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Speciality: Economics/Policies/Infrastructures and Green Hydrogen Technology

Topic:

Comparative efficiency analysis of green hydrogen production with the process of direct air capture (DAC) and desalination in West Africa: A case study of M'bour, Senegal

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ACRONYMS AND ABBREVIATIONS

AEL: Alkaline water Electrolysis

AEM: Anion Exchange Membrane

CE: Cost Efficiency

CO_2: Carbon dioxide

CAPEX: Capital Expenditure

DAC: Direct Air Capture

ERS: Energy Recovery System

ECOWAS: Economic Community of West African States

GHG: Greenhouse gas emissions

H_2: Hydrogen

H_2O: Water

Kg: Kilogram

LCOH: Levelized Cost of Hydrogen

LCOE: Levelized Cost of Electricity

LCOW: Levelized Cost of Water

Mtpa: Million tonnes per annum

OPEX: Operational Expenditure

O_2: Oxygen

PEM: Proton Exchange Membrane

PV: Photovoltaic

R&D: Research and Development

RE: Renewable Energy

RO: Reverse Osmosis

S-DAC: Solid-Direct Air Capture

SOES: Solid Oxide Electrolysis

SMR: Steam Methane Reforming

TEA: Techno-Economic Assessment

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ABSTRACT

In the transition towards a sustainable energy system with low-carbon emissions, green hydrogen production is emerging as a key pathway to reduce dependency on fossil fuels. In West Africa, the abundance of renewable energy sources offers significant opportunities for this transition. However, water scarcity remains a critical challenge. This study compares the efficiency of two water supply processes for green hydrogen production: desalination via reverse osmosis (RO) and direct air capture (DAC) via the solid direct air capture (S-DAC) method, both powered by a hybrid system of solar PV and wind energy coupled with proton-exchange membrane electrolysis (PEM). Using a techno-economic assessment combined with cost efficiency accounting method, with the cost efficiency (CE) as an indicator. The CE is the ratio of ideal and actual costs of production. The analyses evaluate the performance of the two processes under ideal conditions (No losses) and actual conditions (with losses) by using the CE with M'bour, Senegal, as a case study. The levelized cost of hydrogen (LCOH) represents the ideal and actual costs of production, respectively, in the ideal and actual cases. The results show that desalination-based green hydrogen production from seawater desalination is more cost-effective than DAC-based hydrogen production. Under actual conditions, the levelized cost of hydrogen (LCOH) from desalination was 5.304 €/kg compared to 6.209 €/kg for DAC, while both processes yielded nearly identical costs of 3.83 €/kg under ideal conditions. The cost efficiency (CE) analysis of the two methods demonstrates that desalination achieves 72% compared to DAC, with 62%, reflecting lower value losses for desalination-based hydrogen production and a better alignment between theoretical and practical performance. Sensitivity analysis confirmed that the hybrid renewable configuration is the best option in a region where solar and wind are abundant, while production based on wind energy increases the value losses, particularly for DAC. The findings of this analysis suggest that in coastal areas, specially M'bour, where seawater is available, desalination should be prioritized for the production of green hydrogen. Nevertheless, S-DAC is a strategic potential for inland and arid regions.

Keywords: direct air capture, solid direct air capture, desalination, reverse osmosis, green hydrogen, cost efficiency

Résumé

Dans le cadre de la transition vers un système énergétique durable à faibles émissions de carbone, la production d'hydrogène vert apparaît comme un moyen clé de réduire la dépendance aux combustibles fossiles. En Afrique de l'Ouest, l'abondance des sources d'énergie renouvelables offre d'importantes opportunités pour cette transition. Cependant, la pénurie d'eau reste un défi critique. Cette étude réalise une analyse comparative de l'efficacité de deux procédés de production d'hydrogène vert : le dessalement par osmose inverse (RO) et le captage direct de l'air (CDA) par la capture directe de l'air solide (S-DAC), tous deux alimentés par un système hybride d'énergie solaire photovoltaïque et éolienne couplée à l'électrolyse par membrane échangeuse de protons (PEM). À l'aide d'une évaluation technico-économique combinée à une méthode de comptabilité de la rentabilité, avec la rentabilité (CE) comme indicateur. CE est le rapport entre les coûts de production idéaux et réels. L'analyse évalue la performance des deux processus dans des conditions idéales (pas de pertes ou d'inefficacité pendant le processus de production) et dans des conditions réelles (monde réel) en utilisant la rentabilité (coût -efficacité) avec M'bour, Sénégal comme étude de cas. Le coût actualisé de l'hydrogène (LCOH) représente les coûts de production idéaux et réels, respectivement, dans les cas idéaux et réels. Les résultats de cette analyse indiquent que la production d'hydrogène vert à partir du dessalement de l'eau de mer est plus rentable que la production d'hydrogène à travers la capture directe de l'air. Dans des conditions réelles, le coût actualisé de l'hydrogène (LCOH) issu du dessalement était de 5,304 €/kg contre 6,209 €/kg en utilisant le captage direct de l'air, tandis que les deux procédés ont donné des coûts presque identiques de 3,83 €/kg dans des conditions idéales. L'analyse coût-efficacité des deux méthodes démontre que le dessalement a atteint 72 % contre 62 % pour la capture directe de l'air, ce qui reflète des pertes de valeur plus faibles pour la production d'hydrogène basée sur le dessalement et un meilleur alignement entre les performances théoriques et pratiques. L'analyse de sensibilité a confirmé que la configuration hybride renouvelable est la meilleure option dans une région où le solaire et l'éolien sont abondants, tandis que la production basée sur l'énergie éolienne augmente les pertes de valeur, en particulier pour le DAC. Les résultats de cette analyse suggèrent que dans les zones côtières particulièrement à M'bour où l'eau de mer est disponible, le dessalement devrait être privilégié pour la production d'hydrogène vert. Néanmoins, le S-DAC représente un potentiel stratégique pour les régions intérieures et arides.

Mots Clés : captage directe de l'air, capture directe de l'air solide, dessalement, osmose inverse, hydrogène vert, coût-rentabilité

Introduction

As fossil fuels must be replaced to meet greenhouse gas (GHG) emission reduction targets, with respect to the Paris Agreement, it is important to transition away from conventional hydrogen production methods that rely heavily on energy from fossil fuels such as natural gas and coal (Kigle et al., 2024). This transition is essential not only for meeting international climate targets but also for ensuring long-term energy security and fostering sustainable industrial development. Hydrogen is being recognized not just as a chemical commodity, but as a versatile energy carrier capable of supporting a low-carbon future. Its potential to decarbonize hard-to-electrify sectors such as heavy industry, shipping, and aviation has placed it at the center of global strategies for achieving climate goals, attracting both scientific interest and policymakers (Bhandari & Shah, 2021). According to the International Energy Agency (IEA) (2024), the global hydrogen production continues to increase and has reached 97 million tonnes (Mt) in 2024 compared to 2022 (2.5% increase). The amount of CO_2 emission associated with this production accounts for 920 Mt of CO_2, 1.5% more than in 2022. These numbers indicate that while the hydrogen production demand increases, the amount of CO_2 emitted also increases, which is contradictory to the global objective worldwide. This existing hydrogen is produced through steam methane reforming (SMR) or coal gasification (Cormos, 2023). These methods emit significant amounts of carbon dioxide (CO_2), contributing to climate change. To move away from this transition with a net-zero emissions energy system, green hydrogen produced through water electrolysis powered by renewable energy has gained global attention as a clean energy carrier with the potential to decarbonize multiple sectors, including transport and industry (Cormos, 2023). As hydrogen production demand is expected to reach 150 Mtpa by 2030, which is higher than the current hydrogen demand, and 45% of this production is from low-emission sources in the Net Zero Emissions by 2050 Scenario (NZE Scenario) (International Energy Agency (IEA), 2024), there is a need to develop a sustainable water supply system. To meet the projected demand of hydrogen, the production is not only required to have low-emission sources but also to address the water scarcity issue in West Africa.

Water is a critical input for green hydrogen production, particularly in regions like West Africa, where renewable energy potential is abundant but water resources are limited (Ndehedehe, 2019). This study focuses on comparing the efficiency of two innovative water sources for green hydrogen production, such as direct air capture (DAC) and desalination using electricity from renewable energy sources.

DAC plays an important role in reducing the concentration of CO_2 in the atmosphere. DAC technologies are designed to capture CO_2 from the atmosphere at ambient temperatures, but solid direct air capture (S-DAC) is one of the promising DAC technologies, with its ability to capture CO_2 and co-adsorb water, which serves as a by-product for green hydrogen production (Sinha & Realff, 2019). S-DAC is a method that captures carbon dioxide (CO_2) directly from the air using solid materials known as sorbents (Kuru et al., 2023). As air flows over these materials, CO_2 is trapped, and water vapor is also captured during the same process. This co-adsorbed water can be recovered and used to supply the electrolyzer for green hydrogen production. Although S-DAC offers flexibility, since DAC plants can be installed anywhere in inland or arid regions where RE is abundant, without relying on local water resources, it is still an emerging technology and requires significant energy input (Fasihi et al., 2019).

On the other hand, water from the sea is desalinated to produce clean water to supply the electrolyzer using reverse osmosis (RO) technology. RO is a desalination technology that removes salt and impurities from seawater by forcing it through a semi-permeable membrane under high pressure. According to Gorjian et al. (2014), "The main advantages of RO systems compared to other desalination methods are their low energy consumption, modularity, and simplicity in installation and operation''. These advantages made it the most used around the world and are especially useful in coastal areas where seawater is abundant.

Despite the promising potential of green hydrogen in West Africa, the availability of water source technologies presents significant challenges that need to be addressed. West Africa possesses vast renewable energy potential for green hydrogen production (WREI, 2022). According to Africa (2021), the total potential of hydrogen production in West African countries is about 165,000 terawatt-hours (TWh), and 1TWh is equivalent to one billion kilowatt-hours (kWh), but water scarcity is a major challenge. The electrolysis process for green hydrogen production requires a significant amount of pure water. Two main solutions have been proposed: desalination of seawater (for coastal regions) and direct air capture (DAC) with co-adsorption of water, where atmospheric water is harvested during CO_2 removal. Understanding the comparative cost-efficiency of these two water sources is essential for optimizing green hydrogen production.

To support this analysis, the study relies on existing research on green hydrogen production and the technologies involved in water sources for the electrolysis process. A detailed review of the literature examines the use of solid direct air capture (S-DAC) and seawater desalination via reverse osmosis (RO), exploring how each method works and its relevance to West Africa.

While there is growing interest in using renewable energy for green hydrogen production as a clean energy solution, especially in West Africa, choosing the most efficient and sustainable water sources for its production remains a question. From the Africa (2021) report, the Author highlights the need for water supply for green hydrogen production in the Economic Community of West African States (ECOWAS) countries, as groundwater is not sufficient to ensure water supply for the population and H_2 production. This scarcity leads to the need to develop an alternative water supply. Although S-DAC and desalination are both promising technologies, there is a limited understanding of how to compare these technologies in terms of cost efficiency under real conditions. The choice of M'bour, Senegal, as an area of study is because to its coastal location, making it an ideal site to test and compare the two water supply sources, as well as its strong potential for wind and solar resources.

To address this gap, the study focuses on two main research questions:

1. How does the cost of producing green hydrogen in West Africa differ when using water from solid Direct Air Capture compared to desalination?
2. What are the main factors that affect the differences in cost efficiency between using DAC and desalination for green hydrogen production?

By addressing these two questions, the study aims to analyse and compare the costs associated with DAC versus desalination for green hydrogen production in West Africa; identify the parameters that mostly influence the cost efficiency of green hydrogen production for each of the water sources; identify the percentage of the value losses during the production process and propose solutions and recommendation on how to avoid those value losses for each of the processes. The methodological approach used to achieve this objective is cost efficiency accounting, combined with techno-economic assessment

This work contributes to the existing literature by addressing the water scarcity issue in West Africa and the lack of comparative studies on desalination and DAC technologies. It also provides a clear insight for policymakers and the private sector on which technology of water supply to invest for green hydrogen production in West African countries, where the resources (seawater, solar, wind) are abundant. In social aspects, the development and operation of such plants can generate employment opportunities and enhance the reliability of energy supply, particularly in rural areas (Africa, 2021).

The study is outlined into three main chapters, followed by a conclusion and recommendations. Chapter 1 provides a literature review on green hydrogen production within the energy transition by focusing on the role of renewable energy systems in West Africa, reviews the different water electrolysis technologies, and examines the two alternative water source options: direct air capture (DAC) and seawater desalination, highlighting their technologies and relevance in the West Africa context. Chapter 2 presents the methodological approach of the study. It describes the area of study, explains the cost efficiency accounting method, and details the system sizing, including the RE configuration, electrolyser battery storage system, and each process plant, and the techno-economic assessment employed to calculate the levelized cost of hydrogen (LCOH). Chapter 3 focuses on the results and discussion. It compares the cost efficiency of the two water sources, DAC and desalination, by highlighting the energy requirement of each process under ideal and actual conditions, the initial and operational investment of the two processes, and then conducts a sensitivity and area-wise analysis to explore the factors that affect the cost efficiency of the systems. Finally, a summary of the key findings, the policy implications, and draw attention to future research.

Chapter 1: Literature review

This chapter reviews key studies related to the production of green hydrogen using renewable energy with a particular focus on water source options. It is outlined by an overview of green hydrogen production, then the two water sources used for the production, considering the technologies' performance, energy requirements, and their impacts in the West African context.

1.1 Overview of Green Hydrogen Production

In the transition towards global decarbonization, nowadays renewable-powered green hydrogen generation is one way that is increasingly being considered as a means of reducing the dependency on fossil fuels and mitigating climate change (Shiva Kumar & Lim, 2022). West Africa has a huge potential to contribute to this transition. Despite its potential, green hydrogen is not naturally available and must be produced via various methods using an electrolyzer to split water. There are many different methods to produce hydrogen. Currently, the majority of the global hydrogen production comes from non-renewable, fossil fuels, in particular, steam reforming of methane and coal gasification, mainly due to their low cost and high efficiency. These methods involve using natural gas and coal, which are heated and combined with steam under high pressure, usually with the help of a catalyst. The reaction produces a mixture of hydrogen and carbon monoxide, with the carbon monoxide later removed to isolate the hydrogen (Vidas & Castro, 2021). However, these processes also tend to produce less pure hydrogen, releasing harmful greenhouse gases to the atmosphere. Electrolysis is one of the hydrogen production methods that releases minimal greenhouse gases. The procedure uses electrolyzers to separate water into hydrogen and oxygen, utilizing electricity produced from renewable energy sources such as solar PV systems and wind turbines. The basic production of hydrogen via electrolysis using electricity to split molecules in water into hydrogen and oxygen is given by:

$$H_2O \xrightarrow{\textit{Electricity + Heat}} H_2 + \tfrac{1}{2} O_2$$

This reaction illustrates the core principle of green hydrogen production via water electrolysis. The following table gives an idea of the hydrogen production methods, their technologies used during the process, their source of production, and the amount of CO_2 released to the atmosphere.

Table 1: Hydrogen production methods

Hydrogen color	**Technology**	**Source**	**CO_2 emissions**	**Cost range $ kg/H_2**
Brown Hydrogen	Gasification	Lignite	High	1.2-2.1
Black Hydrogen	Gasification	Black coal	High	1.2-2.1
Grey Hydrogen	Reforming	Natural gas	Medium	1-2.1
Blue Hydrogen	Reforming + carbon capture	Natural gas	Low	1.5-2.5
Green Hydrogen	Electrolysis	Water	Minimal	3.6-5.8

Source: (Shiva Kumar & Lim, 2022)

The table clearly shows the impact of its technology and its source of production on the atmosphere and the cost range. Electrolysis is the most promising technology for hydrogen production not only to reduce the dependency on fossil-based production but to mitigate climate change. Despite its environmental benefits, water electrolysis remains economically challenging due to its high energy demands and relatively low hydrogen output, and high cost. To improve efficiency, ongoing research is focused on developing more affordable electrocatalysts and reducing overall energy consumption (Vidas & Castro, 2021).

The high cost of green hydrogen production is mainly due to the types of water electrolysis technologies used. Four types of water electrolysis technologies were introduced based on their characteristics, such as Alkaline water electrolysis (AEL), Proton exchange membrane (PEM) electrolysis, Solid oxide electrolysis (SOES), and Anion-exchange membrane (AEM) (Shiva

Kumar & Lim, 2022). Alkaline electrolysis normally operates at high temperatures, around 70–90 ◦C and uses an aqueous solution as electrolyte. This technology has some negative aspects, such as limited current densities, low operating pressure, and low efficiency (50% - 78%), making this type of electrolyzer suited to operate at almost constant power while connected to the grid. One advantage of AEL is its low cost and long-term stability. To address some of the technical challenges of AEL, PEM electrolysis was developed as an alternative.

The first PEM was idealized by Grubb in the early 1950s, having been later developed by General Electric Co. (Boston, MA, USA) in 1966 to overcome the drawbacks of AEL (Khan et al., 2018). PEM has many important characteristics, such as quick response, high efficiency (50% - 80%), and the potential to operate at high pressures and ambient temperatures. In terms of sustainability and environmental impact, PEM is also found to be one of the most favorable methods for the conversion of renewable energy to highly pure hydrogen (99.9 -99.9999%) (Shiva Kumar & Lim, 2022). This is mainly due to other promising advantages like its compact design, high current density (high efficiency), and small footprint (Millet et al., 2010). The main challenge of PEM is the high cost of the components. The high cost of PEM electrolysis components has encouraged researchers to explore other advanced electrolysis technologies.

Solid Oxide Electrolysis has attracted significant attention due to the conversion process of electrical energy into chemical energy, along with the high-efficiency production of pure hydrogen. SOES operates at high pressures and temperatures, being novel by using water in the form of steam (Brisse et al., 2008). But this technology is still in R&D, and the high capital cost is making it under development. Alongside SOES, Anion exchange membrane (AEM) has emerged as a promising electrolysis technology. According to (Shiva Kumar & Lim, 2022) ‘‘AEM is similar to AEL; the main difference is the replacement of the conventional diaphragms (asbestos) with an anion exchange membrane (quaternary ammonium ion exchange membranes) in AEL’’. AEM offers several advantages, such as high current density compared to AEL, high H_2 purity, but the technology is still in R&D as SOES, and the capital is unknown, making it less competitive.

Among the four (4) water electrolyzer technologies with their advantages and disadvantages, PEM stands out as the most suitable option for green hydrogen production in West Africa. While AEL offers lower capital costs and long-term stability, its limited efficiency and slow response make it less compatible with the variable output of RE in the region. SOEC and AEM remain in early stages of development. However, PEM combines high efficiency and rapid response. These characteristics make it more favorable and align well in West Africa, where RE is abundant but intermittent, enabling stable hydrogen output.

Table 2: Summary of the advantages and disadvantages of the different water electrolysis technologies

Water electrolysis technologies	Advantages	Disadvantages
Alkaline water electrolysis (AEL)	Long-term stability, Low cost, commercialized for industrial applications	Limited current density, crossover of the gases, and high-concentration liquid electrolyte
Proton exchange membrane (PEM)	Compact system design, fast response, and high purity of the gases	Cost of the cell components, noble metal electrocatalysts, and acidic electrolyte
Solid oxide electrolysis (SOES)	High working temperature, high efficiency	Limited stability, under development
Anion-exchange membrane (AEM)	Noble metal-free electrocatalysts, low-concentration liquid electrolyte	Limited stability, under development

Source: (Shiva Kumar & Lim, 2022)

1.2 Direct Air Capture Technologies

The accumulation of greenhouse gases, particularly carbon dioxide (CO_2), has been a key driver of global climate change, contributing to rising temperatures, sea level increases, and more frequent extreme weather events. The use of fossil fuels is the main cause of global climate change in the world, especially in West Africa (Li & Yao, 2024). The Paris Agreement has set a goal to reduce global warming below1.5 ^{o}C (Wang et al., 2024). Direct air capture is one of the innovative technologies that remove CO_2 from ambient air through chemical processes (An et al., 2023). DAC technologies can be grouped into five main types: liquid scrubbing, solid sorbents, electrochemical, cryogenic, and membrane-based (Bouaboula et al., 2024). But the main DAC technologies used are liquid-DAC and solid-DAC. The difference between these two DAC technologies is that S-DAC requires low temperature to operate, while L-DAC requires high temperature (100 ◦C versus 900 ◦C), but S-DAC is more energy intensive compared to L-DAC (7.2–9.5 GJ/tCO2 vs 5.5–8.8 GJ/tCO2). This study is mainly based on S-DAC, the technology is designed to capture CO_2 and co-adsorb water during the process (Kuru et al., 2023). There are two main stages in S-DAC: adsorption and desorption. In the adsorption phase, air passes through a system containing the adsorbent and contractor, where the CO_2-selective material captures CO_2, resulting in the air. As the air contains moisture (humidity), water vapor is also captured during the process. In the desorption phase, the captured CO_2 is released from the adsorbent either by heating the system (temperature swing) or by creating a vacuum (vacuum swing), the adsorbent can be used again, leading to a cycling process. The cooling unit is the separation phase where the water vapor is condensed into liquid water while the CO_2 remains a gas (Sinha & Realff, 2019).

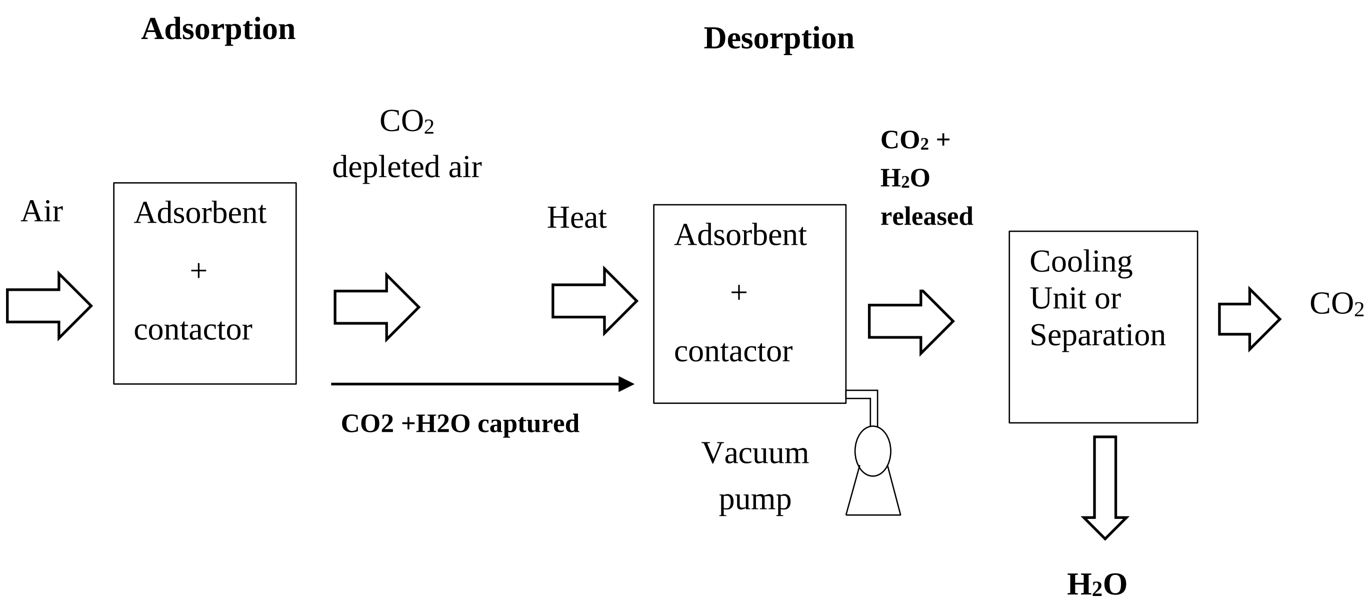

Figure 1: Schematic of S-DAC method

Source: (Sinha & Realff, 2019)

S-DAC is highly dependent on the climate conditions of the chosen site for its performance. West Africa’s climate condition, with generally high variable humidity, offers essential potential for S-DAC operations to co-adsorb a significant amount of water vapor during the air capture process (Seefeldt et al., 2012). This makes the region suitable for using DAC, especially S-DAC, to co-adsorb water from the atmosphere. The purpose of the water co-adsorbent is to produce green hydrogen, and the process does not affect the country's water scarcity.

Previous studies have shown that solid sorbent DAC systems can capture around 75% of $CO_{2,}$ but with significant energy requirements from 1.5 to 3.5 MWh of electricity per ton of CO2 captured (Keith et al., 2018). As the process captures both CO_2 and water, 75% of water will also be co-adsorbed based on the process design.

1.3 Desalination Technologies

In many coastal regions of West Africa, water scarcity is a challenge due to the changes in rainfall patterns, declines in precipitation and runoff, and increased evapotranspiration rates attributable to climate change (Leal Filho et al., 2021). The implantation of green hydrogen production is no longer possible in this condition due to the large amount of water needed for the electrolysis process. Desalination technology powered by renewable energy sources offers a powerful solution to solve this issue. Desalination can be defined as any process that removes salts and impurities from sea to produce fresh water (Singh et al., 2022). By exploiting the coastal area where seawater is available, desalination plants can provide high-quality water even in areas where freshwater is limited. Desalination has been used since the 1950s to overcome the constant increase in freshwater resources (Curto et al., 2021). The two major types of technologies that are used around the world for desalination can be classified as either thermal or membrane. Within those two broad types, there are sub-categories (processes) using different techniques. The major desalination processes are identified in Table 1.

Table 3: Desalination technologies and processes

Thermal Technology	Membrane Technology
Multi-Stage Flash Distillation (MSF)	Electrodialysis (ED)
Multi-Effect Distillation (MED)	Electrodialysis reversal (EDR)
Vapor Compression Distillation (VCD)	Reverse Osmosis (RO)

Source: (Singh et al., 2022)

The main difference between these two technologies is the energy used. In thermal desalination technology, the main energy required is thermal, with high consumption, while in membrane technology, electricity is used as the main source of energy with low consumption. Among the desalination technologies sub-categories, reverse osmosis (RO) is mostly used. RO system provides a high purity of freshwater compared to the other desalination processes and the ability to handle large volumes of seawater. It accounts for 69% of the technology in the total installed desalination capacity worldwide (65.5 million m3/day) (Sources & Asia, 2021).

In most of the literature, the existing desalination plants are powered by fossil fuels. This study, wind, and solar are used to power the desalination plant, and the water is then used for green hydrogen production in West Africa.

The RO system can be divided into five stages: feedwater pre-treatment, RO desalination, and product water post-treatment. Before the water enters the RO membrane, it has to be pre-treated to protect the system and improve the performance by removing the large particles using filtration and the chemical contaminants. After filtration, a high-pressure pump forces the water through semi-permeable membranes, overcoming the natural osmotic pressure and allowing water molecules to pass while rejecting salts and contaminants. The process separates the stream into two outputs: one that has a low concentration of salt (purified) and the other with a much higher concentration than the original feed water, usually referred to as brine or simply as “concentrate”. Following this, post-treatment is conducted to adjust the pH and disinfect the water before using it in the electrolyzer (Mansour et al., 2020). The following figure presents an overview of the process:

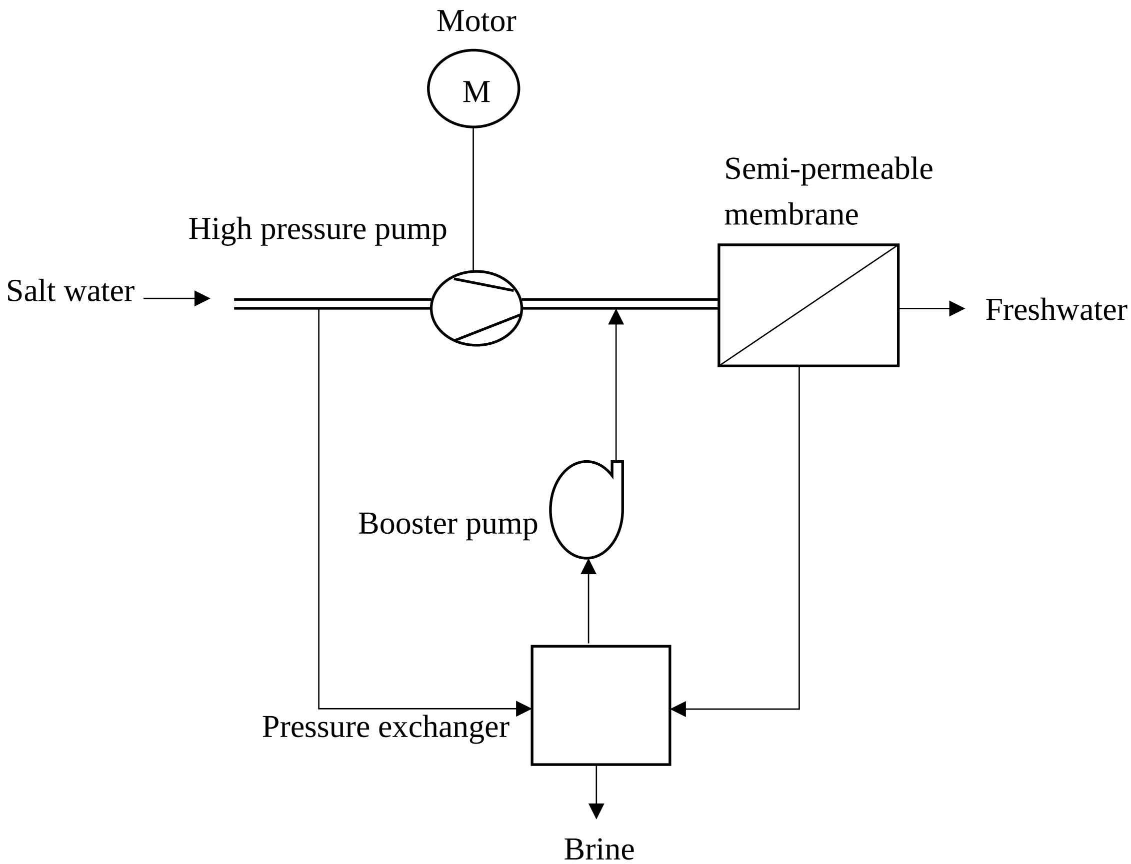

Figure 2: Desalination via RO system (Mansour et al., 2020)

Source: (Mansour et al., 2020)

In the conventional RO systems, the high-pressure pump is driven by a grid-powered electric motor. In this study, the motor is powered by a hybrid renewable energy system. The variable and intermittent nature of renewable sources is managed using a battery storage system to ensure stable motor operation and consistent pressure delivery to the RO membrane.

While global studies exist, empirical reviews of the two process-based hydrogen production remain limited in West Africa, based on the objective and the specific location of the study. The analysis relies on secondary data from published literature. The existing results from the literature are mostly based on techno-economic assessment and modeling in other regions, different from West Africa. For that, the comparative analysis relies on secondary data. Although empirical review offers an insight into real-world data and analysis.

Overall, the reviewed studies show that a range of technologies are available for producing green hydrogen, but their applicability depends on the resources, infrastructure, and technological readiness. In West Africa, the PEM electrolyzer is considered the most suitable option. The choice of water sources plays an important role in determining the system performance and cost efficiency.

Chapter 2: Methodology

This chapter presents the methodological approach used to conduct a comparative efficiency analysis of green hydrogen production using water from direct air capture (DAC) and seawater desalination. The study combines a techno-economic assessment with cost efficiency accounting to analyze the energy use, production costs, and system performance. It also includes the system design, sizing the renewable energy (RE) components, and the calculation of key indicators such as levelized cost of electricity (LCOE), water (LCOW), and hydrogen (LCOH). A case study is carried out in M'bour, Senegal.

2.1Case Study

To compare the efficiency of green hydrogen production using water extraction from direct air capture (DAC) and seawater desalination, M'bour, Senegal, was selected as a case study within the West African countries. M'bour, coordinates Latitude 14.45, Longitude -16.98152, is a coastal city located in the Thiès region of western Senegal. As a coastal area, the chosen site has direct access to seawater, which is essential for a desalination plant, making it a strategic choice for green hydrogen production-based desalination. The city is experiencing rapid demographic and economic growth, which drives an increase in energy demand (International Energy Agency, 2023). This makes it a relevant site to test scalable renewable energy solutions. And, M'bour benefits a favorable renewable energy resources, with an average global horizontal irradiance of 5.5 kWh/m2/day (G. S. Atlas, 2025) and moderate coastal wind speeds of 5-6 m/s (G. wind Atlas, 2025), the region offers significant potential for a hybrid system combining solar and wind energy to supply power to a 10 MW electrolyzer.

Solar PV systems in M'bour generate 1,724.5 kWh/kWp/year (G. S. Atlas, 2025), while wind turbines generate around 1,200 kWh/kW/year (G. wind Atlas, 2025). Therefore, to meet the base load required by the desalination plant, DAC plant, and the electrolysis process with minimal storage, a share of 60% solar and 40% wind to the total energy generation is used to ensure both high energy output and supply stability.

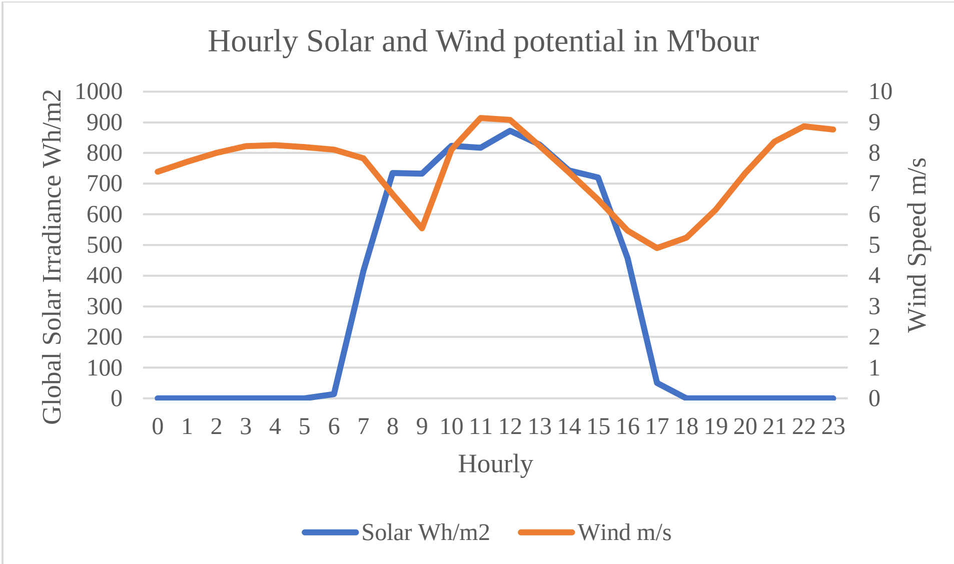

Figure 3: Hybrid system justification in the chosen location

Source: (Nasa Power, n.d.)

This figure shows that the hybrid system is the best option in this particular location to meet the energy demand of the process. Solar is only available between 6 a.m. to 5 p.m., while wind is consistently present throughout the 24 hours but stronger from 12 a.m. to 06 a.m. and 07 p.m. to 11 p.m. This will help to fill the gap as the electricity generation from solar PV systems is limited, only available during the daytime.

2.2 Cost Efficiency Accounting

To compare the efficiency of green hydrogen production from seawater desalination and direct air capture (DAC), cost efficiency will be used as an indicator to measure the value losses during the production process. According to (Dräger & Letmathe, 2022), "Cost Efficiency Accounting is a concept with the objective to measure and reduce value losses during the production processes. It emphasizes a single performance indicator, the cost efficiency, which is defined as the ratio of ideal and actual costs of a reference object":

$$CE = \frac{C_{sideal}}{C_{sactual}} \quad (1)$$

Where:

CE Cost Efficiency of a reference object s

C_s^{ideal} Ideal costs of a reference object s

C_s^{actual} Actual costs of a reference object s

The ideal cost refers to a theoretical minimum cost of production that assumes perfect efficiency, where all input materials, energy, and capacities are used at their optimal levels without any waste, losses, or inefficiencies (Dräger & Letmathe, 2022). To determine the actual cost of production, techno-economic assessment (TEA) will be used to calculate the levelized cost of hydrogen production (LCOH) for each of the processes, taking into consideration losses. The result of this calculation refers to the actual cost of production, while the ideal cost is calculated without losses (no waste of material) by also using TEA, and the formula can be written as:

$$\boldsymbol{CE = \frac{LCOH_{ideal}}{LCOH_{actual}}} \qquad (2)$$

Where: $LCOH_{ideal}$ represent the ideal cost of production

$LCOH_{actual}$ represent the actual cost of production

2.3 System design

The system design illustrates a simplified process of green hydrogen production with two distinct water sources. The process starts with a combined solar PV system and wind turbines that generate electricity. A battery storage system is used to store excess electricity generated during peak production, which can then supply power to the system when RE (solar and wind) is not available. The electricity generation is then used to supply power to the desalination plant and to run an electrolyzer for the first process, and to power a DAC plant and run an electrolyzer for the second process. The desalination plant purifies water from the sea by removing the salt and impurities. The output of this plan gives clean water to supply the electrolyzer, which splits water into hydrogen (H_2) and oxygen (O_2) using electricity from a wind and solar PV system. The DAC plant considered in this study employs the solid-direct air capture (S-DAC) method, a specific type of DAC technology, which primarily captures CO_2 and co-adsorbs water from the atmosphere during the process. In this study, only the water capture is used to supply the electrolyzer for hydrogen production, while the CO_2 is not utilized. In addition, desalination and DAC are the main primary sources of water for producing green hydrogen using renewable electricity from solar and wind. The aim of using these two processes is to analyze and compare the most efficient process for green hydrogen production in West Africa in terms of cost and resource consumption.

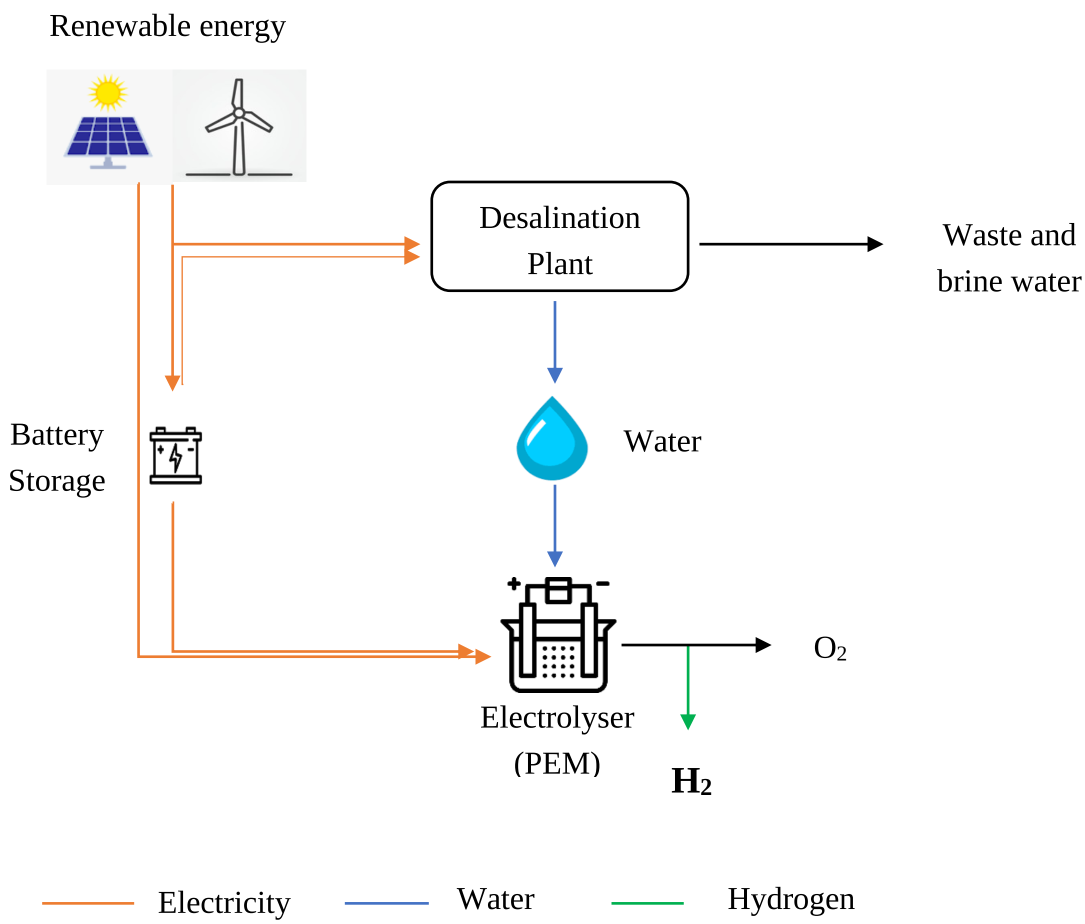

Figure 4: Green Hydrogen produced from seawater desalination (First process)

<u>Source</u>: Author

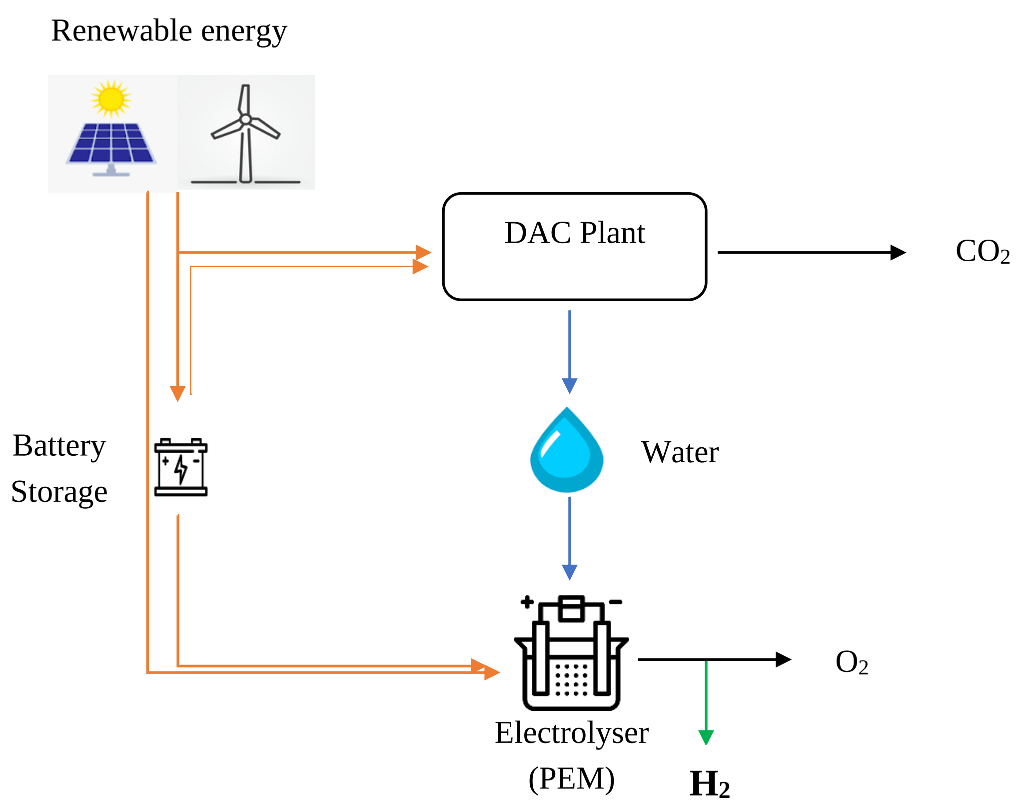

Figure 5: Green Hydrogen produced from DAC (Second process)

Source: Author

2.4 Techno-economic assessment (TEA)

The study aims to comparatively analyze the efficiency of green hydrogen production in West Africa by evaluating two distinct water sources: direct air capture (DAC) and seawater desalination. The analysis focuses on quantifying the energy required, the total amount of water consumed to produce 1kg of green hydrogen, and overall system efficiency from water extraction to hydrogen production via electrolysis, and the cost associated with each component. To achieve this objective, data were collected from existing literature. In addition, TEA is used to determine the levelized cost of hydrogen (LCOH) in ideal and actual conditions during the production process.

A project duration of 20 years is assumed, corresponding to the lifespan of some of the technologies used.

The following tables present the data collected from existing literature for PEM electrolyzer, solar PV system, wind turbines, battery storage system, and the two processes, DAC and desalination, considering the cost of each component and the technical parameters (efficiency, lifetime, energy, and water required in ideal and actual conditions) used to evaluate the LCOH production in actual and ideal cases.

Table 4: PEM Electrolyzer data

Parameters	Value	Unit	Source
Capacity	10000	kW	Assumption
PEM energy required in ideal condition	39.4	kWh/kgH2	(Saur, 2008)
PEM energy required in actual condition	54	kWh/kgH2	(Ali Khan et al., 2021)
PEM water required in ideal condition	8.9	liters/kgH2	(Saur, 2008)
PEM water required in actual condition	10	liters/kgH2	(Ali Khan et al., 2021)
PEM Efficiency	70	%	(Bhandari & Shah, 2021)
PEM lifetime	20	years	(Bhandari & Shah, 2021)
Lifetime stack	5	years	(Bhandari & Shah, 2021)
PEM Capex	1183	$/kW	(Bhandari & Shah, 2021)
PEM Opex	2	% Capex	(Bhandari & Shah, 2021)
Stack replacement cost	496.86	$/kW	(Bhandari & Shah, 2021)
Discount rate	10	%	(IRENA, 2020)
Exchange rate in 2019 € to $	1.1551	$	(UK, 2006)
Exchange rate in 2021 € to $	1.183	$	(UK, 2006)
Exchange rate in 2022 € to $	1.2339	$	(UK, 2006)
Exchange rate $ to €	0.89	€	(UK, 2006)

Table 5: DAC data

Parameters	Value	Unit	Source
DAC energy required	250	kWh/tCO2	(Fasihi et al., 2019)
DAC Capex (730 €/tCO2.a)	843.22	$/tCO2.a	(Fasihi et al., 2019)
DAC Opex	4	% Capex	(Fasihi et al., 2019)
DAC Efficiency	87	%	(Fasihi et al., 2019)
Tank	80	$/liter	Alibaba

Table 6: Desalination data

Parameters	Value	Unit	Source
Desalination energy required	3.85	kWh/m3	(Webber et al., 2024)
RO Pump Efficiency	75	%	(Adda et al., 2024)
Lifetime RO membrane	5	years	(Adda et al., 2024)
Desalination Capex	15.646	$/m3	(Adda et al., 2024)
Desalination Opex	0.158	$/m3	(Adda et al., 2024)
RO membrane replacement cost	452.18	per module	(Adda et al., 2024)
Tank	80	$/liter	Alibaba

Table 7: Solar PV data

Parameters	Value	Unit	Source
Solar irradiance	5.5	kWh/m2/day	(IRENA, 2012)
Solar Capacity factor	0.41		(Allington, 2021)
Solar PV quality factor	0,5		(Bhandari & Shah, 2021)
Efficiency of Solar PV	80	%	(Allington, 2021)
Radiation at standard test condition I_{stc}	1	kW/m^2	(Bhandari & Shah, 2021)
Solar PV Capex	984	$/kW	(Allington, 2021)
Solar PV Opex	1.2	% Capex	(Allington, 2021)

Table 8: Wind turbine data

Parameters	Value	Unit	Source
Wind speed	6	m/s	(IRENA, 2012)
Wind turbine efficiency	60	%	(Allington, 2021)
Wind capacity factor	0.17		(Allington, 2021)
Wind Capex	1191	$/kW	(Allington, 2021)
Wind Opex	2	% Capex	(Allington, 2021)

Table 9: Battery storage data

Lifetime battery storage	10	year	(Bhandari & Shah, 2021)
Depth of discharge (DOD)	50	%	(Bhandari & Shah, 2021)
Battery efficiency	95	%	(Kigle et al., 2024)
Battery Day of Autonomy (DOA)	0.5		Assumption
Battery Capex	690.984	$/kWh	(Bhandari & Shah, 2021)

Battery replacement cost	246.78	$/kWh	(Bhandari & Shah, 2021)
Battery Opex	0.03332	$/kWh	(Bhandari & Shah, 2021)

2.5 Data Analysis

This section provides a detailed analysis of the technical and financial data used in the techno-economic assessment. A 10 MW PEM electrolyser is used to design the system. The electrolyzer has an efficiency of 70 % and an energy requirement of 54 kWh per kg of hydrogen in actual conditions, meaning losses have been taken into consideration. Under ideal circumstances, the electrolyzer requires 39.4 kWh of electricity and 8.9 liters (l) of water at normal conditions (25 ^{o}C and 1 atm) to produce 1 kg of hydrogen (Saur, 2008). This means that in this circumstance, there is no waste of material, no losses, and all the resources are used in their optimal condition.

A bottom-up approach is used to calculate the amount of hydrogen produced per hour. 185.19 kg of hydrogen is produced in actual conditions and 253.81 kg in ideal conditions per hour based on the capacity and the energy consumption of the electrolyzer per kg of H2. From these values, the total water consumed for the electrolysis process was estimated, which corresponds to 16222.22 and 19787.82 tons of water per year for each process, respectively, in actual and ideal conditions. This difference in water consumption in actual and ideal conditions is due to the high output of H2 produced in ideal conditions. In this case, the electrolyzer will require more water than in actual conditions. To obtain these results, a model has been developed using Excel not only to estimate the amount of hydrogen produced but also to determine the cost efficiency of each process. All costs have been taken into account over the lifetime of the project, including initial investment, replacement cost, and operational and maintenance costs, for all the parameters.

In the DAC system, a ratio of 1:1 (CO_2: H2O) is used to estimate the amount of H_2O capture during the air capture process (Kain, 2024) with energy consumption of 250 kWh/tCO_2. In comparison to a desalination system, whose aim is to purify the water from the sea by removing the salt and all impurities. Meaning that in the desalination plant, only water is extracted, and the process requires 3.85 kWh per cubic meter of electricity to purify the water (Webber et al., 2024).

- System sizing

The system sizing consists of determining the required capacities of solar PV systems, wind turbines, and battery storage needed to meet the energy demand for each of the entire process DAC to elctrolysis process and desalination to the electrolysis process.

Equations 1, 2, and 3 are used to size, respectively, the PV system, wind, and the battery capacity.

$$PV\ Capacity\ (kWp) = \frac{E_d(kWh) * I_{stc}(kW/m^2)}{G\left(\frac{kWh}{m^2}\right) * Q} \quad (3)$$

Where:

E_d – Energy demand in kWh per day

I_{stc} – Radiation at standard test condition in kW/m^2 (Value 1kW/m^2)

G – Global solar radiation in kWh/m2/day

Q – Quality factor of performance ratio (Value 0.5 for off-grid)

$$Wind\ Capacity = \frac{E_d(kWh)}{Cf * 24h} \quad (4)$$

Where:

E_d – Energy demand in kWh per day

Cf – Capacity factor of wind for onshore wind in Senegal

$$Battery\ size\ (kWh) = \frac{E_{req}(kWh) * DoA}{(DoD * \eta_{syst})} \quad (5)$$

Where:

E_{req} – Energy required in kWh per day

DoA – Days of Autonomy (0.5)

DOD – Depth of discharge of the battery (assumed value of 50%)

η_{sys} – Overall battery system efficiency

- Levelized cost of Hydrogen

The levelized cost of hydrogen is calculated to determine the actual and ideal costs during the production process. To evaluate these costs, the present value of wind, solar, and battery were calculated in order to determine the levelized cost of electricity (LCOE), then the levelized cost of water (LCOW), with is based on the present value of DAC/Desalination and their energy consumption. These two parameters LCOE and LCOW are inputs to determine the LCOH. Equations 4,5, 6, and 7 are respectively used to determine the present value (PV), LCOE, LCOW, and LCOH corresponding to the actual and ideal cost of production.

$$\boldsymbol{PV = \sum_{t=1}^{n} \frac{C_t}{(1+d)^t}} \qquad (6)$$

Where:

PV – Present Value

C_t – O&M cost in year t

d – discount rate

n – lifetime of the project in years

$$\boldsymbol{LCOE = \frac{I + \sum_{t=1}^{n} \frac{OM_t}{(1+d)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+d)^t}}} \qquad (7)$$

Where:

I – initial investment for the system in €

OM_t – operational and maintenance cost in year t in €

E_t – total energy generation in kWh per year

d – discount rate

n – lifetime of the project in years

$$LCOW = \frac{I + \sum_{t=1}^{n} \frac{CC_t}{(1+d)^t}}{\sum_{t=1}^{n} \frac{V_{w,t}}{(1+d)^t}} \quad (8)$$

Where:

I – initial investment

CC_t – annual cost of operation

$V_{w,\,t}$ – amount of water produced in the year

d – discount rate

n – lifetime of the project in years

$$LCOH = \frac{I + \sum_{t=1}^{n} \frac{OM_t}{(1+d)^t}}{\sum_{t=1}^{n} \frac{H_t}{(1+d)^t}} \quad (9)$$

Where:

I – initial investment for the system in €

OM_t – operational and maintenance cost in year t in €

H_t – total Hydrogen produced per year in kg

d – discount rate

n – lifetime of the project in years

Chapter 3: Results and Discussion

This chapter presents the results of a comparative analysis of green hydrogen production using water sourced from direct air capture and seawater desalination in West Africa, followed by an in-depth discussion.

3.1 Results

3.1.1 Cost efficiency of the processes

- **Energy requirement**

The results show that producing green hydrogen using water from DAC in ideal and actual cases requires higher installed capacities for solar, wind turbines, and battery storage systems compared to using seawater desalination. In the actual case, a total electricity generation of 91,655.56 MWh is required for both capturing water from the air through DAC and the electrolysis process, while the ideal case requires 92,546.95 MWh of electricity for the same purpose. DAC alone accounts for 4% of the total electricity generation (4,055.56 MWh) for the air capture process in the actual case and 5% (4,946.95 MWh) in the ideal case. This is largely due to the energy required for the air capture process, 250 kWh per ton of CO_2, as a ratio of 1 is used CO_2: H2O to determine the amount of water that will be captured during the process, as DAC captures both CO_2 and water at the same time. In comparison, the combined desalination and electrolysis process consumes 87,676.18 MWh of electricity generation in the ideal case and 87,662.46 MWh in the actual case. Desalination alone accounts for approximately 1% of the total electricity generation, which is 62.46 MWh in the actual case and 76.18 MWh ideal case for salt removal and water purification. The similarity of these results is due to the parameters, specifically the energy consumption for the two processes, as it does not change in both conditions. The outcome of the results makes the DAC process more energy-intensive and, thus, necessitates greater renewable infrastructure compared to seawater desalination. The desalination process consumes about 3.85 kWh of energy per cubic meter for salt removal and purification.

Table 10: Total Electricity generation for DAC and desalination in Ideal and Actual cases

Parameters	Ideal case	Actual case	Unit
DAC	92,546.95	91,655.56	MWh
Desalination	87,676.18	87,662.46	MWh

Table 11 represents the installed capacities required for each process under both cases (Ideal and actual):

Table 11: RE installed capacity

Parameters	Ideal case		Actual case	
H2 production process	DAC	Desalination	DAC	Desalination
Solar PV MWp	55.321	52.409	54.788	52.401
Wind MW	24.858	23.550	24.619	23.546
Battery MWh	266.898	252.851	264.327	252.812

Source: Author

The differences between the RE capacity installed in the ideal and actual cases are due to the amount of green hydrogen produced per year. The hydrogen produced in the ideal case is 2,223,350.254 kg per year, which is higher than in the actual case, 1,622,222.22 kg per year. This difference in hydrogen output is largely due to the electrolyser energy consumption and the water required per kilogram of H2. In ideal conditions, the electrolyser consumes 39.4 kWh of electricity and 8.9 liters of water per kg of H_2, while in actual 54 kWh of electricity and 10 liters of water are required per kg of H_2. This will highly affect the total hydrogen produced per year and increase the capacity of RE installed.

- **Cost Efficiency**

Cost consideration is a key aspect of evaluating the implementation of green hydrogen production pathways. The aim of comparing the cost efficiency of the two alternative water supply options for H2 production is to assess their integration with renewable energy systems and electrolysis technologies. A detailed examination of the capital expenditure (CAPEX) and operational expenditure (OPEX) associated with each process helps to point out the main cost drivers and sources of inefficiency by revealing the components that require greater investment or incur higher operation costs, as it is directly related to the cost of green hydrogen production. The following sections present an overview of the total cost in ideal and actual cases and break down these costs to provide a clear picture of how each component contributes to the total production cost under both ideal and actual conditions.

Table 12: Capex and Opex of the two processes

Parameters	**Ideal case**		**Actual case**	
H2 production process	DAC	Desalination	DAC	Desalination
Total CAPEX million USD	298.56	268.06	292.685	201.38
Total OPEX million USD/year	2.158	1.441	2.026	1.438

Source: Author

This table shows that the total cost of production in the ideal case is higher than the total cost of production in the actual case for both processes and approximately the same operational and maintenance cost (total Opex).

- **Cost Breakdown**

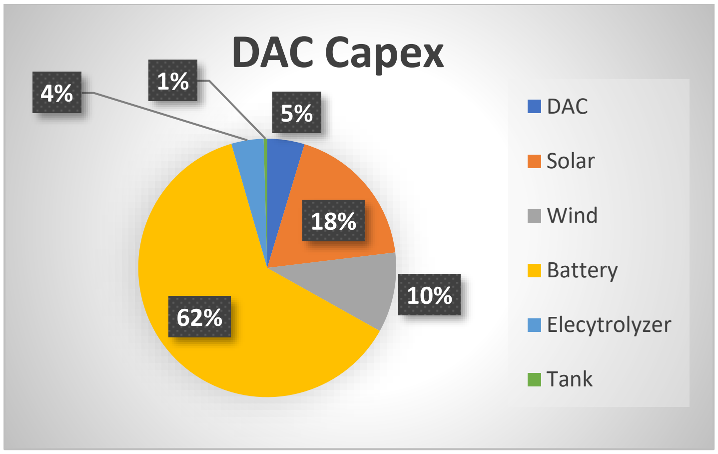

Figure 4: DAC Capex

Source: Author

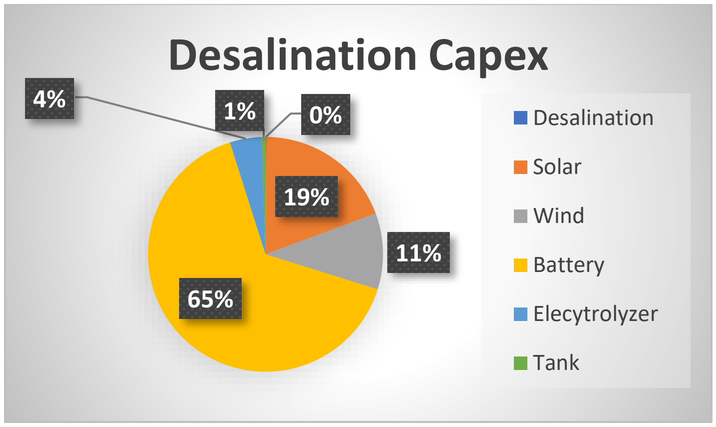

Figure 5: Desalination Capex

Source: Author

Figures 4 and 5 provide a detailed breakdown of the Capital Expenditure (Capex) for green hydrogen production using DAC and seawater desalination. These visualizations highlight the distribution of costs across key system components, allowing a deeper understanding of the main cost drivers. The two figures show that for both DAC and desalination, battery systems dominate the capital investment. As RE is not always available because of its intermittency and the system is designed to run 24 hours, the battery is the only device that will supply power to either DAC or desalination for water extraction/purification, and the electrolyzer. The Share of solar PV and wind reflects the need for various and substantial renewable inputs to power DAC, desalination, and the electrolysis process. Electrolyser accounts for 4 % of the total cost for both processes, which is small compared to the other components. In contrast, the DAC system contributes around 5 % of the total cost, showing that the air capture process is a core element of the DAC plant and therefore represents a significant investment.

In comparison, desalination itself contributes around 1 % (similar to the tank for both processes) of the total cost, lower than the DAC system because the RO system equipment requires low capital costs (e.g, membranes, pumps, and pre-treatment systems) (Tech, 2024) compared to the sorbent components. Overall, both systems are heavily dependent on battery and the RE investments; DAC adds extra capital investment through its infrastructure, making the system more expensive than desalination.

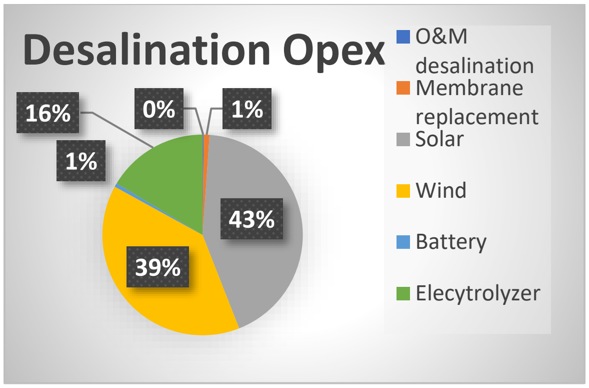

Figure 7: Desalination Opex Breakdown

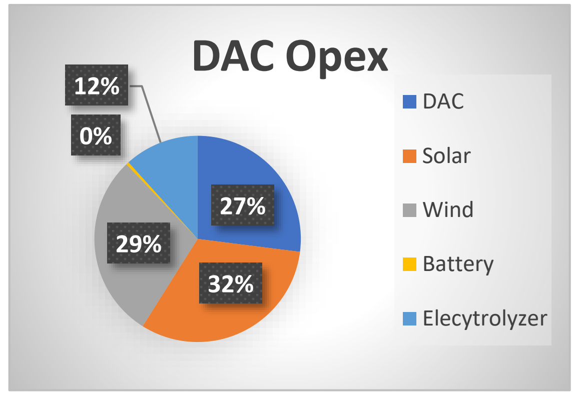

Figure 6: DAC Opex breakdown

Source: Author

As in the Opex breakdown, solar energy accounts for a larger share of operational expenditure in the desalination system compared to the DAC system. This difference can be explained by the small share of desalination systems, membrane replacement, and the battery, which, in turn, makes solar appear more dominant in the cost structure. In contrast, the DAC system has a more balanced distribution of Opex compared to the desalination process, particularly the DAC unit itself and electrolyzer, thereby reducing the large share of the solar PV system.

Based on these results, we see that the cost of producing green hydrogen using water from DAC is relatively high compared to the cost of green hydrogen production from seawater desalination. The LCOE and the LCOW are inputs for calculating the LCOH. As described in the methodology, the LCOH reflects the actual and ideal production costs in each case. Results confirm that green hydrogen from seawater desalination is more cost-effective than from DAC.

Table 13: LCOH results-DAC Process

Parameters	Ideal case	Actual case	Unit
LCOE	0.081	0.081	€/kWh
LCOW	0.0087	0.09	€/kg
LCOH	3.833	6.209	€/kg

Source: Author

Table 14: LCOH results-Desalination Process

Parameters	Ideal case	Actual case	Unit
LCOE	0.081	0.081	€/kWh
LCOW	0.0053	0.0053	€/kg
LCOH	3.832	5.304	€/kg

Source: Author

The observation from tables 12 and 13 is the similarity in the LCOE for both DAC and desalination systems in ideal and actual cases. In all scenarios, the LCOE remains constant at 0.081 €/kWh. This consistency is expected, as LCOE is calculated based on the lifetime cost of electricity generation from renewable sources like solar and wind. Since the assumptions regarding system size, lifespan, and generation potential are the same in both the ideal and actual cases, the LCOE does not change even though the downstream processes (like water purification or electrolysis) may perform differently.

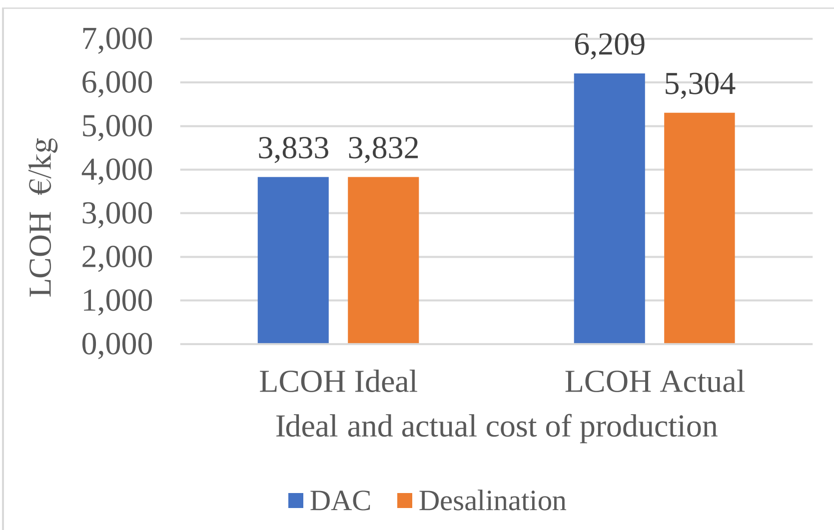

Figure 8: Ideal and actual cost comparison of DAC and desalination

Source: Author

This figure gives a clear picture of the cost difference between using DAC or desalination for hydrogen production. In the actual scenario, DAC's LCOH reaches 6.209 €/kg, significantly higher than 5.304 €/kg for desalination. This confirms the cost advantage of using seawater desalination for H_2 production.

When we look at the LCOH in the ideal case, we also see that the result is almost identical for both processes: 3.833 €/kg for DAC and 3.832 €/kg for desalination. This small difference can be explained by the fact that, under ideal conditions, both systems are assumed to operate at high efficiency, with minimal energy losses and optimized resource use. For example, the electrolyzer energy consumption is reduced to 39.4 kWh per kilogram of hydrogen, and the water requirement drops to 8.9 liters per kilogram. Since both systems use the same electricity input cost and require only a relatively low amount of energy for water processing under ideal conditions, the cost difference between them becomes negligible.

These findings highlight that in an ideal circumstance, the efficiency of the electrolyzer is the main driver of production cost, while the method of water sourcing, whether from the air or the sea, has relatively little impact. It is only when we shift to actual scenarios, where technical losses and real-world constraints come into play, that is where the differences between DAC and desalination become more pronounced. This makes the difference in the cost efficiency; the higher the actual cost of production, the lower the CE, which will lead to a system inefficiency (value losses). The lower value losses in the desalination process reflect a better alignment between theoretical assumptions and actual performance, reinforcing its technological maturity and system stability.

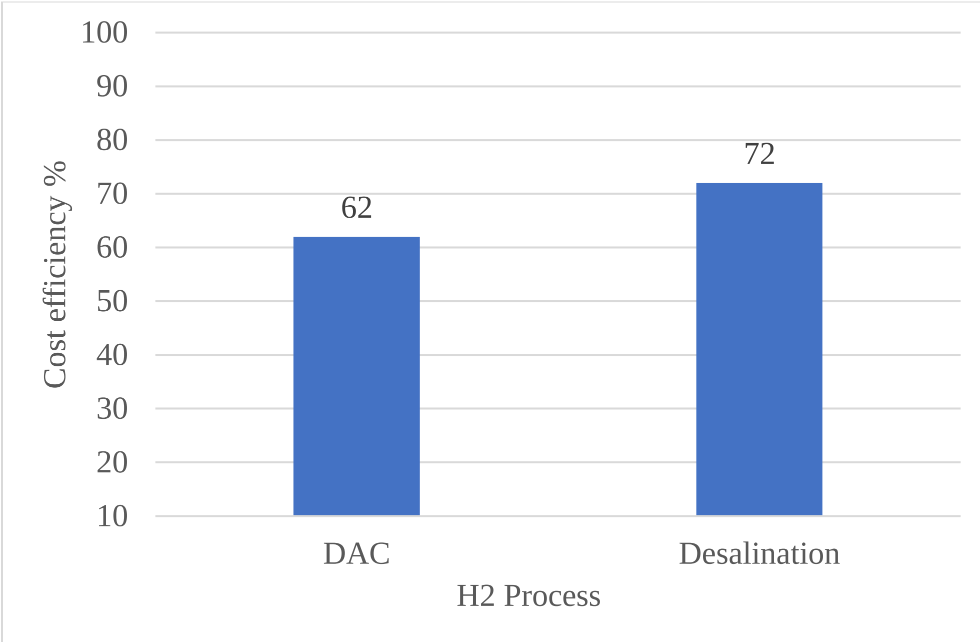

Figure 9: Cost efficiency comparison of the two processes

Source: Author

3.1.2 Sensitivity analysis

A sensitivity analysis was conducted to identify the parameters that most influence the cost efficiency of the two processes. Three scenarios were analysed, while the battery remains the same based on the system sizing.

Scenario 1: Equal share of solar and wind

In this scenario, green hydrogen production using DAC becomes more cost-effective with higher installed capacities of solar and wind compared to the desalination system, which uses lower RE capacities. When solar and wind contribute equally to the energy supply, the actual cost of hydrogen production using DAC drops from 6.209 €/kg to 5.980 €/kg. Although this is a comparatively low reduction, it reflects the benefit of optimized renewable integration. However, desalination still remains cheaper, with costs at 5.646 €/kg. Notably, the ideal cost for DAC remains static, implying that the gains are only significant under actual operating conditions. These results directly affect the CE of the two processes by an increase in DAC system and a decrease in desalination, making it less efficient than DAC.

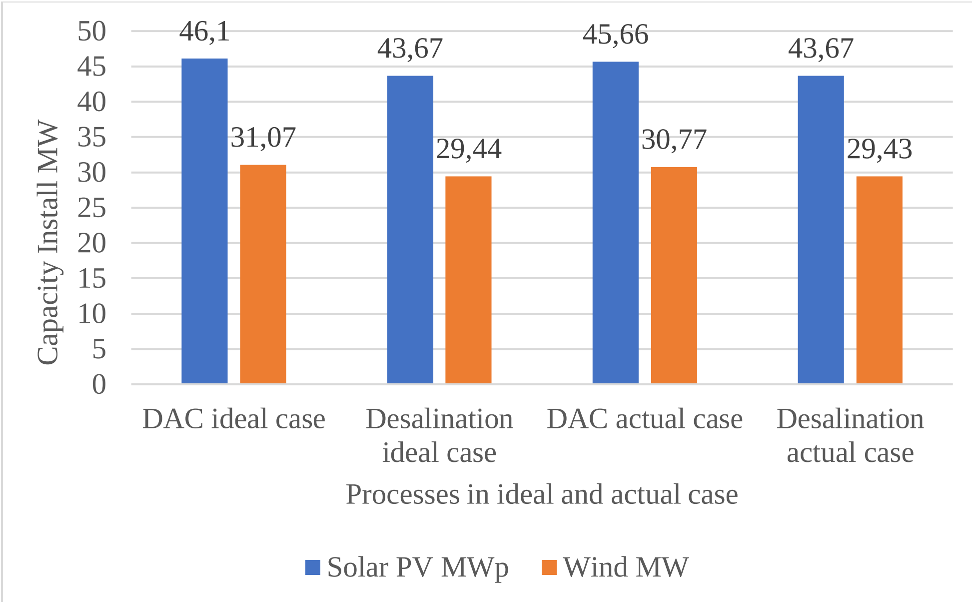

Figure 10: Equal share of Solar and Wind Capacities installed in actual and ideal cases

Source: Author

Table 15: LCOH and CE results comparison

Parameters	**Ideal cost €/kg**	**Actual cost €/kg**	**Cost Efficiency %**
DAC	3.833	5.980	64
Desalination	3.584	5.646	63

Source: Author

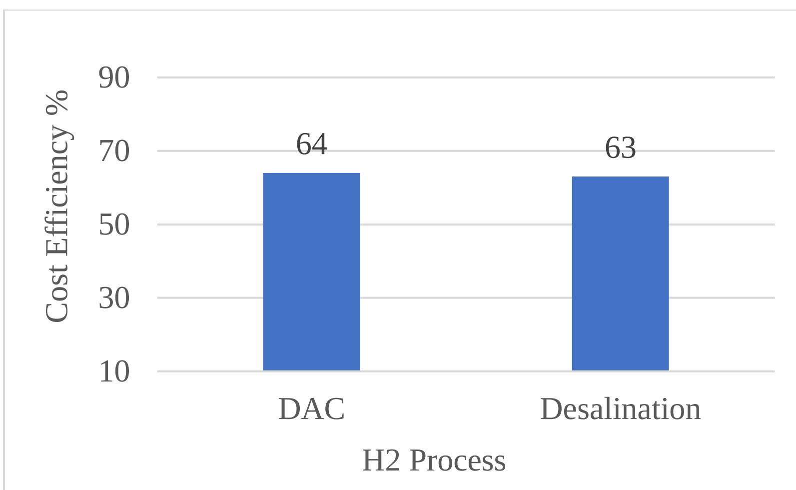

Figure 11: Cost efficiency comparison for an equal share of wind and solar PV systems

Source: Author

Scenario 2 & 3: Only Solar/Wind

These scenarios explore the use of only solar or wind and battery for green hydrogen production for each of the processes. Solar-only configurations slightly improve the cost performance of DAC compared to wind-only. In the second scenario, DAC under solar PV operation reaches 5.980 €/kg, while desalination achieves 5.782 €/kg. This supports the idea that solar energy may be more compatible with both DAC and desalination in regions with high solar irradiance, like most of the West African countries. In the third scenario, wind-only systems show a sharp cost increase, particularly for DAC. The actual cost rises drastically to 19.026 €/kg, compared to 11.882 €/kg for desalination. These results indicate that wind power, in isolation, is a less effective option for DAC-based hydrogen production due to its intermittent nature and the constant energy needs of DAC systems. Wind-based hydrogen production for DAC thus appears economically unviable unless wind capacity factors are substantially improved or energy storage becomes significantly cheaper.

Table 16: Solar PV system sizing result

Parameters	Ideal case		Actual case	
H2 process	DAC	Desalination	DAC	Desalination
Solar PV MWp	92.20	87.35	91.31	87.33

Source: Author

Table 17: Ideal and actual cost of production and CE for Solar-based production

Parameters	Ideal cost €/kg	Actual cost €/kg	Cost efficiency %
DAC	3.585	5.980	60
Desalination	3.832	5.782	66

Source: Author

Table 18: Wind turbine system sizing result

Parameters	Ideal case		Actual case	
H2 process	DAC	Desalination	DAC	Desalination
Wind turbine MW	62.15	58.87	61.55	58.87

Source: Author

Table 19: Ideal and Actual cost of production and CE for Wind-based production

Parameters	Ideal cost €/kg	Actual cost €/kg	Cost efficiency %
DAC	7.250	19.026	38
Desalination	7.250	11.882	61

Source: Author

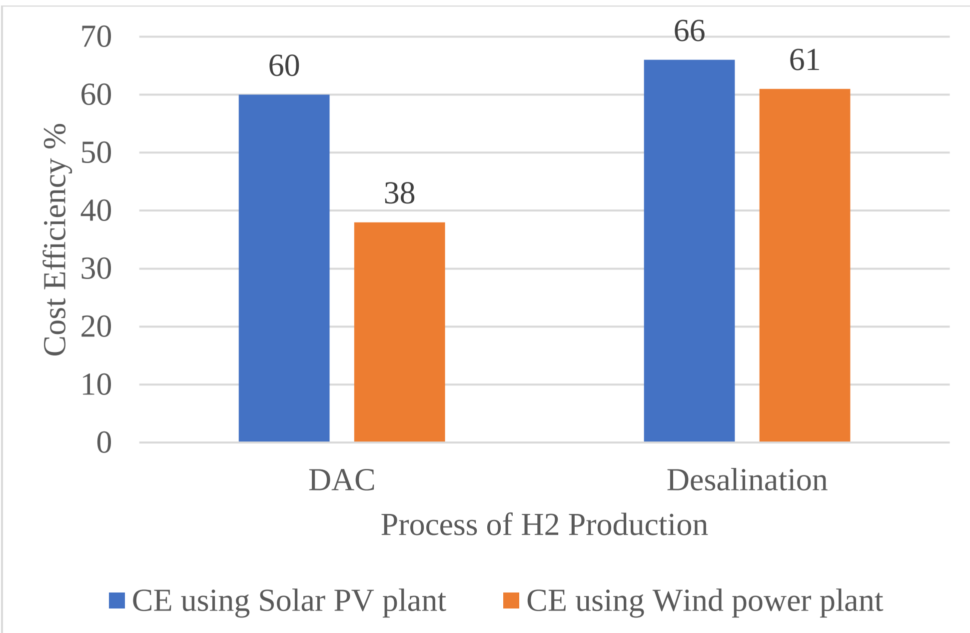

Figure 12: Cost efficiency comparison for Wind/Solar-based production

Source: Author

3.1.3 Area-wise Analysis

The area-wise assess the value losses during the production process to gain a deeper understanding of how each green hydrogen production process performs. This analysis helps to quantify the value losses due to system inefficiency and later discusses how to avoid them. The following formula is used to determine the value losses:

$$CL_{as} = \frac{C_{actual} - C_{ideal}}{C_{actual}} \text{ or } 1 - CE \qquad (10)$$

Based on the results presented in Figure 9, in the base case, DAC and desalination, respectively, show a cost efficiency (CE) of 62% and 72%. Using the formula in (10 will yield 38% for DAC and 28% for desalination as value losses. These results show that the DAC process experiences greater inefficiency during the production process. This is due to the higher energy demand during the air capture process, the complexity of capturing water from the air, and technological maturity. In comparison to the desalination process, which presents a lower value loss, it demonstrates better system stability and more mature technology. The sensitivity analysis confirms this approach by showing in all the scenarios how the value loss increased in the DAC process.

By combining all these results, DAC is not yet competitive with desalination for green hydrogen production, especially in West Africa, where coastal access is available in many regions. However, DAC may still be a promising solution for inland or arid zones lacking water resources.

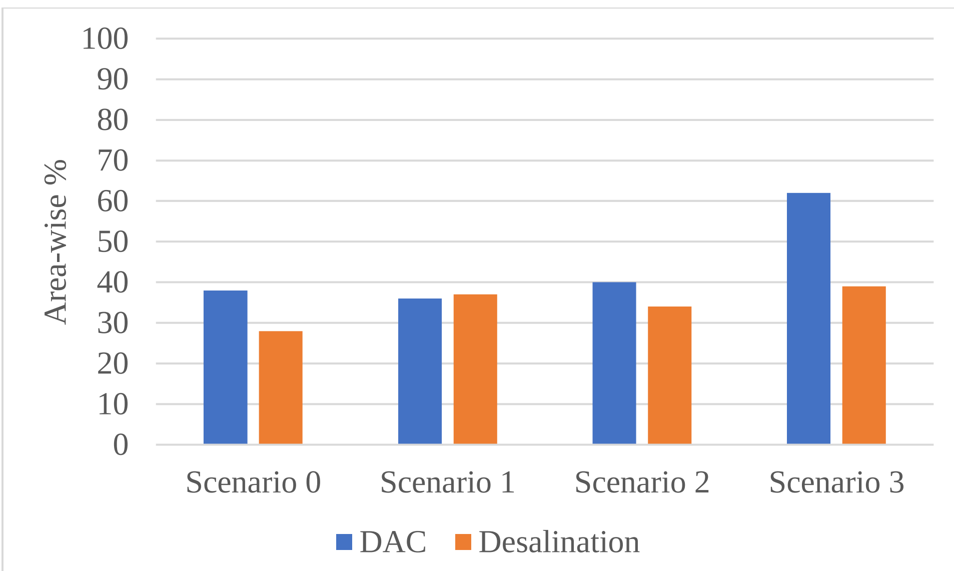

Figure 13: Area-wise comparison in the base case (Scenario 0) and the sensitivity analysis

Source: Author

3.2 Discussion

This study focuses on comparing the cost-efficiency of green hydrogen production in West Africa by using two different water sources: seawater desalination and DAC (S-DAC), both powered by renewable energy (wind and solar). The findings provide a clear insight into the performance of each process under ideal conditions (No losses during the production process) and actual conditions, which can be considered as real-world conditions where no system can perform at perfect (ideal) conditions. This section gives a deep understanding of those results in the context of the research questions and the existing research based on the two technologies used.

3.2.1 Cost comparison of desalination and DAC

The specific objective of this study is the comparison of the production costs of green hydrogen when using desalinated seawater versus water obtained through solid direct air capture (S-DAC). This subsection discusses how the cost of producing green hydrogen in West Africa differs under actual and ideal conditions and what drives these differences. The results have shown that green hydrogen production using seawater desalination is more cost-effective compared to using water from the atmosphere through DAC. Under actual conditions, the LCOH of desalination was 5.304 €/kg while DAC reached 6.209 €/kg. In ideal conditions, both systems gave nearly the same costs, approximately 3.83 €/kg. the difference in actual condition is largely due to the high energy consumption required for the DAC system. Although S-DAC provides an alternative water source, its operational complexity and limited technological maturity currently limit its economic viability (Breyer et al., 2020)& (Realmonte et al., 2019). The similarity of the results in the ideal case is due to that the parameters used in both systems were maintained, the only difference was made in the electrolyzer in ideal conditions, giving a high rate of H2 production 2,223,350.254 kg/year. As the LCOH is inversely dependent on the total H2 output, the higher the production, the lower the value.

3.2.2 Factor influencing cost efficiency

Beyond absolute costs, understanding the factors that drive system efficiency is essential. This subsection examines the main contributors to cost efficiency (CE) for both processes, highlighting the sources of value losses and inefficiencies that explain why desalination outperforms DAC under real-world conditions

Comparing the cost of green hydrogen production is essential for two different water sources, but understanding the factors that drive the system efficiency is also essential. This subsection examines the main contributors to cost efficiency (CE) for both processes, highlighting the sources of value losses and inefficiencies. We got from the results a cost efficiency of 72% for desalination and 62% for DAC. These differences show that DAC incurs greater value losses during the production process due to its energy intensity, more expensive infrastructure, and double function of capturing CO_2 and water at the same time. In contrast, desalination via reverse osmosis (RO) benefits from higher technological maturity compared to DAC, with low energy requirements of about 3.85 kWh per cubic meter for water treatment, leading to low cost (Gorjian et al., 2014). As a result, the desalination result gives a lower inefficiency and aligns better between theoretical and practical performance.

The high value loss in the DAC system with solid sorbents (S-DAC) is mainly due to the higher energy requirements for capturing and releasing water and CO_2 from the atmosphere. According to (Fasihi et al., 2019), the high energy consumption is often in a range of 7.2-9.5 GJ per ton of CO_2, and is driven by the need for fan operation, heating process for the sorbent material, and vacuum pumps used during the desorption phase. These components mentioned above contribute to the overall energy consumption and system inefficiency.

For a seawater desalination plant, value losses are mostly in the high-pressure pump, membrane fouling, and brine management. (Webber et al., 2024) found that up to 60 % of the total energy consumption in the reverse osmosis (RO) system is attributed to the high-pressure pumping, with additional losses occurring from friction and turbulence in the piping system. While (Mansour et al., 2020) mentioned that membrane fouling is a result of biofilm formation, scaling, or particulate clogging, leading to increased transmembrane pressure requirements to force the system to operate, and this can reduce the water flux. This leads to frequent maintenance or membrane replacement, which can be an additional cost for the system. In addition, for both systems, coupling desalination and DAC with the intermittency of renewable energy sources introduces its own losses from battery charge/discharge cycles, partial load operation of pumps, and occasional downtime (Adda et al., 2024).

The sensitivity analysis emphasizes the impact of system design on the performance of cost efficiency for green hydrogen production. In the base case, the system was configured to draw 60% of its energy from a solar PV system and 40% from wind. From this share, the cost efficiency reached 72% for seawater desalination and 62% for the DAC system. The results indicate that the share of RE sources is the primary factor influencing the overall cost efficiency in both systems. When solar and wind were balanced equally, DAC's cost efficiency improved slightly to 64%, while desalination decreased to 63%. This is largely due to the reduction in the LCOH for DAC, which directly increased its cost efficiency. However, when the production relied on solar PV systems or wind, value losses increased for both systems. This was due to the higher installed capacity required for each source, which in turn raised both capital and maintenance costs, leading to an increase in the LCOH. The worst performing configuration was wind-only production, which resulted in low efficiency and high value losses, particularly in the DAC system, because of the additional cost of wind components.

In addition, the sensitivity analysis confirms that a hybrid solar wind configuration offers the best performance in the cost efficiency for green hydrogen production in West Africa. While DAC benefits most from a balanced or solar PV system supply, desalination remains comparatively stable across different configurations. Wind-only-based production is economically unviable for DAC under current conditions, underscoring the importance of diversified renewable integration for cost-effective hydrogen production.

These findings are important for infrastructure planning, particularly in regions where land availability and renewable energy resources are limited. The higher capacity requirements for DAC imply increased land use, higher initial investments, and possibly longer development timelines. Therefore, in regions with abundant seawater and available coastline, desalination is more viable from an infrastructure efficiency perspective.

From an operational perspective, minimizing value losses in both RO and DAC systems is essential to improve the cost efficiency of the overall system. In the RO desalination system, the efficiency depends highly on the pump. To improve the efficiency of desalination-based RO, an energy recovery system (ERS) can be integrated, such as pressure exchangers (Mansour et al., 2020). This allows for the reuse of energy from high-pressure brine streams to pre-pressurize incoming seawater, also reducing the load on the high-pressure, leading to significant electricity savings. As seen in the results, desalination has lower value losses and greater cost efficiency compared to the DAC system. Integrating ERS would likely amplify this advantage by decreasing the energy consumption per cubic meter of seawater desalination. According to (Mansour et al., 2020), the energy consumption can be reduced to 2.58 kWh/m^3 for the pump system, saving 67% of the initial value, leading to an efficiency of 97.5%. This reduces the renewable energy infrastructure needed for seawater desalination and the capital expenditure. Additionally, optimizing pre-treatment steps to prevent membrane fouling and adopting advanced membrane technologies with higher salt rejection and permeability can significantly improve throughput while extending membrane lifespan. Using variable speed drives and smart control systems can further ensure that pump operation adapts to real-time demand, avoiding unnecessary energy use. On the DAC side, system efficiency can be enhanced by employing sorbents with higher water and CO_2 selectivity, which can reduce the amount of air required per unit of water captured. However, combining low-grade waste heat or geothermal energy with DAC systems (as explored by Kuru et al., 2023) could reduce energy costs for desorption. Moreover, modular system design and location-specific climate optimization, especially in high-humidity areas, can improve water capture rates and reduce auxiliary energy consumption (Wang et al., 2024). In both cases, regular monitoring and predictive maintenance are essential for minimizing downtime and resource losses.

From a technical perspective, the results validate previous studies in these two technologies. S-DAC is still in development stages and involves high initial investment and energy costs (Fasihi et al., 2019) ; (Bouaboula et al., 2024). In contrast, desalination through RO has gone through years of development and refinement, making it efficient, reliable, and scalable for large-scale freshwater production, making it the most widely adopted method in worldwide (Curto et al., 2021); (Gorjian et al., 2014). The results of this research build on these established conclusions by providing a comparative assessment of the two technologies within the West African context, thereby addressing the gap in global techno-economic evaluations where the region is often underrepresented.

3.2.3 Environmental impact of water sourcing in M’bour

In addition to the cost efficiency the environmental impact of the two-water sourcing is important for the long-term sustainability of green hydrogen production in Senegal. The environmental footprint of water sourcing is an important dimension of green hydrogen production in M’bour. Seawater desalination via reverse osmosis (RO) is technologically mature but produces brine, a concentrated saline effluent. If not carefully managed, brine discharge can raise local salinity, reduce dissolved oxygen, and negatively impact marine ecosystems and fisheries, which are critical to M’bour’s coastal economy (Mansour et al., 2020)& (Curto et al., 2021). However, since the proposed desalination system is powered entirely by renewable energy, the carbon footprint is minimized compared to fossil-fuel-based desalination (Adda et al., 2024). The integration of energy recovery systems also reduces pressure on local resources by lowering electricity demand (Mansour et al., 2020).

By contrast, solid direct air capture (S-DAC) does not withdraw water from local sources. Instead, it co-adsorbs moisture from the atmosphere during CO_2 capture, which avoids exacerbating freshwater scarcity in Senegal (Sinha & Realff, 2019)& (Kuru et al., 2023). This makes DAC particularly attractive for inland or arid regions. Nonetheless, DAC is more energy-intensive, with requirements in the range of 7.2–9.5 GJ per ton of CO_2 captured (Fasihi et al., 2019), and large-scale deployment may increase land competition for solar and wind installations in M'bour's coastal zone.

Overall, desalination in M'bour presents localized marine risks that require mitigation measures, while DAC reduces water stress but entails higher energy and land-use demands. A combined strategy desalination for coastal areas and DAC for inland regions could balance these environmental trade-offs in Senegal's hydrogen economy.

3.2.4 Limitation of the study

Despite its strengths, the analysis has limitations. In the techno-economic assessment, all the data were collected from secondary sources or modeled assumptions. Real-world performance of DAC systems in West Africa is not yet documented at a commercial scale. The case study focuses on M'bour, Senegal, and the location offers both seawater access and favorable RE resources (solar and wind). The results may not fully generalize to a West African country where renewable energy sources are weak or an inland with high infrastructure constraints. Furthermore, the analysis does not include the transmission, distribution, hydrogen storage, and transport costs. This could be an additional cost for the overall system and can highly affect the cost efficiency of the system. In the DAC-based hydrogen production, the study does not highlight the use of CO_2 after separation of the water co-adsorbent, which is a key limitation that can serve for further research. Additionally, external socio-political or environmental constraints, such as land availability, policy incentives, or water governance, were not considered but may significantly influence deployment feasibility.

Additionally, from the comparison, seawater desalination currently represents a more cost-efficient and technically mature solution for green hydrogen production in West Africa, particularly in coastal areas. While S-DAC remains less competitive under current conditions, it holds strategic potential in arid or inland zones with limited water resources. Furthermore, differences in component lifespans and operational efficiencies may vary across time and location, and they can affect the results, while exchange rate fluctuations can also influence the overall costs. Reducing value losses in both systems through smarter design, technology upgrades, and energy integration will be key to unlocking their full potential. Policymakers and stakeholders should prioritize investment in coastal regions for green hydrogen infrastructure while simultaneously supporting innovation in DAC technologies for a more inclusive and adaptive regional hydrogen strategy.

Conclusion and recommendations

The comprehensive analysis presented in this work assesses the technical performance of green hydrogen production from seawater desalination and direct air capture (DAC), both powered by a hybrid renewable energy system in West Africa, by evaluating the cost efficiency (CE). PEM electrolyzer offers the best alignment for this production based on the literature review among the other electrolysis technologies because of its high efficiency, fast response, and ability to produce high hydrogen purity. The choice of water source for H_2 production is a key determinant of overall system performance and cost efficiency.

The results from the techno-economic assessment and cost efficiency comparison show that green hydrogen production from seawater desalination via reverse osmosis (RO) is more cost-efficient compared to green hydrogen production from the DAC system (S-DAC) under ideal and actual cases. While both processes produce the same amount of hydrogen in each case, desalination is the promising pathway for water sourcing in West Africa, because of its low energy requirements, technological maturity, and low investments. Under ideal conditions, the cost of production was similar; actual conditions reveal a higher production cost, leading to higher value losses for S-DAC, driven by its greater energy intensity and less developed commercial readiness for water co-adsorption. Sensitivity analysis further demonstrated that hybrid renewable energy configurations optimize cost efficiency for both processes, whereas reliance on solar and wind-only systems significantly increases the production costs, especially for the DAC system and the value losses.

These findings suggest that in the short term, coastal regions of West Africa would benefit the most from investments in desalination-based green hydrogen production, leveraging existing access to seawater and mature desalination technologies. However, S-DAC may have strategic value for inland or arid regions where water scarcity limits other options, provided that continued technological advances reduce its energy demand and capital costs. Ultimately, improving system efficiency, reducing value losses, and optimizing the integration of renewable energy supply with electrolysis operations are key to make green hydrogen a viable and scalable contributor to West Africa's sustainable energy transition.

The prospects for green hydrogen production in West Africa highlight significant potential, especially in coastal regions where seawater desalination can be effectively combined with solar PV systems and wind resources. Desalination is a reliable pathway and represents technological maturity; its efficiency can be improved through the integration of ERS (energy recovery system) and advanced operational strategies. In contrast, S-DAC is still at an emerging stage with limited commercialization, but it is a strategy for inland and arid regions where access to seawater is limited (Realmonte et al., 2019). The competitiveness of the S-DAC will depend on future technological advancements that can reduce the energy intensity and investments for carbon removal and water co-adsorption. As renewable energy component prices continue to fall and regional hydrogen strategies too, desalination-based hydrogen production is expected to dominate the near-term deployment landscape, while DAC could gain relevance as a complementary solution, particularly if policy incentives align with carbon removal and climate change mitigation goals.

In line with these findings, several recommendations can be made. Investment can be expected to prioritize desalination via reverse osmosis for green hydrogen production projects in coastal areas, based on the technologies and cost efficiency of the systems. At the same time, R&D efforts should be directed towards the advancement of DAC technologies, especially S-DAC, by reducing the investment costs, energy consumption, and improving the selectivity of the sorbents. From a system design perspective, integrating energy recovery systems into desalination plants and optimizing renewable energy through smart hybrid configurations can significantly reduce value losses. Policymakers and stakeholders should also establish investment frameworks and encourage regional cooperation to accelerate deployment and the integration of green hydrogen technologies in West Africa.

References

Adda, A., Bezari, S., Abbas, M., & Hanini, S. (2024). Techno-Economic Feasibility of Reverse Osmosis Desalination Scale Coupled with Solar Energy: Case of Algeria. *The Journal of Engineering and Exact Sciences*, *10*(3), 1–14. https://doi.org/10.18540/jcecvl10iss3pp18299

Africa, H. (2021). *Good chances for "green" hydrogen from West Africa*. https://www.h2atlas.de/de/news/detail/h2-atlas-tool-started?utm

Allington, L. (2021). *Selected 'Starter Kit' energy system modelling data for Senegal*. 1–13. https://www.researchgate.net/publication/367955008_Selected_'Starter_Kit'_energy_system_modelling_data_for_Senegal_CCG/fulltext/63db4bc2c97bd76a8256341c/Selected-Starter-Kit-energy-system-modelling-data-for-Senegal-CCG.pdf

An, K., Li, K., Yang, C. M., Brechtl, J., & Nawaz, K. (2023). A comprehensive review on regeneration strategies for direct air capture. *Journal of CO2 Utilization*, *76*(June), 102587. https://doi.org/10.1016/j.jcou.2023.102587

Atlas, G. S. (2025). *No Title*. https://globalsolaratlas.info/map?s=14.303261,-16.858521&m=site&c=14.417093,-16.739044,10

Atlas, G. wind. (2025). *No Title*. https://globalwindatlas.info/en/

Bhandari, R., & Shah, R. R. (2021). Hydrogen as energy carrier: Techno-economic assessment of decentralized hydrogen production in Germany. *Renewable Energy*, 1–17. https://doi.org/10.1016/j.renene.2021.05.149

Bouaboula, H., Chaouki, J., Belmabkhout, Y., & Zaabout, A. (2024). Comparative review of Direct air capture technologies: From technical, commercial, economic, and environmental aspects. *Chemical Engineering Journal*, 1–20. https://doi.org/10.1016/j.cej.2024.149411

Breyer, C., Fasihi, M., & Aghahosseini, A. (2020). Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: a new type of energy system sector coupling. *Mitigation and Adaptation Strategies for Global Change*, *25*(1), 1–23. https://doi.org/10.1007/s11027-019-9847-y

Brisse, A., Schefold, J., & Zahid, M. (2008). High temperature water electrolysis in solid oxide cells. *International Journal of Hydrogen Energy*, 1–8. https://doi.org/10.1016/j.ijhydene.2008.07.120

Cormos, C. C. (2023). Green hydrogen production from decarbonized biomass gasification: An integrated techno-economic and environmental analysis. *Energy*, 1–11. https://doi.org/10.1016/j.energy.2023.126926

Curto, D., Franzitta, V., & Guercio, A. (2021). A Review of the Water Desalination Technologies. *Applied Sciences*, *11*(2), 670. file:///C:/Users/LENOVO/Downloads/applsci-11-00670-v2.pdf

Dräger, P., & Letmathe, P. (2022). Value losses and environmental impacts in the construction industry – Tradeoffs or correlates? *Journal of Cleaner Production*, *336*(June 2021), 1–9.

https://doi.org/10.1016/j.jclepro.2022.130435

Fasihi, M., Efimova, O., & Breyer, C. (2019). Techno-economic assessment of CO 2 direct air capture plants. *Journal of Cleaner Production*, 1–24. https://doi.org/10.1016/j.jclepro.2019.03.086

Gorjian, S., Ghobadian, B., Tavakkoli Hashjin, T., & Banakar, A. (2014). Experimental performance evaluation of a stand-alone point-focus parabolic solar still. *Desalination*, *352*, 1–17. https://doi.org/10.1016/j.desal.2014.08.005

International Energy Agency. (2023). Senegal 2023 - Energy Policy Review. *Iea*, 1–133. https://iea.blob.core.windows.net/assets/b80ed5fc-7483-4b65-ae73-d39d5b2de40d/Senegal2023.pdf

International Energy Agency (IEA). (2024). Global Hydrogen Review 2024 - Transport by pipeline. *Global Hydrogen Review 2024*, 1–295. www.iea.org//reports/global-hydrogen-review-2024

IRENA. (2012). *Senegal Renewables Readiness Assessment*. 1–76. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2013/IRENA-Senegal-RRA.pdf?rev=7b9208bf1bba443c805e154fe6804cbd

Kain, W. (2024). *A Combined Water and CO 2 Direct Air Capture System*. 1–21. https://netl.doe.gov/sites/default/files/netl-file/24CM/24CM_CDR_6_Rangnekar.pdf

Keith, D. W., Holmes, G., St. Angelo, D., & Heidel, K. (2018). A Process for Capturing CO2 from the Atmosphere. *Joule*, *2*(8), 1–27. https://doi.org/10.1016/j.joule.2018.05.006

Khan, M. A., Zhao, H., Zou, W., Chen, Z., Cao, W., Fang, J., Xu, J., Zhang, L., & Zhang, J. (2018). Recent Progresses in Electrocatalysts for Water Electrolysis. In *Electrochemical Energy Reviews* (Vol. 1, Issue 4). Springer Singapore. https://doi.org/10.1007/s41918-018-0014-z

Kigle, S., Schmidt-Achert, T., & Pérez, M. Á. M. (2024). The impact of country-specific investment risks on the levelized costs of green hydrogen production. *International Journal of Hydrogen Energy*, *73*, 1–12. https://doi.org/10.1016/j.ijhydene.2024.05.303

Kuru, T., Khaleghi, K., & Livescu, S. (2023). Solid sorbent direct air capture using geothermal energy resources (S-DAC-GT) – Region specific analysis. *Geoenergy Science and Engineering*, *224*(November 2022), 211645. https://doi.org/10.1016/j.geoen.2023.211645

Leal Filho, W., Totin, E., Franke, J. A., Andrew, S. M., Abubakar, I. R., Azadi, H., Nunn, P. D., Ouweneel, B., Williams, P. A., & Simpson, N. P. (2021). Understanding responses to climate-related water scarcity in Africa. *Science of the Total Environment*, *806*, 1–18. https://doi.org/10.1016/j.scitotenv.2021.150420

Li, G., & Yao, J. (2024). Direct Air Capture (DAC) for Achieving Net-Zero CO2 Emissions: Advances, Applications, and Challenges. *Eng*, *5*(3), 1–39. https://doi.org/10.3390/eng5030069

Mansour, T. M., Ismail, T. M., Ramzy, K., & Abd El-Salam, M. (2020). Energy recovery system in small reverse osmosis desalination plant: Experimental and theoretical investigations.

Alexandria Engineering Journal, *59*(5), 1–13. https://doi.org/10.1016/j.aej.2020.06.030

Millet, P., Ngameni, R., Grigoriev, S. A., Mbemba, N., Brisset, F., Ranjbari, A., & Etiévant, C. (2010). PEM water electrolyzers: From electrocatalysis to stack development. *International Journal of Hydrogen Energy*, *35*(10), 1–10. https://doi.org/10.1016/j.ijhydene.2009.09.015

Nasa Power. (n.d.). https://power.larc.nasa.gov/data-access-viewer/

Ndehedehe, C. E. (2019). The water resources of tropical West Africa: problems, progress, and prospects. *Acta Geophysica*, *67*(2), 1–29. https://doi.org/10.1007/s11600-019-00260-y

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

Saur, G. (2008). *Wind-To-Hydrogen Project: Electrolyzer Capital Cost Study.* 1–48. https://docs.nrel.gov/docs/fy09osti/44103.pdf?utm

Seefeldt, M. W., Hopson, T. M., & Warner, T. T. (2012). A Characterization of the variation in relative humidity across West Africa during the dry season. *Journal of Applied Meteorology and Climatology*, *51*(12), 1–13. https://doi.org/10.1175/JAMC-D-11-0196.1

Shiva Kumar, S., & Lim, H. (2022). An overview of water electrolysis technologies for green hydrogen production. *Energy Reports*, *8*, 1–21. https://doi.org/10.1016/j.egyr.2022.10.127

Singh, J., Sivabalan, V., & Lal, B. (2022). Introduction to desalination. *Gas Hydrate in Water Treatment: Technological, Economic, and Industrial Aspects*, 1–7. https://doi.org/10.1002/9781119866145.ch1

Sinha, A., & Realff, M. J. (2019). A parametric study of the techno-economics of direct CO2 air capture systems using solid adsorbents. *AIChE Journal*, *65*(7), 1–8. https://doi.org/10.1002/aic.16607

Sources, E., & Asia, E. (2021). Comparison of Desalination Technologies Using Renewable Energy Sources with Life Cycle, PESTLE, and Multi-Criteria Decision Analyses. *Water*, 1–27. https://www.mdpi.com/2073-4441/13/21/3023

Tech, G. W. (2024). *Seawater RO Operating Costs Analysis: A Comprehensive Guide*. https://genesiswatertech.com/blog-post/seawater-ro-operating-costs-analysis/?utm

UK, E. R. (2006). *Exchange Rates UK*. https://www.exchangerates.org.uk/EUR-USD-spot-exchange-rates-history-2019.html

Vidas, L., & Castro, R. (2021). Recent developments on hydrogen production technologies: State-of-the-art review with a focus on green-electrolysis. *Applied Sciences (Switzerland)*, *11*(23), 1–27. https://doi.org/10.3390/app112311363

Wang, Y., Qu, L., Ding, H., Webley, P., & Li, G. K. (2024). Distributed direct air capture of carbon dioxide by synergistic water harvesting. *Nature Communications* , *15*(1), 1–11. https://doi.org/10.1038/s41467-024-53961-4

Webber, M., Aliyu, A., Jin, S. H., Sadiq, M. M., Sohani, B., & Elseragy, A. (2024). A techno-economic review of direct air capture of moisture processes: sustainable versus energy-intensive methods. In *International Journal of Environmental Science and Technology* (Vol. 22, Issue 1). Springer Berlin Heidelberg. https://doi.org/10.1007/s13762-024-05720-7

WREI. (2022). *Accelerating renewable energy investment in West Africa*. 1–29. https://www.pwc.com/m1/en/publications/documents/accelerating-renewable-energy-investment-in-west-africa.pdf

Appendix

- System sizing
  - **PEM Electrolyser**

Parameters	**Formula**	**Value**	**Unit**
H2 produced per hour	Electrolyzer Capacity/ Electrolyzer Energy consumption	185.19	kg/h
H2 produced per day	H2 produce per hour*24h	4444.44	kg/day
H2 produced per year	H2 produced per day *365	1622222.22	kg/year
Electrolyzer water consumption per year	H2 produced per year* water required per kg H2	16222222.22	liters/year
Electrolyzer energy required per year	H2 produce per year*Electrolyzer energy consumption	87600000.000	kWh/year
Electrolyzer energy required per day	Electrolyzer required per year/365	240000	kWh/day
Electrolyzer water consumption per day	Electrolyzer water consumed per year/365	44444.44	liters/day
Electrolyzer water consumption per day		44.44	kg/day

- **DAC process**

Parameters	**Formula**	**Value**	**Unit**
CO2 capture		16222.22	tCO2/year
Water extracted		16222.22	tWater/year
DAC energy required	Water capacity* DAC energy consumption	4055555	kWh/year
Total Energy required per year	Electrolyzer energy required+DAC energy required	91655555.00	kWh/year
Total Energy per day	(Electrolyzer energy required+DAC energy required)/365	251111.11	kWh/day

Solar, Wind, and Battery capacities for the DAC process

Parameters	Formula	Value	Unit
Solar	Daily energy consumption*Isct/Quality factor*Solar irradiance	54787.88	kWp
Wind	Energy from Wind/Capacity factor*24h	24618.74	kW
Battery	Daily energy consumption*DOA/(efficiency*DOD)	264327.4838	kWh

Energy generation from wind and solar

Parameters	Value	Unit
Operating time for wind	1489.2	h/year
Operating time for solar	3591.6	h/year
Energy generation from Solar	3935522885	kWh
Energy generation from Wind	733244440	kWh
Total output from Solar and Wind	4668767325	kWh

Initial investment

Parameters	Capacity	Unit	Unit Cost	Unit	Total Cost in $
DAC	16222.22	tCO2	843.22	$/tCO2	13678900.35
Solar	54787.88	kW	984	$/kW	53911272.400
Wind	24618.74	kW	1191	$/kW	29320914.855
Battery	264327.4838	kWh	690.984	$/kWh	182646062.1
Electrolyzer	10000	kW	1183	$/kW	11830000
Tank	16222.22	liters	80		1297777.6
Total					**292684927.3**

Operational and maintenance costs

Parameters	OM	Total Cost in $
DAC	0.04	547156.0139
Solar	0.012	646935.2688
Wind	0.02	586418
Battery	0.0333153	8806.14942
Electrolyzer	0.02	236600
Total		**2025916**

Present Value

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total
Present value of Solar	533774.9743	528490.0735	523257.4985	518076.7312	512947.2586	507868.5729	502840.1712	497861.5556	492932.2333	488051.7162	483219.5209	478435.1692	473698.1874	469008.1063	464364.4617	459766.7938	455214.6473	450707.5716	446245.1204	441826.8518	9728587.216
Present Value of Wind	725765.2192	718579.4249	711464.7772	704420.5714	697446.1103	690540.7033	683703.6666	676934.3234	670232.0034	663596.0429	657025.7851	650520.5793	644079.7815	637702.7539	631388.8653	625137.4904	618948.0103	612819.8122	606752.2893	600744.8409	13227803.05
Present value of Battery	8718.959822	8632.633487	8547.161869	8462.536503	8378.749013	8295.791102	8213.654557	8132.331244	8051.813113	7972.092191	7893.160585	7815.010481	7737.634139	7661.0239	7585.172178	7510.071464	7435.714321	7362.093387	7289.201373	7217.031062	158911.8358
Present Value of DAC	2162171.555	868557.6616	859958.0808	851443.6444	843013.5093	834666.8409	826402.8127	818220.6067	810119.4126	802098.4283	794156.8597	786293.9205	778508.8321	770800.8239	763169.1326	755613.0026	748131.6857	740724.4413	733390.5359	726129.2435	17273571.03
Present Value PEM	9179416.371	9088531.061	8998545.605	8909451.094	8821238.707	13414545.67	8647425.455	8561807.381	8477037.011	8393105.952	12763479.92	8227728.607	8146265.947	8065609.849	7985752.326	12144013.19	12023775.44	7750892.531	7674151.021	7598169.327	184870942.5
Sum THP	1606160.616	1590258.036	1574512.907	1558923.67	1543488.782	1528206.715	1513075.955	1498095.005	1483262.382	1468576.615	1454036.253	1439639.854	1425385.994	1411273.262	1397300.259	1383465.603	1369767.924	1356205.865	1342778.084	1329483.252	29273897.03
Sum Vwt	16061606.16	15902580.36	15745129.07	15589236.7	15434887.82	15282067.15	15130759.55	14980950.05	14832623.82	14685766.15	14540362.53	14396398.54	14253859.94	14112732.62	13973002.59	13834656.03	13697679.24	13562058.65	13427780.84	13294832.52	292738970.3

- **Desalination process**

Parameters	Formula	Value	Unit
Water purification		16222.22	m3/year
Desalination energy required	Water capacity*Desalination energy consumption	62455.547	kWh/year
Total energy required per year	Electrolyzer energy required+Desalination energy required	87662455.547	kWh/year
Total energy required per day	Electrolyzer energy required+Desalination energy required/365	240171.1111	kWh/day

Solar, Wind, and Battery capacities for the Desalination process

Parameters	Formula	Value	Unit
Solar	Daily energy consumption*Isct/system efficiency*Solar irradiance	52400.96969	kWp
Wind	Energy from Wind/Capacity factor*24h	23546.18736	kW
Battery	Daily energy consumption*DOA/(efficiency*DOD)	252811.6959	kWh

Energy generation from wind and solar

Parameters	Value	Unit
Operating time wind	1489.2	h/year
Operating time solar	3591.6	h/year
Energy generation from Solar	3764066455	kWh
Energy generation from Wind	701299644.4	kWh
Total output from Solar and Wind	**4465366099**	**kWh**

Initial investment

Parameters	Capacity	Unit	Unit Cost	Unit	Total Cost in $
Desalination	16222.22	m3	15.646	$/m3	253812.8541
Solar	52400.97	kW	984	$/kW	51562554.18
Wind	23546.19	kW	1191	$/kW	28043509.15
Battery	252811.696	kWh	690.984	$/kWh	174688836.9
Electrolyzer	10000	kW	1183	$/kW	11830000
Tank	16222.22	liters	80	$/liter	1297777.6
Total					**201379529.7**

Operational and maintenance costs

Parameters	OM	Total Cost in $
O&M desalination	0.158	2563.11076
Membrane replacement	452.18	13396.58613
Solar	0.012	618750.6501
Wind	0.02	560870
Battery	0.0333153	8422.497492
Electrolyzer	0.02	236600
Total		**1438040**

Present Value

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total
Present Value of Solar	612624.4061	606558.8179	600553.285	594607.2129	588720.0128	582891.1018	577119.9027	571405.8443	565748.3607	560146.8918	554600.8829	549109.7851	543673.0545	538290.153	532960.5475	527683.7104	522459.1192	517286.2567	512164.6106	507093.6738	11165697.63
Present Value of Wind	555317.0128	549818.8246	544375.0738	538985.2216	533648.7343	528365.0834	523133.746	517954.2039	512825.9445	507748.4599	502721.2474	497743.8093	492815.6528	487936.2899	483105.2375	478322.0174	473586.1558	468897.184	464254.6376	459658.057	10121212.59
Present value of Battery	8339.106428	8256.541017	8174.793086	8093.854541	8013.717367	7934.373631	7855.815476	7778.035125	7701.024876	7624.777105	55928173.45	7474.538874	7400.533539	7327.260929	7254.713791	7182.884942	7111.767269	7041.353732	6971.637358	6902.611246	56072612.79
Present Value of Desalination	8141.832972	8061.220764	7981.406697	7902.382868	7824.141454	20366.86484	7669.974957	7594.034611	7518.84615	7444.402128	19378.37306	7297.717997	7225.463363	7153.924122	7083.09319	18437.85705	6943.528272	6874.780467	6806.713334	6739.320132	184445.8784
Present Value PEM	8189804.46	8108717.29	8028432.96	7948943.53	7870241.12	12472963.89	7715166.27	7638778.49	7563147.02	7488264.37	11867597.17	7340715.98	7268035.63	7196074.88	7124826.61	11291611.50	6984439.38	6915286.52	6846818.33	6779028.05	162638893.45
SumTHP	1606160.62	1590258.04	1574512.91	1558923.67	1543488.78	1528206.71	1513075.96	1498095.01	1483262.38	1468576.62	1454036.25	1439639.85	1425385.99	1411273.26	1397300.26	1383465.60	1369767.92	1356205.87	1342778.08	1329483.25	29273897.03
Total Vwt	16061606.16	15902580.36	15745129.07	15589236.70	15434887.82	15282067.15	15130759.55	14980950.05	14832623.82	14685766.15	14540362.53	14396398.54	14253859.94	14112732.62	13973002.59	13834656.03	13697679.24	13562058.65	13427780.84	13294832.52	292738970.34

- **Sensitivity Analysis of DAC system**

Share of 1/2 Solar and Wind

Initial investment

Parameters	Capacity	Unit	Unit Cost	Unit	Total Cost in $
DAC	16222.22	tCO2	843.22	$/tCO2	13678900.35
Solar	45656.57	kW	984	$/kW	44926060.334
Wind	30773.42	kW	1191	$/kW	36651143.569
Battery	264327.4838	kWh	690.984	$/kWh	182646062.1
Elecytrolyzer	10000	kW	1183	$/kW	11830000
Tank	16222.22	liters	80	$/m3	1297777.6
Total					**291029943.9**

Operational and Maintenance Cost

Parameters	OM	Total Cost in $
DAC	0.04	547156.0139
Solar	0.012	539112.724
Wind	0.02	733023
Battery	0.0333153	8806.14942
Elecytrolyzer	0.02	236600
Total		**2064698**

Sum Vwt	Sum THP	Present Value PEM	Present Value of DAC	Present value of Battery	Present Value of Wind	Present value of Solar	Year
16061606.1	1606160.61	9179416.37	2162171.55	8718.95982	725765.219	533774.974	1
15902580.3	1590258.03	9088531.06	868557.661	8632.63348	718579.424	528490.073	2
15745129.0	1574512.90	8998545.60	859958.080	8547.16186	711464.777	523257.498	3
15589236.7	1558923.67	8909451.09	851443.644	8462.53650	704420.571	518076.731	4
15434887.8	1543488.78	8821238.70	843013.509	8378.74901	697446.110	512947.258	5
15282067.1	1528206.71	13414545.6	834666.840	8295.79110	690540.703	507868.572	6
15130759.5	1513075.95	8647425.45	826402.812	8213.65455	683703.666	502840.171	7
14980950.0	1498095.00	8561807.38	818220.606	8132.33124	676934.323	497861.555	8
14832623.8	1483262.38	8477037.01	810119.412	8051.81311	670232.003	492932.233	9
14685766.1	1468576.61	8393105.95	802098.428	7972.09219	663596.042	488051.716	10
14540362.5	1454036.25	12763479.9	794156.859	7893.16058	657025.785	483219.520	11
14396398.5	1439639.85	8227728.60	786293.920	7815.01048	650520.579	478435.169	12
14253859.9	1425385.99	8146265.94	778508.832	7737.63413	644079.781	473698.187	13
14112732.6	1411273.26	8065609.84	770800.823	7661.0239	637702.753	469008.106	14
13973002.5	1397300.25	7985752.32	763169.132	7585.17217	631388.865	464364.461	15
13834656.0	1383465.60	12144013.1	755613.002	7510.07146	625137.490	459766.793	16
13697679.2	1369767.92	12023775.4	748131.685	7435.71432	618948.010	455214.647	17
13562058.6	1356205.86	7750892.53	740724.441	7362.09338	612819.812	450707.571	18
13427780.8	1342778.08	7674151.02	733390.535	7289.20137	606752.289	446245.120	19
13294832.5	1329483.25	7598169.32	726129.243	7217.03106	600744.840	441826.851	20
292738970.3	29273897.03	184870942.5	17273571.03	158911.8358	13227803.05	9728587.216	Total