricted range of temperature -15-35°C but all RH variations are taking in account CLIMEWORKS (2018). The higher maximum value of our results is due to the fact operating temperature are very high (46°C max) which led to a lower productivity.

IEA (2022) has given a range of 7.2-9.5 GJ/t_{CO2} for the total energy requirement, while heat requirement represent 75-80% of the total energy requirement which translate into an heat requirement range of 1500 -2100 kWh/ t_{CO2}.

Sabatino et al. (2021) extremely low range 222-500kWh/ t_{CO2} (0.8–1.8 MJ/kg) in his study, but no weather data were mentioned for the operating condition of the DAC and the water adsorption was described using the Guggenheim-Anderson-de Boer (GAB) model, which makes it difficult to understand their results.

Under the optimal circumstances prevailing in Ziguinchor, coupled with elevated humidity levels, there is an observable reduction in the dimensions of the Direct Air Capture (DAC) system required to meet the equivalent demand in both locations. This reduction in DAC size naturally results in a diminished heat requirement, subsequently leading to a reduced scale of the Concentrated Solar Power (CSP) facility. Additionally, a discernible positive correlation is noted between the dimensions of the DAC component and those of the electrolyser. An economic analysis will highlight the implication of such results on cost.

4.1.2 Economical analysis

- **Power generation**

The results of the Levelized Cost of Electricity (LCOE) and Levelized Cost of Heat (LCOH) analyses figure 8, will provide more insights into the economic feasibility and allow comparison.

Electricity is provided to the plant by PV and batteries, but the battery size remains zero for all case study due to high cost. These results confirmed the findings of Bhandari & Shah (2021) when stating that even though they only give a little amount of electricity to the electrolyzers, batteries have the largest part in the $LCOH_2$ for the off-grid system. It therefore suggested to connect the electrolyzer and PV plant directly. Even if these results are only dedicated to hydrogen production, it can be applied to an integrated system of hydrogen production and carbon capture because as show on Figure 10 the majority of electricity demand comes from the electrolyser. However, operating without battery, coupled with the intermittency of solar sources reduces considerably the capacity factor of the plant.
Breyer et al. (2019) holds dissenting viewpoint concerning this concept, it was affirmed in this research that it is a common misconception to that solar running for few hours per day could be used for DAC. Thorough cost analyses showed that the least expensive rate of CO2 capture is at 6,000–8,000 full load hours per year.
The calculation of the levelized cost of electricity therefore only takes in account solar PV system.

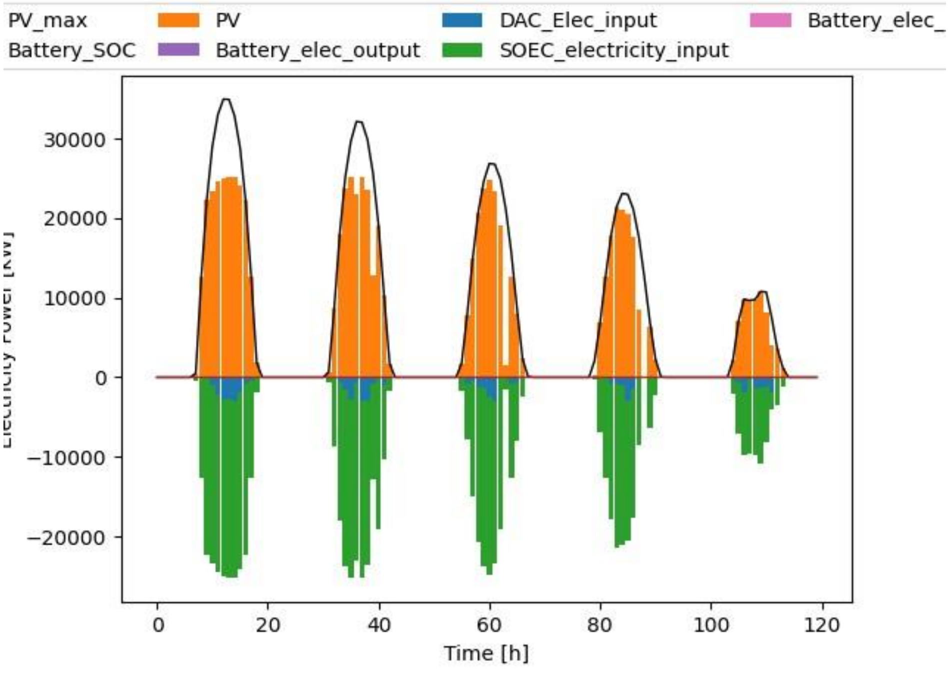


Figure 10:Electricity demand distribution, case of Saint Louis

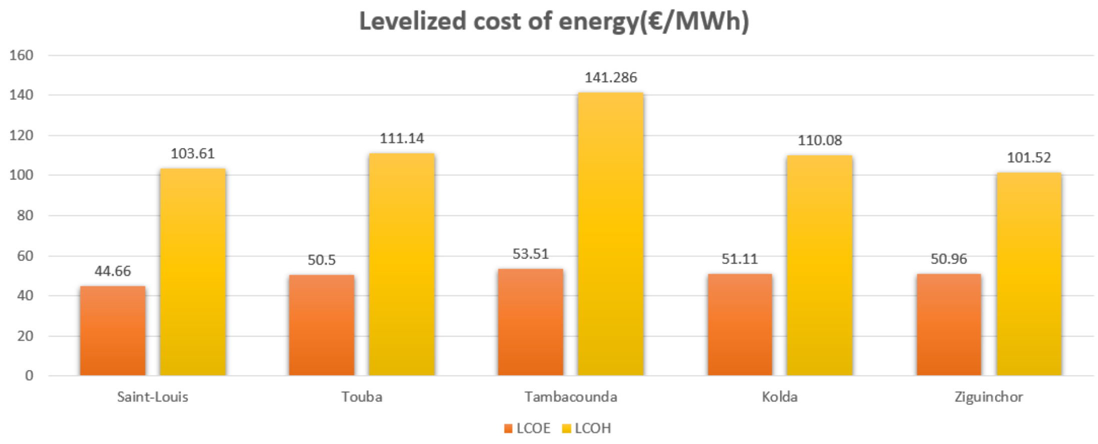


Figure 11:Levelised cost of electricity and heat

The geographical site of Saint-Louis demonstrated the most favourable outcome in terms of the Levelized Cost of Electricity (LCOE), registering a value of 44.66 €/MWhel. This outcome is attributable to the geographic reality that Saint-Louis stands as the locale boasting the most favourable solar potential. In contrast, the LCOE reached its peak in Tambacounda, reaching 53.51 €/MWhel. Hence our findings ranging from 44.66 €/MWh to 53.51 €/MWh.

According to IRENA (2022), the global weighted average LCOE is computed at 44.17

€/MWh (equivalent to USD 0.048 per kWh). Discrepancies between our results and this global average can be elucidated by considering that the operational mode of the constituent elements can significantly influence the levelized cost of energy (LCOE). This stems from the fact that the calculation of the levelized cost hinges not on the total energy generated, but rather on the total energy consumed. As a result, the implementation of curtailment serves as a catalyst for an increase in the LCOE. Additionally, it is noteworthy that the choice of discount rate exerts a considerable impact on the LCOE; in our study, a value of 0.6 was employed.

Regarding the levelized cost of heat, the most economically advantageous figure is identified in Ziguinchor at 101.52 €/MWhth, while the highest cost persists in Tambacounda at 141.286 €/MWhth. Unlike electricity, the demand for heat is primarily driven by the DAC component, as depicted in the Appendix figure 2. This is attributed to the demand curve, as illustrated in Figure 9. The demand for thermal energy in Ziguinchor exhibits a more consistent pattern throughout the year, resulting in an optimal sizing of the plant and efficient utilization of the generated heat. Conversely, in three-fourths of the year, the demand for DAC is notably low, followed by a brief period of heightened demand, necessitating an oversized power plant for the remainder of the year, consequently leading to increased curtailment.

(Seitz et al., 2017) reported an LCOH of 160 €/MWh_{th}, which is still higher than the maximum value derived from our findings. The paucity of studies directly utilizing heat from CSP, as opposed to electricity, to operate similar power plants limits our comparative analyses. Nevertheless, the comparisons with the results of (Seitz et al., 2017) indicate that Senegal exhibits significant potential for CSP.

Upon concluding the levelized cost analyses for power generation, it becomes evident that for standalone systems, cost efficiency is more pronounced in cases characterized by a consistent operational behavior. This principle applies both to the power generator and the supplying component. Indeed, a substantial disparity between the maximum and minimum values, be it in solar radiation or power demand, leads to an oversized system, resulting in escalated costs. An alternative approach to mitigate this issue is to explore avenues for selling surplus energy.

- **Levelized cost of carbon and hydrogen**

To assess DAC and SOEC components, LCOD and $LCOH_2$ for all five cases are presented on figure 12

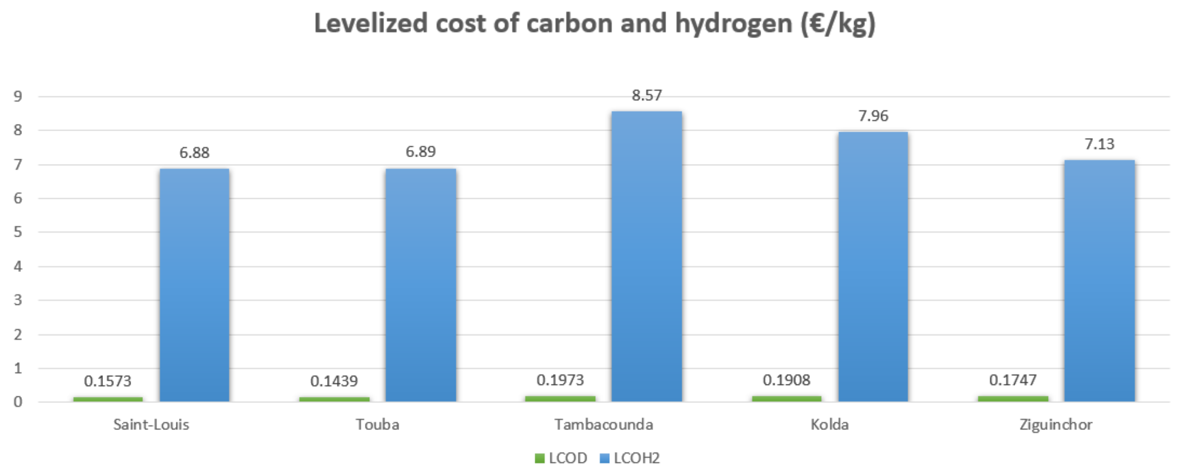


Figure 12:Levelized cost of carbon and hydrogen

The employment of DAC (Direct Air Capture) technology yielded the most cost-effective carbon levelized cost in Touba, amounting to 143.9 €/t_{CO2} (0.1439 €/kg_{CO2}) which is due to the coupled effect of smallest DAC size and smallest CO2 storage capacity see Table 8. Conversely, the most elevated carbon levelized cost was observed in Tambacounda, reaching 197.3 €/tonCO2. This observation aligns with its highest recorded LCOE and LCOH, thereby offering a comprehensible correlation and underlighting the strong impact of the cost of energy in the LCOD. However , based on the distribution of energy requirement heat account for 75-80% (IEA, 2022) which gives a leading effect the cost of heat. These results show the strong effect of the capital investment (DAC + CO_2 storage) and the energy cost on the LCOD.

According to the findings of Fasihi et al. (2019), in the cost distribution of LCOD , DAC plant, Opex, electricity and heat represent respectively 21, 10.4 ,8.3 and 29.7% of the LCOD. These results are in accordance with those of Sabatino et al., (2021), who showed that the cost of heat is the primary determinant of cost of capture. IEA. (2022), has set a range of 115 -308 €/t_{CO2} (USD 125-335 t_{CO2}) what encompasses our range of results. The novelty of the subject and the scarcity of data (capex, Opex) and the transparency does not allow a comparative analysis between results.

In relation to the $LCOH_2$, the most economically favourable rate emerged in Saint-Louis, standing at 6.88 €/kgH2, while the opposite end of the spectrum showcased the highest cost in Tambacounda, amounting to 8.57 €/kgH2. Intermediate values were also notable: 6.89 €/kgH2, 7.13 €/kgH2, and 7.96 €/kgH2 for Touba, Ziguinchor, and Kolda respectively.
The case of Tambacounda reveal once more the impact of the cost of energy, however the results from Saint-Louis suggest that the cost of electricity has a stronger impact compare to the cost of heat. The impact of the investment cost SOEC on the $LCOH_2$ is not that clear, but we notice that for the case of Touba, Kolda and Ziguinchor that have similar LCOE and LCOH; the $LCOH_2$ ranking has the same as the SOEC's size ranking order with order. These aspects reveal that cost of plant does have an impact on the LCOH2 but only a minor one compare to cost of energy.

According to Gerloff (2023) the $LCOH_2$ has a value of 5.96 €/t_{CO2} when powered by renewable with a capacity factor of 4000h. The difference with our results lies in fact that an assumption of 50€/MWh_{el} was made for the LCOE that covers the heat needs. This finding raises questions about the relevance of using CSP to provide heat. However, we should not overlook the fact that the system includes carbon capture in addition to hydrogen production.

- **Cost efficient case**

The highest total annual investment cost happened in Tambacounda see table 8 , with an amount of 13 784 222 €/a and a lowest investment cost happened in Ziguinchor with a total annual investment cost of 12 890 414 €/a; a difference of cost of 893 808 €. The study case of Ziguinchor is therefore the optimal study case as well as in terms of DAC and SOEC size as in terms of annual investment cost.

The obtained results unveil a notable synergy among the components comprising the system, rendering a separate assessment of these elements inconsequential. The comprehensive consideration of the total annualized cost of the system provides a more informed basis for comparative analysis, especially when contemplating the system in its entirety.

At the end of this analysis, we can conclude that the climatic conditions have an undeniable impact on the functioning of the components, which influences the technical aspects of the system, which in turn influences the costs. The best regions for hydrogen production integrated with a water cooperative DAC are those that are Cooler and humid, still with a good renewable potential. We will therefore continue the study with the case of Ziguinchor.

4.2 Sensitivity analyses

In this analysis, we delve into the "Waste Heat" scenario and a “capital reduction at 10%”. By evaluating the alterations in critical parameters, we aim to unravel the intricate effects on performance metrics such as Levelized Cost of Electricity (LCOE), Levelized Cost of Hydrogen (LCOH), Levelized Cost of Delivery (LCOD), and annual total cost. The summary of the sensitivity analyses results is presented in Table 9.

Table 8:Summary of sensitivity analyses

	Base case	**Waste heat**	**Reduction of capital cost of 10%**
LCOE	50.96	53.89	50.96
LCOH	101.52	108.88	101.52
LCOD	0.174	0.019	0.174
LCOH	7.133	7.37	7.133
Annual total cost	12 890 414	11 590 180	12 889 858

In the waste heat scenario, the LCOE rises from 50.96 to 53.89 €/MWh and the LCOH from 101.52 to 108.88 €/MWh, this change echoes the intricate balance between enhanced energy inputs and the associated costs of diverse technologies. The LCOD, which still encompasses the cost of electricity demonstrates a remarkable reduction from 0.174 to 0.019 €/t_{CO2} reveal the determining effect of the cost of heat the levelized cost of carbon. However, relying on waste heat imposes restriction on the choice of DAC, which constitute one of its advantages. The annual total cost, a comprehensive indicator of the system's financial feasibility, exhibits a notable decrease from 12,890,414 to 11,590,180 €. This reduction validates the efficacy of waste heat utilization in enhancing overall economic viability.

The “capex reduction of 10%” scenario does not have an impact on the levelized cost of carbon, but a light decrease on the annual total investment is observed. These analyses indicate the minor impact of the capex on the LCOD. Sabatino et al. (2021) findings shows that when a high mass transfer is accomplished, LCOD is less dependent on the cost of installation.

4.3 Implications of the result for Senegal

- **Economic implications**

The novelty of a hydrogen production trough DAC makes it not economically attractive for now. However, costs are expected to fall. In areas with high potential for renewable energy and while utilizing the finest technologies for generating electricity and heat, DAC prices may be below USD 100/tCO_2 by 2030.
Additionally given the ambitious plan of Senegal to move from fossil fuels and the Just Energy Transition Partnership, Senegal could benefit from investments and capacity building for the implementation of such project. When implemented, the project will provide jobs, infrastructures and could contribute to increase the share of renewables and access to cheap electricity if the system is connected to the grid to sell surplus. Last but not least, Senegal could position itself as an exporter in case of low local demand.

- **Environmental implications**

Senegal claimed that its GHG emissions could be reduced by 23% in 2025 and 29% in 2030. (Senegal, 2020b). In conformity with their goal to reduce greenhouse gas, implementing carbon capture will contribute to speed up the process. However, an appropriate LCA as to be carry out to quantify the quantity of emissions avoided.

- **Social Analyses**

In West Africa, energy project encounters less opposition from the populations when compared to developed regions like Europe. This is due to the lack of access to electricity and the lack of awareness. Moreover, given the fact that it concerns green technologies and which do not require arable land. Last but not least, the oxygen from the electrolyser can be exploited by hospitals.

5 Conclusion

In this study, we set out to investigate the potential impacts of weather conditions on an hydrogen production with a water cooperative DAC in Senegal. The research problem centred around understanding how the temperature and the relative humidity could affect the output and the cost of direct air capture (DAC), and the overall cost drivers of such a system. Our primary objective was to provide insights of DAC behaviour when exposed to varying weather conditions, identify geographical regions that offer the best trade-off in terms of cost, and further determine the cost drivers related to DAC.

The simulation of the system across the five different regions yields a range of LCOD, spanning from 143.9 €/tCO2 to 197.3 €/t_{CO2}, as well as $LCOH_2$ figures 6.88 €/kg and 8.57 €/kg of H_2. These values, although not competitive yet, are promising and reveal the potential of Senegal for such system, suggesting room for improvement and cost reductions. Furthermore, analysis shows humidity and temperature do have an impact on the sizes of the components and on cost . Furthermore, the analysis reveals a notable factor influencing these diverse levelized costs—the cost of energy, specifically the expense related to heat. In this context, the cost of heat emerges as a significant determinant. Introducing waste as a heat source for DAC operations results in a reduction of LCOH by an impressive margin, decreasing from 174 €/tCO2 to just 19 €/tCO2. Additionally, this innovative heat supply approach contributes to up to a 10% reduction in annualized investment costs. This indicates the potential for substantial cost optimization and efficiency enhancement through inventive heat sourcing strategies, particularly when combined with the promising prospects of SOEC technology advancement.

Based on these findings, it is evident that weather conditions exert a significant influence on the performance of DAC and the overall system. As anticipated, the utilization of a water-cooperative adsorption model for direct air capture proves to be more economically viable in humid and cooler regions that also boast favourable and affordable energy costs. Fresh water availability is no more a barrier for green hydrogen production in such regions

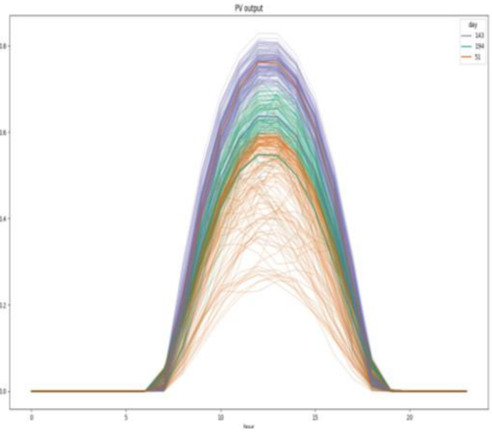
Analysing these results through the lens of the three pillars of sustainability, we can draw several conclusions. From an economic standpoint, these results are promising and could elevate Senegal to a position of potential exporter of synthetic fuels. The implementation of such system will lead to job opportunities and transfer of know-how. On a social level, implementing such systems can lead to positive impacts. It can contribute to increased local employment opportunities which will increase the quality of life and act as a catalyst for capacity building, particularly since this technology represents a novel approach. From an environmental perspective, producing hydrogen and carbon aligns with low-carbon technology principles, and can speed up the energy transition of the country. Moreover, Direct Air Capture (DAC) has demonstrated its potential as a negative carbon technology. However, the lack of policy and framework hinges the deployment of such technology.

It is important to acknowledge that our results are subject to certain limitations. The novelty of Direct Air Capture (DAC) technology and the availability of comprehensive, detailed data have posed challenges. Furthermore, the method of annualization requires in-depth economic data that we lacked for this study. Additionally, the economic data used might not accurately reflect the specific context of Senegal, which can impact the precision and applicability of our results. These limitations emphasize the need for further research and data collection to enhance the accuracy and comprehensiveness of our findings. As DAC technology evolves and more detailed and localized economic data become available, future studies can address these gaps and provide a more comprehensive understanding of the economic and practical implications of integrating DAC with renewable energy sources in the Senegalese context.

APPENDIX

Table 1: Technical assumption other components

Parameter		value	Source
Battery	lifetime	10 years	(Bhandari & Shah, 2021)
	efficiency	0.91	(Fasihi et al., 2019)
CSP	lifetime	30 years	(Wiegner et al., 2022)



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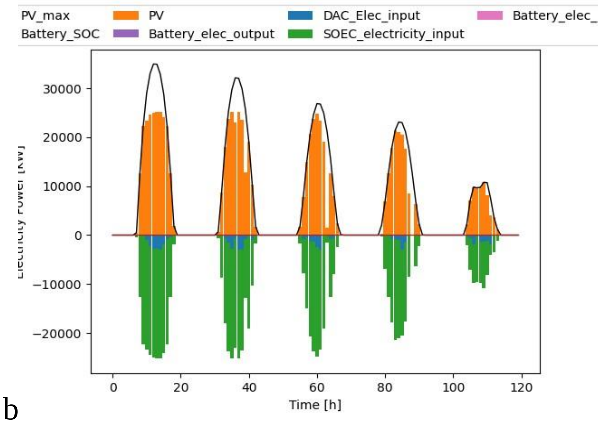
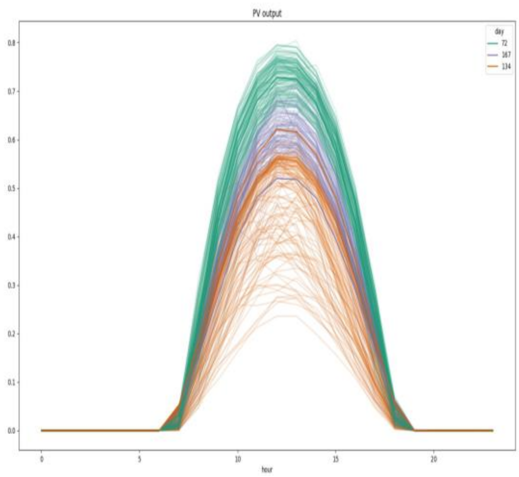


b

1-Saint-Louis



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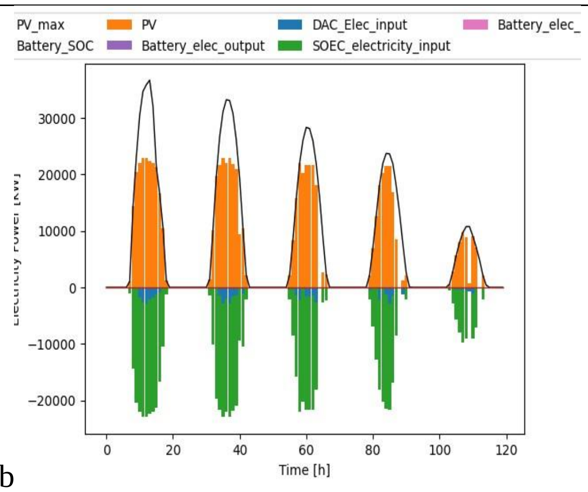

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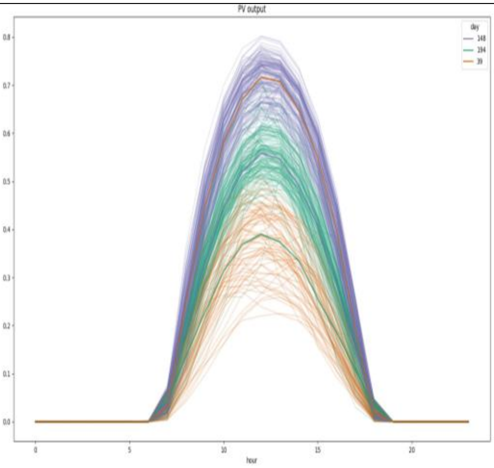
2-Touba



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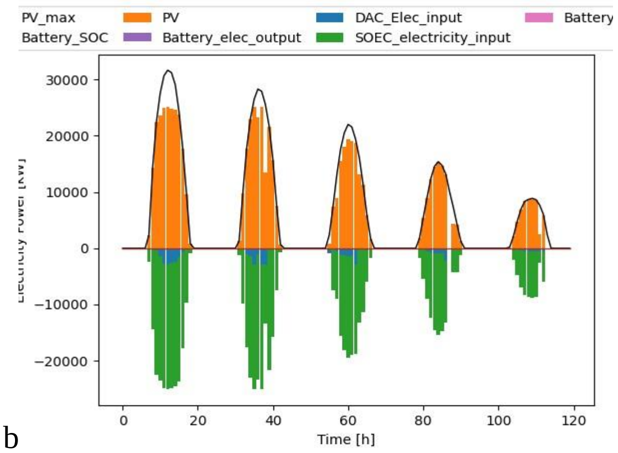

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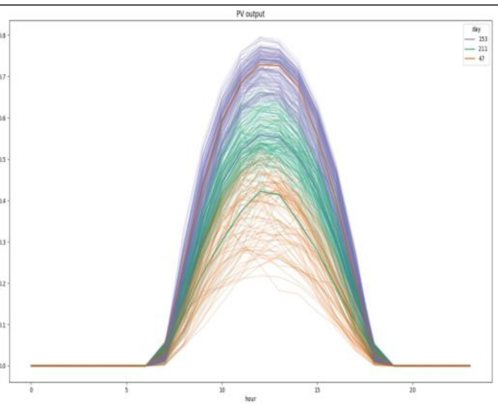

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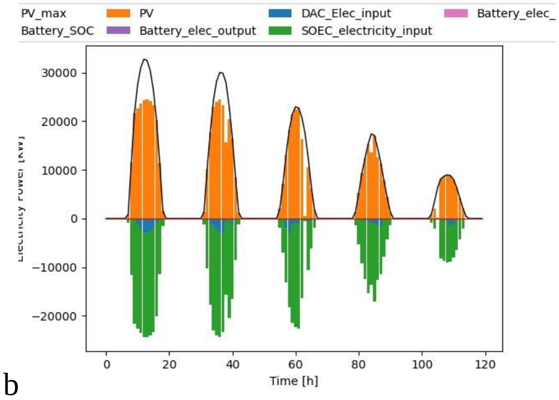

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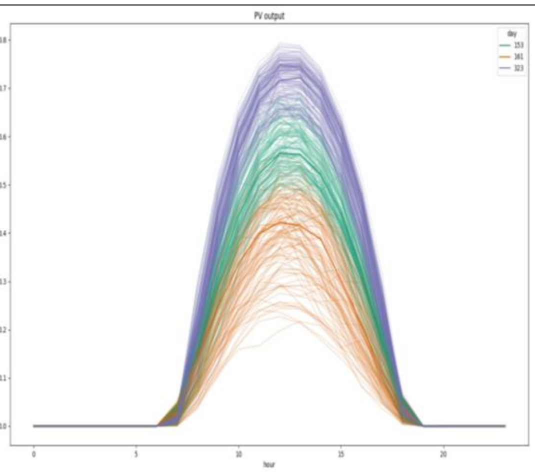
3-Kolda



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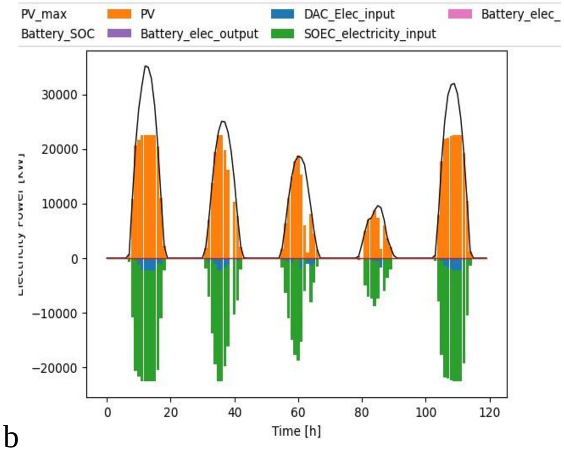

b

5-Ziguinchor

3-Tambacounda

Figure 1:Clustered data of electricity generation

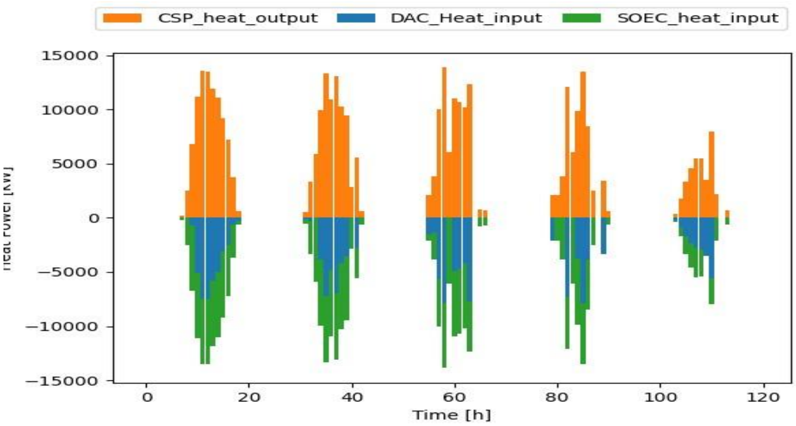

Figure 2:Heat requirement distribution in Touba

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