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MASTER THESIS

Speciality: Economics/Policies/Infrastructures and Green Hydrogen Technology

Topic:

" Economic and Environmental Evaluation of Green Hydrogen Plants Carrying Out Desalination in Dakar, For Export to Germany"

Presented by:

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Dedication

I dedicate this dissertation to my beloved family, whose unwavering support and encouragement laid the foundation for my educational journey. Your sacrifices and belief in my potential have inspired me to reach this significant milestone. This achievement is as much yours as it is mine.

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Acronyms and abbreviations

APIX: Agence pour la Promotion des Investissements et des Grands Travaux

CAPEX: Capital Expenditure

CO_2: Carbon Dioxide

CRF: Capital Recovery Factor

CUI: Common User Infrastructure

DFI: Development Finance Institution

ECOWAS: Economic Community of West African States

ECREEE: ECOWAS Centre for Renewable Energy and Energy Efficiency

EGHDU: ECOWAS Green Hydrogen Development Unit

HDPE: High-Density Polyethylene

IEA: International Energy Agency

IRENA: International Renewable Energy Agency

kW: Kilowatt

LCOH: Levelized Cost of Hydrogen

LLC: Limited Liability Company

MWh: Megawatt Hour

NH_3: Ammonia

OPEX: Operational Expenditure

PEM: Proton Exchange Membrane

PPA: Power Purchase Agreement

RO: Reverse Osmosis

RWTH: Rheinisch-Westfälische Technische Hochschule (Aachen University)

SCDI: Southern Corridor Development Initiative

SDG: Sustainable Development Goals

SENELEC: Société Nationale d'Électricité du Sénégal

VCS: Verified Carbon Standard

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ABSTRACT

This study explores the economic and environmental feasibility of producing green hydrogen in Dakar, Senegal, using wind energy and desalinated seawater, with the aim of exporting it to Germany. The motivation for this research arises from the global need to decarbonize industrial sectors and shift to cleaner energy systems. West Africa, especially Senegal, offers a unique opportunity due to its favourable coastal wind conditions and increasing energy demand, yet it remains underexplored in existing green hydrogen research. The study addresses this gap by establishing a desalination-integrated hydrogen model in West Africa, providing insights into economic diversification, environmental sustainability, and technical scalability.

To address this gap, the study employs a mixed-method approach using AnyLogic simulation modeling to assess the technical, environmental, and financial viability of a large-scale hydrogen system. This model integrates key components such as wind power generation, reverse osmosis desalination, PEM electrolysis, storage, and maritime export logistics. Quantitative results included capital expenditures, operational costs, water and energy consumption rates, and hydrogen market pricing.

The results reveal that while the Levelized Cost of Hydrogen (LCOH) is estimated at €9.97/kg, falling within the upper range of current international benchmarks, the project offers considerable environmental benefits, including the annual avoidance of over 51,000 tonnes of CO_2 emissions from the steel sector and significant brine discharge management from desalination. Economically, the project is strengthened by export revenues, job creation in local supply chains, and potential tax income for the Senegalese government. For Germany, the benefits include access to green hydrogen, which aligns with its decarbonization strategy and international partnership goals.

In conclusion, the research demonstrates that Dakar-based green hydrogen export is both technically and environmentally feasible, economically dependent on supportive policies and investment frameworks. The broader implications underscore the role that such projects can play in advancing multiple Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water), SDG 7 (Affordable Clean Energy), SDG 8 (Economic Growth), SDG 13 (Climate Action), and SDG 17 (Partnerships).

Keywords: Green hydrogen, Desalination (Reverse Osmosis), Renewable energy (Wind energy), Electrolysis (Proton Exchange Membrane), Levelized Cost of Hydrogen (LCOH), Sustainable Development Goals (SDGs), Energy-water nexu

RÉSUMÉ

Cette étude explore la faisabilité économique et environnementale de la production d'hydrogène vert à Dakar, au Sénégal, à partir de l'énergie éolienne et de l'eau de mer dessalée, en vue de l'exporter vers l'Allemagne. Cette recherche répond à la nécessité mondiale de décarboner les secteurs industriels et de passer à des systèmes énergétiques plus propres. L'Afrique de l'Ouest, et plus particulièrement le Sénégal, offre une opportunité unique grâce à ses conditions de vent côtières favorables et à sa demande énergétique croissante. Pourtant, ce secteur reste sous-exploré dans la recherche actuelle sur l'hydrogène vert. L'étude comble cette lacune en établissant un modèle d'hydrogène intégré au dessalement en Afrique de l'Ouest, offrant ainsi des perspectives sur la diversification économique, la durabilité environnementale et l'évolutivité technique.

Pour combler cette lacune, l'étude utilise une approche mixte utilisant la modélisation par simulation AnyLogic pour évaluer la viabilité technique, environnementale et financière d'un système d'hydrogène à grande échelle. Ce modèle intègre des composantes clés telles que la production d'énergie éolienne, le dessalement par osmose inverse, l'électrolyse PEM, le stockage et la logistique d'exportation maritime. Les données quantitatives comprenaient les dépenses d'investissement, les coûts d'exploitation, les tarifs de consommation d'eau et d'énergie, et la tarification du marché de l'hydrogène.

Les résultats révèlent que, bien que le coût actualisé de l'hydrogène (LCOH) soit estimé à 9,97 €/kg, se situant dans la fourchette supérieure des références internationales actuelles, le projet offre des avantages environnementaux considérables, notamment l'évitement de plus de 51 000 tonnes d'émissions de CO_2 par an provenant du secteur sidérurgique et une gestion significative des rejets de saumure issus du dessalement. Sur le plan économique, le projet est renforcé par les recettes d'exportation, la création d'emplois dans les chaînes d'approvisionnement locales et les recettes fiscales potentielles pour le gouvernement sénégalais. Pour l'Allemagne, les avantages incluent l'accès à l'hydrogène vert, ce qui s'inscrit dans sa stratégie de décarbonation et ses objectifs de partenariat international.

En conclusion, l'étude démontre que l'exportation d'hydrogène vert depuis Dakar est réalisable à la fois techniquement et écologiquement, et dépend économiquement de politiques et de cadres d'investissement favorables. Les implications plus larges soulignent le rôle que ces projets peuvent jouer dans la réalisation de plusieurs Objectifs de développement durable (ODD), notamment l'ODD 6 (Eau propre), l'ODD 7 (Énergie propre et abordable), l'ODD 8

(Croissance économique), l'ODD 13 (Lutte contre les changements climatiques) et l'ODD 17 (Partenariats).

Mots-clés : Hydrogène vert, Dessalement (Osmose inverse), Énergie renouvelable (Énergie éolienne), Électrolyse (Membrane échangeuse de protons), Coût actualisé de l'hydrogène (CILH), Objectifs de développement durable (ODD), Lien énergie-eau.

1. Introduction

Reverse osmosis is a desalination technology through which seawater can be freshwater, in turn converted into hydrogen and oxygen using an electrolyser and electricity. Electrolysis plays a central role in the production of renewable hydrogen. As a global effort to decarbonise energy systems continues, green hydrogen has become Green hydrogen allows the use of renewable energy to produce clean fuels for applications across industry, transport, and energy. The process is critical in water-scarce regions where desalination is an essential technology for providing the high-purity water needed for hydrogen electrolysis. In this regard, green hydrogen plants that incorporate desalination go beyond addressing energy needs to introduce more intricate, often competing socio-economic dimensions related to their effects on people, economies, and resource management practices (REN21 2021).

The socio-economic implications of integrated desalination and hydrogen plants are especially important for the less developed areas where access to water and energy is still uneven. Green hydrogen production is expected to promote economic diversification, provide job opportunities, and assure energy security. However, this will require substantial investments in infrastructure such as wind farms, desalination units, and electrolyzers. Our study will focus on examining the economic and environmental impacts from the integration of a desalination plant with green hydrogen production in Dakar.

The environmental impact assessment will focus on the CO_2 emissions saved from the use of green hydrogen in Germany. Other environmental impacts linked to desalination, such as brine production, will be accounted for in the simulation model. Another aspect of the study will focus on the economic revenue accrued to Senegal from the trade with Germany. The study will also evaluate the capital and operational expenditures of installing wind turbines, a reverse osmosis (RO) desalination plant, Proton Exchange Membrane (PEM) technology for the electrolysers, pumping pipes for transferring seawater from the Atlantic Ocean to the desalination plant, the storage tanks for green hydrogen, and the land acquisition. This study precludes the social impact on the construction, as we believe this would merit a separate assessment and perhaps require some time lapse after the establishment of the facility.

Clean hydrogen is enjoying unprecedented political and business momentum, with the number of policies and projects around the world expanding rapidly. Further acceleration of efforts is critical to ensuring a significant share of hydrogen in industrial systems in the coming decades. Most studies focus on technical feasibility, with less attention paid to how these projects reshape country revenues, environmental impacts and resource access. This gap is especially evident in regions like sub-Saharan Africa, where water scarcity and energy poverty coexist, yet where green hydrogen could play a transformative role if implemented thoughtfully. By examining Senegal's coastal capital, Dakar, as a case study, this thesis aims to bridge this gap, exploring how the water-energy nexus in green hydrogen plants influences environmental and economic outcomes (IEA, 2022).

1.1: Background of the Study Area

Senegal is located on the western part of the African continent. Situated on the Atlantic Ocean coastline. It borders Mauritania to the north, Mali to the east, Guinea to the southeast, and Guinea-Bissau to the south. Senegal nearly surrounds The Gambia, a country occupying a narrow sliver of land along the banks of the Gambia River, which separates Senegal's southern region of Casamance from the rest of the country. (***Trazee Travel 2022***) It also shares a maritime border with Cape Verde. Senegal's economic and political capital is Dakar.

Senegal is the westernmost country in the mainland of the Old World or Afro-Eurasia. It owes its name to the Senegal River, which borders it to the east and north (**Janet H et al, 2009**). Senegal has a tropical climate with well-defined dry and humid seasons that result from northeast winter winds and southwest summer winds. The dry season (December to April) is dominated by hot, dry, harmattan wind. The climate is typically Sahelian, though there is a rainy season. Senegal covers a land area of almost 197,000 square kilometres (76,000 sq mi) and has a population of around 18 million. (World *Population Prospects 2022*) The state is a unitary presidential republic. Since the country's foundation in 1960, it has been recognized as one of the most politically stable countries on the African continent. Senegal is ranked 68th in electoral democracy worldwide and 10th in Electoral democracy. (*V-Dem Institute 2023*).

The state was formed as part of the independence of French West Africa from French colonial rule. Because of this history, French is the official language, but it is understood by only a minority of the population. Over 30 languages are spoken in Senegal. Wolof is the most widely spoken, with 80% of the population speaking it as a first or second language(***(**Jacques Leclerc2010**)***) and acting as Senegal's lingua franca alongside French.

Dakar, the capital of Senegal, is a bustling coastal city located on the westernmost point of Africa, the Cap-Vert Peninsula, along the Atlantic Ocean. With a population of approximately 1.18 million in the Dakar Department (as of 2023 estimates) and a metropolitan area exceeding 3 million, it serves as Senegal's economic and political hub, contributing over 50% of the nation’s GDP. The city’s strategic location, coupled with its growing urbanization and industrial activity, has intensified demands for water and energy, straining existing resources like groundwater and distant freshwater supplies such as Lac de Guiers, located 250 km away (World Bank, 2022)

Dakar’s potential for green hydrogen production using desalination is bolstered by its coastal proximity, which provides abundant seawater for desalination processes like reverse osmosis (RO). The city’s wind resources, with speeds ranging from 3.7 to 6.1 m/s, offer a renewable energy source to power both desalination and electrolysis, despite Dakar being on the lower end for optimal wind energy generation. Senegal’s government has already embraced desalination to address water scarcity, with projects like the mamelles desalination plant (50,000–100,000 m^3/day capacity, expected 2025) and the planned Grande Côte plant (400,000 m^3/day), demonstrating infrastructure readiness that could support hydrogen production (ACWA Power, 2024). This makes Dakar a promising location to pilot green hydrogen projects coupled with desalination in sub-Saharan Africa (IEA, 2023).

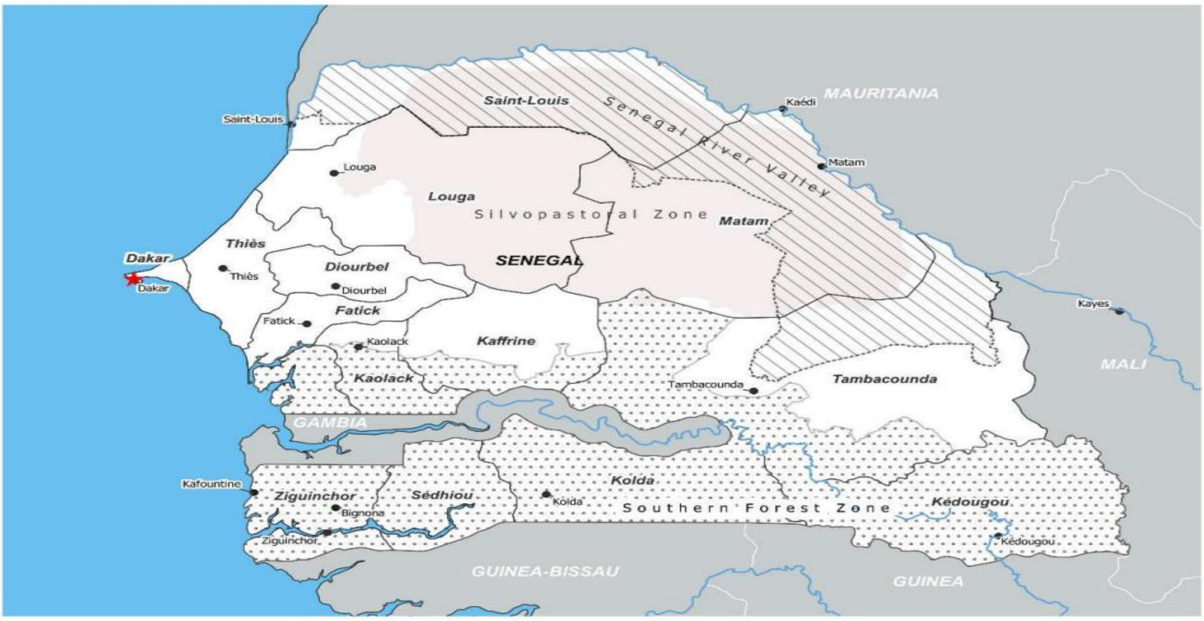

Figure 1 Map Showing Senegal boundaries

Retrieved from: *Safety and Quality of Milk and Milk Products in Senegal—A Review, Article in Foods · November 2022.*

1.2: Significance of the study

The study will reveal the economic feasibility and environmental impact of green hydrogen production from desalination in a West African setting. This holds significant potential for

Senegal's revenues by exploring how green hydrogen plants, integrated with desalination which can transform the country's economic landscape through the water-energy nexus, for the production and export of green hydrogen, a clean fuel that is high in demand to generate substantial earnings. This pathway will be diversify Senegal's revenue streams beyond traditional exports like fish and phosphates, aligning with the Plan Sénégal Émergent (PSE) for economic growth by 2035 as the demand for hydrogen increases to tap in to future global markets such as Europe.

Furthermore, the research emphasizes the revenue potential from job creation and industrial development tied to constructing and operating these facilities, including wind farms, desalination units, and electrolyzers, which could attract foreign investment and boost tax income. It also addresses the socio-economic balance by assessing how desalination's water supply supports hydrogen production without straining local resources such as the depletion of groundwater use for green hydrogen production.

These findings will guide strategic decision-making for policymakers as well as industry leaders and community stakeholders, providing empirical and actionable insights for promoting sustainable practices and socio-economic well-being in relation to green hydrogen production and desalination and which can position the country as a model for green hydrogen adoption in sub-Saharan Africa and contribute to broader global discussions on sustainable energy transitions.

1.3: Objectives and Research Questions

Research Question 1: *What are the economic and environmental implications of green hydrogen plants carrying out desalination on onshore wind power?*

Research Question 2. *What are the technical opportunities and challenges in integrating wind-powered desalination with green hydrogen production in Dakar for export to Germany?*

Objective 1: *Analyse Economic Implications and Opportunities*

This specific objective intends to evaluate the economic feasibility of producing green hydrogen using wind power and desalination in Dakar for export to Germany. Hence, it covers the analysis of the Technologies for operation, employment generation, export revenues, and their induced effects on the Senegalese economy, together with financial viability, regarding wind farms, desalination units, electrolyzers, and shipping infrastructure specifically oriented towards meeting German demand

Objective 2: *Assess Environmental Impacts and Sustainability*

The second objective of the study is to examine the environmental impacts of running green hydrogen plants equipped with desalination technology in Dakar through onshore wind. It further aims to quantify the advantages in terms of carbon emissions savings that accrue to the German energy transition and upscale revenue gain to the Senegal government, and develop an integrative approach for economic stability.

Objective 3*: Address Regional Research Gaps*

There is currently no operational green hydrogen plant using desalination in West Africa, so this objective is closing the knowledge gap: It would take a pioneering inquiry in the very case of Dakar. It will be used to build insights from simulation and comparative analyses on the economic and environmental outcomes of future export-oriented developments in Senegal and the region.

1.4: Research Methodologies

A mixed-methods research design will be applied:

The research aims to investigate the economic and environmental impact of the construction of a desalination plus hydrogen plant in Dakar. Since this is a hypothetical case study with no other reference examples in West Africa, we will employ the following research method:

A quantitative model of a desalination plant in Dakar coupled with green hydrogen production powered by wind is constructed in simulation software AnyLogic. Specifically, the system dynamics module is used through stock and flow diagrams. In addition to the technical production specifications, economic variables are added via parameters and dynamic variables. These latter ones allow for input in the form of capital investments such as wind turbines and infrastructure for water piping, while being complemented with operational expenditure variables such as salaries. The values for these variables are sourced from our own research through the literature.

The study explores the feasibility of producing green hydrogen in Dakar, Senegal, through wind-powered desalination and electrolysis, positioning green hydrogen as a crucial element of global decarbonization and a strategic opportunity for water-scarce regions. Senegal's coastal location, renewable wind resources, and developing desalination infrastructure make it a promising candidate for such projects, which could promote economic diversification, job creation, foreign investment, and export revenues in line with the Plan Sénégal Émergent (PSE

2035). The research aims to assess economic feasibility, environmental impacts, regional knowledge gaps, and integration challenges, using AnyLogic simulation modeling to analyze outcomes. While the study highlights significant potential benefits for both Senegal's economy and Germany's decarbonization efforts, it does not address critical social issues such as community perceptions, gender equity, or displacement, which should be prioritized in future research to ensure inclusivity and sustainability. Ultimately, the findings emphasize that Dakar has the potential to become a pioneering hub for green hydrogen in sub-Saharan Africa, with the capacity to reshape regional development, contribute to global decarbonization, and serve as a model for sustainable energy transitions worldwide.

The subsequent chapter will critically examine existing literature on hydrogen production, desalination integration, and export logistics, providing a foundation for the methodology and discussion.

2: Chapter One: Literature Review

The production of green hydrogen has emerged as a cornerstone of global decarbonization efforts. This chapter will critically examine existing literature and case studies on hydrogen production, desalination integration using wind power energy to drive electrolysis, emphasizing proton exchange membrane (PEM) for its efficiency with details extensive exploring its economic potential, and environmental benefits. In this chapter I employed a systematic search strategy aimed at identifying relevant literature related to the topic "*Economic and environmental Implications of Green Hydrogen Plants Carrying Out Desalination"* The search process began with the formulation of key research questions and identification of relevant keywords and phrases such as "green hydrogen" AND "reverse osmosis" AND "wind power".I used academic databases, including Google Scholar, Scopus, Web of Science, and Science Direct, along with institutional repositories such as those from the IEA, IRENA, and ECOWAS.

Table 1: Research engine explored

Research Engine	Results Explored	Relevant Papers Identified	Notes on the Filtration Process
Web of Science	10	5	Narrowed by CAPEX/OPEX data and hydrogen-desalination links
Science Direct	20	11	Focused on desalination performance and hydrogen economics
Google Scholar	30	15	Included IEA/IRENA reports and case studies And CAPEX/OPEX data of wind and RO
Scopus	20	5	Selected for technical parameters on PEM electrolyzers and wind energy integration

2.1: Review analysis in green hydrogen economics with desalination impacts

Recent studies on green hydrogen, such as those by the International Renewable Energy Agency (IRENA, 2020), project significant economic potential for green hydrogen as a cornerstone of global decarbonization. IRENA's report highlights that declining costs of renewable energy and electrolyzer efficiency improvements could make green hydrogen cost-competitive with grey hydrogen by 2030 in regions with abundant renewable resources, such as Senegal. Similarly, Kahsay et al. (2020) emphasize Africa's solar potential, estimating that green hydrogen production costs could reach \$5–8/kg in optimal locations by 2030, fostering economic opportunities through export markets like Germany. These studies often assume access to water resources, yet they rarely address the cost implications of desalination in water-scarce regions. Conversely, desalination studies lack region-specific analyses for Sub-Saharan Africa, justifying this thesis's focus on Dakar as a novel case study.

Desalination-focused research raises significant environmental concerns that challenge the optimistic economic narrative of green hydrogen. (Elsaid et al., 2020) Critically examine the environmental impacts of reverse osmosis (RO) desalination, a technology proposed for green hydrogen plants in arid regions. Their study highlights the issue of brine disposal, which, if mismanaged, can harm marine ecosystems. Furthermore, (Faroon et al., 2023)underscore the energy intensity of RO, which could increase the carbon footprint of green hydrogen production if not powered entirely by renewables. These environmental balances are often absent from green hydrogen studies, revealing a gap in integrated analyses of coupled hydrogen-desalination systems powered by wind energy.

2.2: The Electrolysis

Electrolysis is the process of using electricity to decompose water (H_2O) into hydrogen (H_2) and oxygen (O_2) through an electrochemical reaction in a device called an electrolyzer, typically powered by renewable energy sources for green hydrogen production (IRENA,2020). Electrolysis is a chemical process driven by electric current to split water molecules into hydrogen and oxygen, typically using electrolyzers that operate with renewable electricity to produce zero-emission green hydrogen (Kahsay et al., 2020)

Electrolysis is a key process in generating green hydrogen through a device called an electrolyser, which consists of two electrodes, an anode and a cathode, immersed in water and separated by an electrolyte.

When an electric current is applied (Kahsay et al., 2020) :

- At the cathode, water molecules are reduced to hydrogen gas (H2) and hydroxide ions (OH).
- At the anode, water molecules are oxidised to oxygen gas (O_2) and hydrogen ions (H+).
- The electrolyte allows ions to move between the electrodes, completing the circuit.

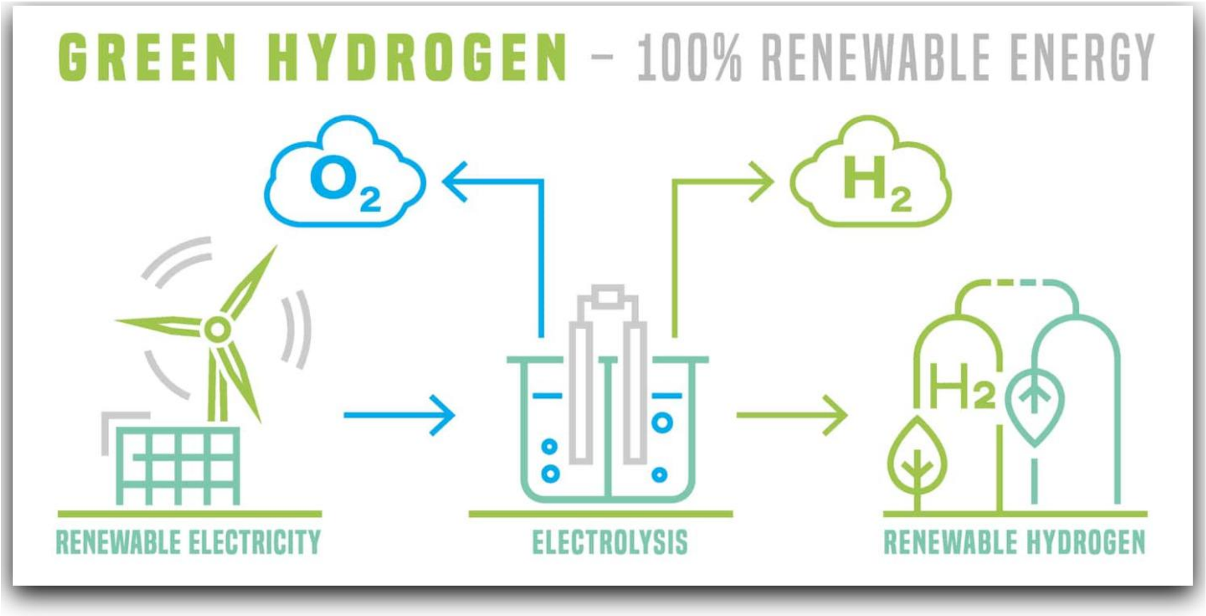

Figure 2 Green Hydrogen 100% Renewable Energy

2.3: Desalination and Green Hydrogen

Desalination and green hydrogen are two technological advancements that hold significant promise for our sustainable future. They are each critical, addressing two of the world's most pressing issues:

The need for clean water and that for clean energy.

Desalination is a process that removes dissolved salts and other minerals from seawater or brackish water, converting it into freshwater that is suitable for human consumption or irrigation. This process is particularly crucial for water-scarce regions, where natural freshwater resources are inadequate to meet the demands of the population and industries.

Green hydrogen, on the other hand, is hydrogen produced using renewable energy sources. Hydrogen is a clean-burning fuel, producing only water vapor when used in a fuel cell or when combusted. However, the majority of hydrogen production today relies on a fossil-based pathway, generating substantial greenhouse gas emissions. This problem can be addressed by using renewable energy, such as wind power, to split water molecules into hydrogen and oxygen through a process known as electrolysis, thus producing green hydrogen.

The relevance of these technologies in a sustainable future cannot be overstated. With the increasing scarcity of freshwater resources due to climate change and population growth, desalination offers a potential solution to water shortages. Similarly, as the world seeks to transition away from fossil fuels to combat climate change, green hydrogen presents a viable, clean alternative that could replace fossil fuels in various sectors, including industry and transportation. Intriguingly, these two technologies can be integrated: desalinated water can be used in the electrolysis process to produce green hydrogen. This combination offers a pathway to concurrently address water and energy challenges, especially in regions that are rich in renewable energy resources but scarce in freshwater resources. *(Desalination and Green Hydrogen: A Pathway to Sustainable Water and Energy Solutions*)

2.4: Water-Energy Nexus in Desalination

Over the last 50 years, expensive desalination technologies have offered many water-poor but energy-rich countries in the Middle East and North Africa (MENA) region a way to produce and supply water for their populations, largely for drinking water purposes. Half of the world's desalination capacity is within the MENA region (Borgomeo et al., 2018,); desalination provides the Gulf Cooperation Council (GCC) countries with a large share of their drinking water needs, ranging from 27% in Oman to 87% in Qatar (IRENA, 2016).

Wind energy is particularly abundant on islands, coastal areas, and mountain stations, especially in West Africa (Maatallah, T., et a, 2013; Ahmed Shata, A.S., and R. Hanitsch 2008), and thus it is a favourable source of energy for desalination in such environments. As opposed to solar energy where availability is limited to the availability of sunlight during daytime, wind energy is readily available to be harvested over both day and night, assuming suitable wind resources (Peinke, J., et al. 2004.) This makes wind energy a superior alternative, in locations that are rich in terms of wind resources, compared to solar power for continuous powering of different processes, reducing the need for long-term energy storage. The use of wind energy for powering membrane-based desalination technologies was investigated by several researchers (Park, G.L., A.I. Schäfer, B.S. Richards, 2011; Subiela, V.J., et al., 2009), and was found to be economically feasible for some technologies, including ultrafiltration (UF) and reverse osmosis (RO) (Garcia-Rodriquez, L. 2003)

Comparisons between solar-powered and wind-powered membrane techniques (e.g., 3.4 kWh/m3 for a wind-RO system versus 4 kWh/m3 for a PV-RO system, using the same reverse osmosis module in both of the setups and desalinating from similar seawater feeds (32,800–34,300 mg/L TDS) ,(Miranda, M.S., D. Infield 2003). The overall cost of desalination was also suggested to be lower when using wind energy as opposed to solar energy for powering the membrane systems (Gilau, A.M., M.J. Small 2008). In a review by El-Ghonemy2012, the costs of water production from brackish water desalination were reported to be 6.7 and 2.7 $ US /m3 for PV-RO systems and wind-powered RO systems, respectively, in the USA and Europe.

The demand for beneficial, sustainable, and renewable sources of energy, such as hydrogen, is increasing due to GHG emissions, rising prices, and major environmental problems from fossil fuels. Along with biogas and biodiesel, hydrogen is recognized as one of the most eco-friendly energy sources due to its high energy content. Suppose the entire projected demand for clean hydrogen is considered, including its applications in heating, construction, transport, chemical synthesis, and energy storage. In that case, global hydrogen demand is estimated to reach 2.3 gigatonnes (Gt) per year by mid-century (Oliveira et al., 2021). If this hydrogen is produced through water electrolysis powered by renewable energy, global carbon dioxide emissions from the energy sector could be reduced by up to 10.2 Gt annually (IEA, 2016). Based on the stoichiometry of water splitting, approximately 9 kg of water is required to produce 1 kg of hydrogen. Consequently, producing 2.3 Gigatons of hydrogen annually would require approximately 20.5 Gigatons of water (20.5 billion cubic meters per year), which represents only around 1.5 parts per million of the available freshwater on Earth. When hydrogen is used, water is released either through combustion or in fuel cells; however, although it can be recovered, it is often treated as waste. However, water used in chemical synthesis cannot be recovered. For example, assuming the production of 540 million tons of hydrogen via such processes, approximately 4.8 billion cubic meters of water would be consumed, equivalent to 0.3 parts per million of global freshwater per year (Oliveira et al., 2021).

2.5: Case study 1: Dolphyn Hydrogen Project.

The Dolphyn Hydrogen project was identified through the literature search and mentioned in the following studies: Dolphyn,Hydrogen Phase 1 Final report 2019 and Dagnachew & Solf, 2024. It was developed by Environmental Resources Management (ERM) and detailed in its Phase 1 Final Report (9 October 2019), explores large-scale green hydrogen production from offshore floating wind turbines in the North Sea, integrating desalination and electrolysis for bulk hydrogen supply. Funded by the United Kingdom, the project aimed to decarbonize energy systems by producing hydrogen at a competitive cost (£1.65–1.93/kg undiscounted at scale) for the UK market, with potential export implications. Phase 1 included two sub-phases: Phase 1a (Concept Select) evaluated design options, and Phase 1b (FEED) advanced a 2 MW prototype of the full system to the Front End Engineering Design (FEED) stage**.**

Three options were assessed—Case 1 (Dolphyn: decentralized electrolysis on floating platforms with pipeline export), Case 2 (centralized offshore electrolysis), and Case 3 (onshore electrolysis with power cables). The semi-submersible Dolphyn design was selected for its economic (£1.93/kg at 10 MW scale) and technical feasibility, leveraging existing technologies (for example, Wind Float, Proton Exchange Membrane electrolysis). The Feed Development (Phase 1b) focused on refining design, costs, and timelines, with a development plan scaling to 4 GW (400 x 10 MW turbines) by 2037.

The design process components are as follows: each 10 MW unit integrates a wind turbine generator (WTG), semi-submersible sub-structure (Wind Float), desalination unit, PEM electrolyzer (30–50 bar output), and export pipeline (flexible risers to a sub-sea manifold). A 4 GW array (400 units) produces 360,000 tonnes of hydrogen per year, and Hydrogen is piped 50–250 km to shore at 30–50 bar, leveraging pipeline storage capacity.

The Revenue targets is £2/kg competitiveness with natural gas, projecting £270 billion Gross Value Added(GVA) to 2100 for the UK, with 8.4 million Full Time Equivalent (FTE)years of employment. The project impact is zero-carbon hydrogen production replacing grey hydrogen and reducing CO_2 emissions (e.g., 12 TWh/year from 4 GW offsets fossil fuel use).

2.6: Case 2: Hyphen Hydrogen Energy Project

This Hyphen hydrogen project case study was identified during the literature search and mentioned in the study.*(Hyphen Hydrogen Energy Ammonia-Namibia,* Dagnachew & Solf, 2024) and some hydrogen conferences attended. The Hyphen Hydrogen Energy project, a Namibian initiative by Hyphen Hydrogen Energy (a partnership between Nicholas Holdings and Enertrag), was selected in November 2021 by the Namibian government to develop a large-scale green hydrogen production facility in the Tsau//Khaeb National Park, near Lüderitz. With a total investment of USD 10 billion, the project integrates 5 GW of wind and solar capacity with 3 GW of electrolyzer capacity to produce 300,000 tonnes of green hydrogen annually, converted into 1.7 million tonnes of ammonia for international, regional, and domestic markets.

The project unfolds in two phases: Phase 1 (USD 4.5 billion, 0.7 million tonnes ammonia by 2026) and Phase 2 (full capacity by 2029), leveraging Namibia's exceptional renewable resources and proximity to a deep-water port.

Figure 3 Hyphen Hydrogen Energy– Namibia

(Source: hyphenafrica.com)

This case study serves as a model for a similar project in Dakar, Senegal, adapting Hyphen's hybrid renewable approach to a 1000 MW onshore wind-powered system**.**

Hyphen's methodology was a phased development process. Phase 1 targets final investment decision by 2024 and production by 2026 (0.7 million tonnes ammonia), with Phase 2 scaling to full capacity by 2029 (300,000 tonnes H_2). Detailed engineering agreements were expected from 2022. The project's evaluation metrics focused on economic viability (USD 10 billion cost vs. Namibia's GDP), job creation (15,000 construction, 3,000 operational), and scalability to support 3 million tonnes H_2/year regionally. These specifications will be adapted to the Dakar case study. Hyphen's 5 GW wind-solar mix will be replaced with a 1000 MW onshore wind farm (200 x 5 MW turbines) due to Dakar's favourable wind potential (3.7–6.1 m/s).

The revenue source is ammonia sales to Europe and East Asia (USD 500–700/tonne market price), potentially reaching USD 850 million–1.2 billion/year at full capacity, plus regional electricity sales. Financing consists of 24% government equity, with debt from Development Finance Institutions (DFIs) and commercial lenders, leveraging blended finance to de-risk USD 10 billion.

2.7: Taiba N'Diaye Wind Power Project

Senegal shows potential for exploiting wind power as a renewable source. An example that demonstrates this potential is the project of the Taiba N'Diaye Wind Power plant, Senegal's first large-scale wind energy initiative, which is a 158.7 MW wind farm located in Taiba N'Diaye, approximately 100 km northeast of Dakar. Developed by Lekela and owned by Parc Eolien Taiba N'Diaye S.A.U. (PETN), it was commissioned in December 2019 as part of the "Plan Senegal Emergent" to enhance energy security. Featuring 46 Vestas wind turbines (3.45 MW each), the project generates clean electricity for SENELEC under a 20-year power purchase agreement (PPA), increasing Senegal's generation capacity by 15% and providing electricity to over 2 million people. This study is informative to our case study in Dakar that implements wind power energy to power reverse osmosis to desalinate water and electrolysis to produce green hydrogen.

Figure 4 *Taiba N'Diaye Wind Farm*

Lekela Power, project developer of the Taiba N'Diaye Wind Farm, built 20 miles of feeder roads to connect 36 villages and allow mango fields to be co-located with the wind farm. Photo: Africa Digest News

The Methodology applied development Process is initiated under Senegal's renewable energy strategy. Parc Eolien Taiba N'Diaye (PETN) was selected through a competitive process, with Lekela leveraging international expertise and Vestas technology. Construction spanned 2017–2019, followed by commissioning. The implementation was a Standardized wind turbine deployment in a high-wind area (coastal Senegal), supported by a long-term power purchase agreement (PPA), with SENELEC to ensure revenue stability.

This project applies to our thesis by mirroring Taiba N'Diaye's project in the government-backed model, with a Power Purchase Agreement (PPA)-like off-take agreement with Germany (e.g., H2Global) and carbon credit registration.

2.8: Algeria's Desalination Program

The selection of the Algeria desalination plant as a reference for our green hydrogen project model in Dakar, Senegal draws on the plant's relevance as a benchmark for operational and economic insights in a similar North African coastal context, due to its use of reverse osmosis (RO) technology, which aligns with the proposed desalination method in Dakar. Both regions share comparable environmental conditions, such as access to seawater and a semi-arid climate. The Dakar project benefits from proven strategies in a geographically and technologically similar setting, enhancing the feasibility and environmental sustainability of producing fresh water for green hydrogen production and export.

Algeria's desalination program, addresses severe water scarcity in a country projected to face extreme water stress by 2030. With three-quarters of its population and industrial/agricultural activities concentrated along a 1,200 km coastal zone, Algeria relies heavily on desalination to supplement dwindling freshwater resources, exacerbated by pollution and climate-driven droughts. The program involves multiple large-scale reverse osmosis (RO) plants to produce potable water, targeting integrated water resource management for domestic and industrial use. it emphasizes desalination as a strategic response to rainfall variability (2,000 mm/year in the north to <100 mm/year in the Sahara) and water demand**.**

Algeria is planning a national strategy focused on deploying reverse Osmosis plants along the coast, leveraging seawater availability, and the design technology is due to energy efficiency (3–4 kWh/m^3) and reliability, with pre-treatment and brine disposal systems to manage environmental impacts.

The theses mirror the Algerian desalination program by utilizing a Reverse Osmosis technology plant to desalinate seawater for the Proton exchange Membrane electrolyzers to produce green hydrogen using renewable-powered (wind energy). The impact is to reduce groundwater overexploitation and pollution, stabilizing the coastal water supply.

2.9: Green Hydrogen plus Desalination: Economic and Environmental Implications.

Currently, countries are formulating strategies for the production and use of green hydrogen. These might have stated investments that run into billions for green hydrogen production and supply chains by the European Union, Australia, Japan, and the United States. By the year 2050, green hydrogen will account for a maximum of 25% of global final energy consumption as forecasted by analysts. It is a decarbonization alternative for heavy industry, shipping, and aviation (BloombergNEF, 2024)..The International Energy Agency (IEA) estimates that transitioning to green hydrogen could save approximately 830 million tonnes of CO2 emissions annually, compared to hydrogen produced from fossil fuels *What Is Green Hydrogen and Its Importance - Iberdrola, n.d).*

Cost Reduction Strategies: The high cost of green hydrogen production is a significant barrier. However, as renewable energy becomes cheaper and more widely available, the production costs of green hydrogen are expected to decrease. The World Hydrogen Council predicts that production costs could fall by 50% by 2030, making green hydrogen more competitive with traditional fossil fuels.(*What Is Green Hydrogen and Its Importance - Iberdrola*, n.d.)

Efficiency Improvements: Current electrolyzers operate at around 50 kWh/kg of hydrogen, achieving an efficiency of just under 79%. Improving the efficiency of these systems is crucial for reducing costs and enhancing the economic viability of green hydrogen. Additionally, integrating hydrogen production with renewable energy sources can optimize the use of excess energy generated during peak production times.(*-How Feasible Is Green Hydrogen? Some Back-of-the-Envelope Calculations - ESIG, n.d. by Eric Gimon, Energy Innovation LLC 2024)*

Integration with Renewable Energy: Desalination processes, particularly reverse osmosis, require significant energy inputs. By integrating desalination with green hydrogen production, facilities can utilize excess renewable energy to power desalination plants, thereby reducing operational costs and enhancing sustainability. This synergy can lead to a more resilient water supply system, especially in arid regions.(*What Is Green Hydrogen and Its Importance - Iberdrola*, n.d.)

Innovative Technologies: Advances in desalination technologies, such as wind desalination and the use of hydrogen as an energy source, can improve the sustainability of water production.

Economic Viability: The economic feasibility of desalination powered by onshore wind power hinges on the cost of renewable energy and the efficiency of the desalination process. As the price of renewable energy continues to decline, the overall cost of desalinated water can become competitive with traditional water sources, especially in water-scarce region.

Policy Support and Investment: Government policies and investments play a crucial role in promoting the development of green hydrogen and desalination technologies. Supportive frameworks, such as subsidies for renewable energy projects and research funding for innovative desalination methods, can accelerate the adoption of these technologies (*How Feasible Is Green Hydrogen? Some Back-of-the-Envelope Calculations - ESIG*, n.d.)

2.10: Brine Management

Brine is a high-salinity solution, typically produced as a byproduct of desalination processes like reverse osmosis (RO). In desalination, seawater is processed to extract fresh water, leaving behind a concentrated saline solution (brine) with salinity often equal to the process fresh water. Various management options relate to brine, the term usually given to saline wastewater from industrial operations. These are grouped into two: brine treatment and brine disposal. Brine treatment is the desalination of the brine for reuse and generating a concentrated brine (less liquid waste volume) or residual solids (zero liquid discharge). Brine disposal includes the discharge of brine into sewers, surface water, injection wells, or to environmental service providers. The cost and environmental impact of each option vary significantly due to many factors. Choosing management options for the waste brine requires careful consideration of applicable discharge regulations, availability of disposal methods, and the economic feasibility of treating the brine (Albrecht, Uwe Ball, Michael Bünger et al., 2022) (Jones et al., 2019).

2.11: Green Hydrogen Policies Focus on ECOWAS Countries

The **ECOWAS Green Hydrogen Policy and Strategy Framework**, adopted on July 7, 2023, by the 90th Ordinary Session of the ECOWAS Council of Ministers in Bissau, Guinea-Bissau, outlines a comprehensive approach to position West Africa as a competitive producer and supplier of green hydrogen while fostering socio-economic growth and sustainable development. This response describes the key green hydrogen policies detailed in the document, organized into strategic vision, objectives, targets, strategic actions, and institutional framework.

Strategic Vision

The policy envisions positioning the ECOWAS region as one of the most competitive producers and suppliers of green hydrogen and its derivatives globally, while addressing regional socio-economic growth and sustainable development (Page 6, 14, 46). It leverages West Africa's vast renewable energy potential—solar, wind, and hydro—to produce green hydrogen via electrolysis, targeting both domestic decarbonization and export markets like Germany. The focus on green hydrogen, defined as hydrogen produced using renewable energy with minimal carbon emissions, aligns with global decarbonization trends and complements the updated ECOWAS Energy Policy (2023), which emphasizes clean energy (Page 6, 18).

Institutional Framework

The policy establishes the ECOWAS Green Hydrogen Development Unit (EGHDU**)** within ECREEE to oversee implementation, with a working group comprising ECREEE, WASCAL, WAPP, EBID, and national representatives (Page 60–61). EGHDU's responsibilities include:

- ✓ Supporting national policy development.
- ✓ Coordinating research &development, training.
- ✓ Developing regulations and certifications.
- ✓ Facilitating investments and industry collaboration.
- ✓ Reviewing targets every 5 years, with annual meetings to monitor progress (Page 61).

Value Addition and Socio-Economic Focus

The policy emphasizes domestic benefits alongside exports, targeting job creation (manufacturing, operations), infrastructure growth (cement, steel), and local market development (e.g., green buses, fertilizers) (Page 63). It integrates gender equity and ensures desalination supports community water needs, aligning with ECOWAS Vision 2050 and SDGs (Page 6, 51).

Risk Assessment and Monitoring

The policy identifies risks like delayed national policies, inadequate budgets, and infrastructure gaps, proposing mitigation via early policy consensus, nodal agencies for land/clearances, and concessional financing (Page 65). A monitoring and evaluation mechanism tracks EGHDU's performance using KPIs and quarterly MIS reports, ensuring accountability (Page 67)

2.12: Senegal Business Climate Reforms **(2013–ongoing)**: (Invest in Senegal,)

Senegal has implemented over 50 measures to improve competitiveness, ranking among the top 10 global reformers in business regulations.*(A country private sector diagnostic creating markets in Senegal, 2020)*. Among recently implemented reforms are fast-tracked company registration (within 24 hours), fast-tracked online building permits, and simplified licensing and tax processes

Challenges for Investors

Despite these policies, investors continue to face hurdles. Some of the main ones include substantial bureaucracy, which complicates tax administration, and complex customs procedures, which can delay investments. These can pose a risk in our case study for the import of wind turbines to Senegal. The judicial system is characterized by inefficient courts and documented bias in arbitration clauses. Senegal's energy and transport infrastructure remains underdeveloped and may increase logistic costs in the case of exports. Finally, real estate and energy costs may raise the OPEX for industrial projects.

This chapter has critically examined the interplay between green hydrogen production, desalination, and renewable energy, particularly wind power, as innovative responses to water scarcity, energy transition, and climate change. Drawing on global and regional case studies, such as the Dolphyn project in the UK, Hyphen in Namibia, and Senegal's Taiba N'Diaye wind farm, the literature illustrates the growing feasibility of integrating desalination with electrolysis powered by renewable sources. These projects underscore both the technological maturity and the economic potential of green hydrogen, while also highlighting regional adaptation strategies in West Africa.

The analysis reinforces the importance of policy frameworks, such as the ECOWAS Green Hydrogen Strategy, in enabling large-scale deployment through institutional support, financing, and regional cooperation. It also outlines the socio-economic and environmental benefits, including job creation, carbon reduction, resource resilience, and challenges such as infrastructure deficits, brine disposal, and regulatory barriers.

The reviewed literature provides a foundational understanding of the technological, economic, and policy dimensions of green hydrogen production. It lays the groundwork for assessing the viability of a Dakar-based green hydrogen project, emphasizing the need for context-specific design, strong governance, and sustainable infrastructure planning. The next chapter outlines the materials and methods framework used to assess the technical feasibility, economic viability, and environmental implications of exporting green hydrogen from Dakar to Germany.

3 : Chapter 2: Materials and Methods

This chapter outlines the methodological framework used to analyze the production, storage, and export of green hydrogen from Dakar, Senegal, to Germany using AnyLogic simulation software. The study adopts a systems-based approach to model the interconnected components of a green hydrogen value chain powered by renewable wind energy. It highlights the integration of seawater desalination through Reverse Osmosis (RO) and electrolysis with Proton Exchange Membrane (PEM) electrolyzers. The chapter also provides a detailed discussion of the selected study area and the sampling strategy employed.

3.1: Study Area

Dakar was chosen as the study area for evaluating the economic and environmental implications of a green hydrogen plant focused on desalination and export to Germany due to its unique geographical and climatic advantages. The region is located on the Cape Verde peninsula along the Atlantic coast, it has average wind speeds often exceeding 4.9 meters per second, as documented in regional meteorological studies (https://windy.app/forecast/senegal). These conditions are optimal for wind farm operations, ensuring a reliable and renewable energy supply for the project.

Dakar’s proximity to the Atlantic Ocean provides a significant advantage for the desalination and electrolysis process required in green hydrogen production. Seawater is readily available, and the city’s coastal infrastructure supports efficient seawater pumping systems. This accessibility reduces the costs associated with water sourcing, enhancing the project's economic viability while ensuring a sustainable water supply without the depletion of underground water.

Dakar Port is one of West Africa’s largest and most developed maritime hubs, equipped to handle large-scale shipping operations. The port’s strategic location along major transatlantic shipping routes facilitates efficient and cost-effective transportation, bolstering the economic competitiveness of the project while reducing the carbon footprint associated with long-distance shipping, as shorter routes contribute to lower fuel consumption.

Senegal is recognized for its political stability in a region often characterized by volatility, creating a favorable environment for long-term investments in renewable energy projects. Furthermore, the Senegalese government has shown a commitment to sustainable development through initiatives like Senegal Vision 2050, which focuses on renewable energy and green technology. This policy framework fosters foreign investment and technological partnerships.

Figure 5: Administrative Map of Dakar (Source: Wikimedia Commons)

3.2: Methodology

A mixed-methods approach has been adopted to allow for a comprehensive analysis combining the precision of quantitative modeling for economic and environmental assessments, with qualitative insight from the literature.

3.3: Data Collection.

Three sources of data were employed in our study: peer-reviewed literature, industry case studies, and report sheets from renewable energy companies. In the context of Dakar-to-Germany exports, attention was devoted to identifying applications of desalination, wind energy integration, and Proton Exchange Membrane (PEM) electrolyzer systems in the real world.

Case studies from international projects, such as Nel Hydrogen electrolyzer project, Siemens Gamesa's 5 MW wind turbines, Algeria Desalination Plant, and Taiba N'Diaye Wind Power Project in Senegal, were scrutinized to extract key performance data, CAPEX and OPEX estimates, and insights into the operational ethos. In parallel, literature sources from the International Renewable Energy Agency (IRENA), the International Energy Agency (IEA), the MECO EDI Water Systems website, and academic journals. Engineering data were also reviewed from engineers' reports and project documentation, enabling the system simulation to accurately simulate hydrogen production, seawater, freshwater, and energy flows. These sources ensured the study was grounded in current best practices and scalable technological options applicable to West African and European hydrogen markets.

The data collected for this study were organized into three main categories: economic, environmental, and technical. The economic data include capital expenditure (CAPEX) and operational expenditure (OPEX) for PEM electrolyzers, desalination plants, and wind turbines, as well as cost benchmarks for hydrogen production and export logistics costs, such as shipping and storage.

The environmental data consist of carbon dioxide emissions avoided through the substitution of fossil fuel with green hydrogen, water consumption requirements for hydrogen production measured as seawater input and freshwater output, environmental impacts of desalination, including brine discharge, and contributions to decarbonization.

Finally, the technical data encompass wind speed and power output measurements from projects such as the wind turbines, the efficiency of PEM electrolysers, hydrogen production capacities per day, desalination plant performance indicators such as output capacity, and detailed energy flow balances of electricity input and output, and engineering specifications including system design parameters and configurations

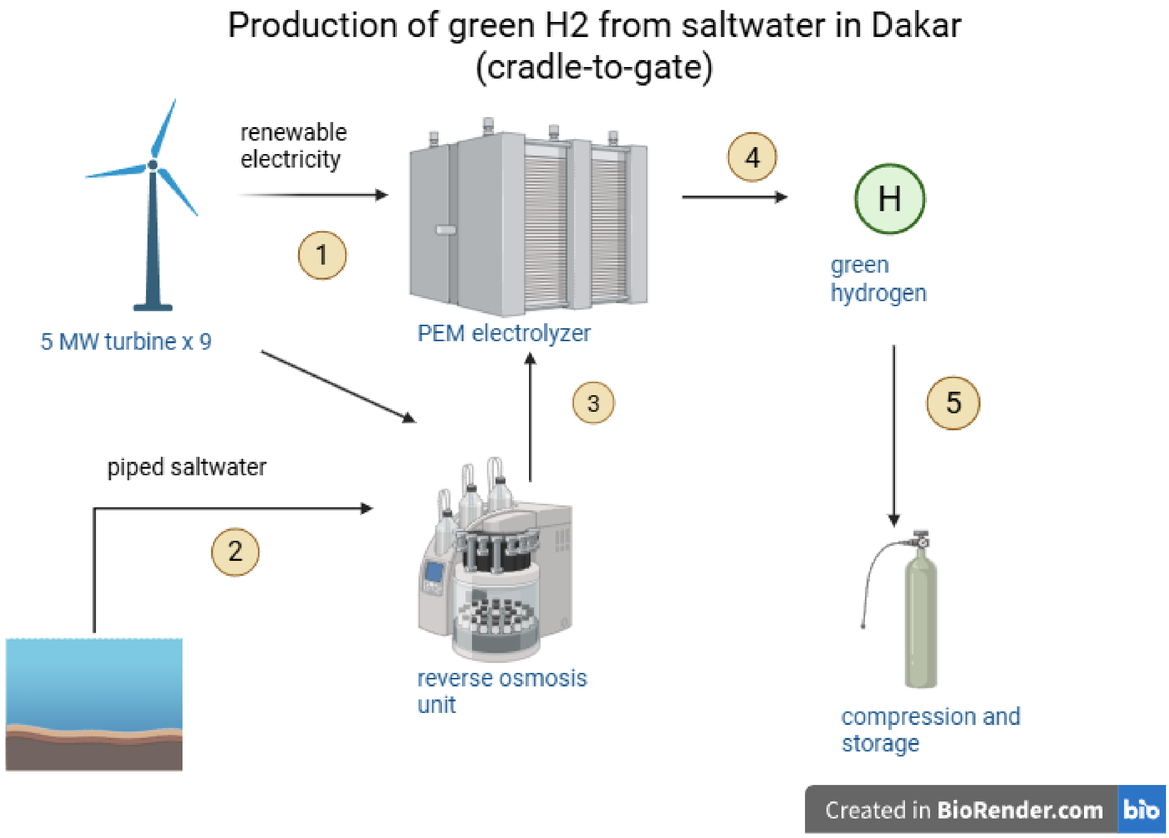

Figure 6 *Schematic illustration of the desalination system coupled with water electrolysis* (*own work in BioRender*)

3.4: Methods and data analysis

Anylogic Software

AnyLogic is a multi-method simulation tool that integrates system dynamics, discrete event, and agent-based modeling, making it an ideal choice for analyzing complex systems like green hydrogen production, which involves wind energy, seawater desalination, electrolysis, storage, and shipping logistics. We used the system dynamics capabilities of AnyLogic to simulate a green hydrogen production facility.

In our work, AnyLogic was used to construct a simple system dynamics model of green hydrogen production and associated costs. After constructing a stock-and-flow diagram modelling the operation of an electrolyzer running on filtered seawater, we analyzed the CAPEX and OPEX of the system. For CAPEX, we calculated the associated cost components for green hydrogen production. For OPEX, we also calculated the associated costs for the ongoing operation of green hydrogen production. The simulation runs for 365 days; hence, OPEX refers to annual operational expenses.

The decision to use AnyLogic as the primary modeling and simulation tool for this research is motivated by the complexity of the problem, which requires capturing the technical, economic, and environmental interactions between green hydrogen production, desalination, and export logistics. Traditional tools such as excel-based cost models or static optimization software (e.g. HOMER, RETScreen) are useful for preliminary feasibility assessments, but they cannot represent dynamic feedback, uncertainties, and system interdependencies over time (Mokshin et al., 2019).

Multi-Method Simulation Capability AnyLogic uniquely integrates system dynamics and discrete event simulation modeling in a single environment.(Mokshin et al., 2019) This is particularly important in this study because:

- ❖ System Dynamics can model long-term economic and environmental trends, such as the CAPEX and OPEX of technologies, green hydrogen production, and carbon dioxide saved.
- ❖ Discrete Event Simulation can capture the operation of desalination and hydrogen export logistics, such as shipping schedules and resource bottlenecks.

Visualization and Stakeholder Communication: AnyLogic provides strong visualization features that allow dynamic simulation of the hydrogen desalination system, making it easier to communicate complex findings to policymakers, investors, and stakeholders. This is critical in a context like Senegal, where decision-makers need transparent and intuitive models to justify investment in new technologies (Borshchev et al., 2002)

Proven Track Record in Energy and Environmental Systems: Finally, AnyLogic has been successfully applied in renewable energy planning, hydrogen supply chain design, and water resource management studies. Its flexibility and reliability make it a credible tool for addressing the integrated economic-environmental challenges at the core of this research (Zhang et al., 2012).

The arrows show the material flows, resources, and dependencies between variables and processes. For example, flows allow the connection of the desalination process to the energy production and distribution. This demonstrates how capital investments influence energy output by tracking hydrogen output, storage, and shipping, which in turn links the hydrogen revenue streams and the amounts of CO_2 saved. The figure below shows the AnyLogic simulation and its different components.

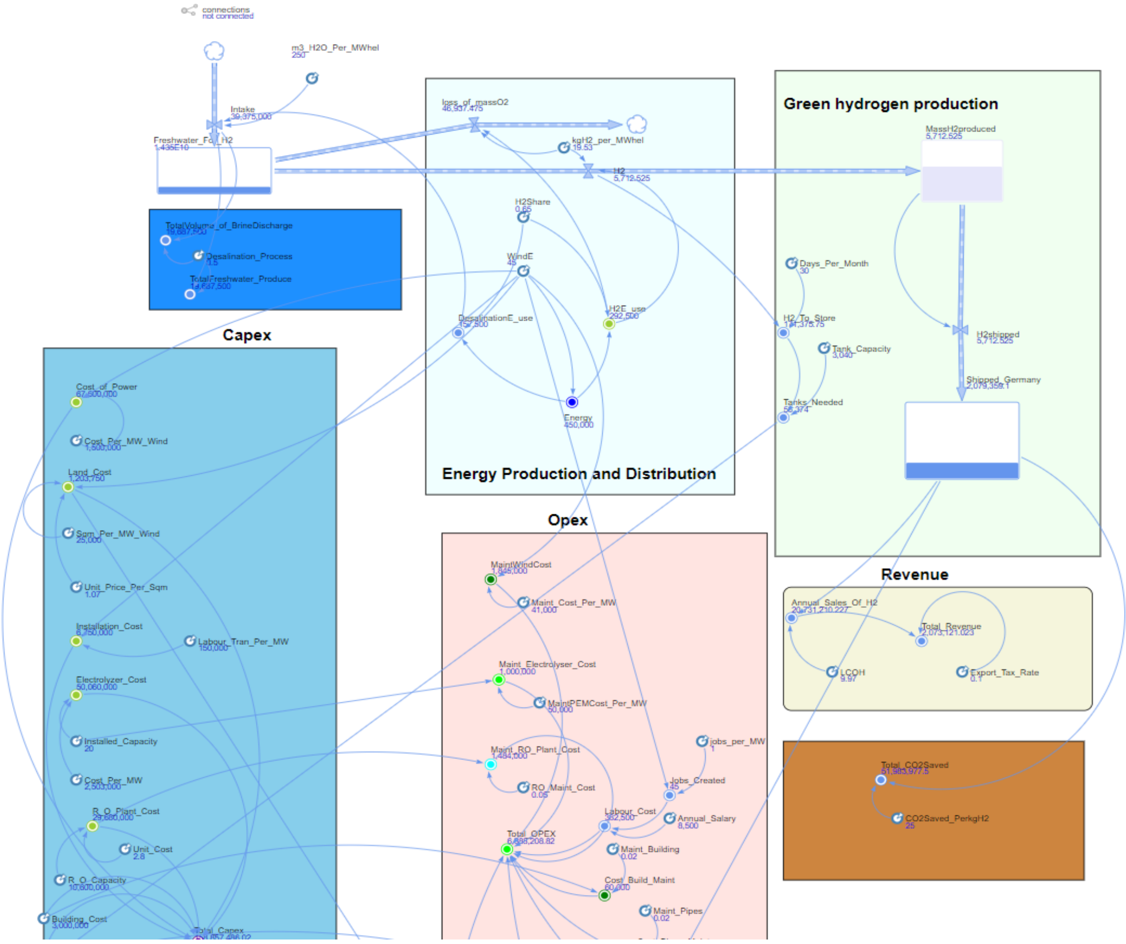

Figure 7 *AnyLogic simulation components (own work)*

The project assumes a capital investment fully funded by the German government and affiliated German institutions. This funding covers the total capital expenditure (CAPEX) of green hydrogen infrastructure development in Dakar, Senegal, including renewable energy systems (such as wind turbines), desalination plants, electrolysers, hydrogen storage tanks, transportation infrastructure, installation, and training. By fully financing the project, Germany seeks to establish long-term trade relations for green hydrogen, support its national and industrial decarbonization goals, and meet the Paris Agreement targets. The key environmental implication for Germany is the significant reduction in carbon dioxide (CO_2) emissions. The imported green hydrogen will be used to decarbonize industrial sectors, particularly the German steel industries, which are major contributors to greenhouse gas emissions. By replacing fossil fuels with renewable hydrogen, Germany would reduce its reliance on carbon-intensive energy sources.

For Senegal, the host country of the hydrogen production facility, the economic implications are twofold. First, the government of Senegal benefits from direct fiscal revenues through an export tax levied on the hydrogen sold to Germany, offering a sustainable stream of income that can be reinvested in national development priorities such as education and health. This revenue model positions Senegal as a key stakeholder in the green hydrogen value chain. Secondly, the project brings substantial employment opportunities to the local population. During both the construction and operational phases, the initiative is expected to create jobs, ranging from engineers and technicians to logistics personnel and administrative staff. This not only supports local capacity-building but also fosters knowledge transfer in renewable technologies and industrial management

3.5: Simulation Components

Siemens Gamesa SG 5.0-145 Turbine for wind power

The selection of the Siemens Gamesa SG 5.0-145 turbine, with a rotor diameter of 145 meters and a rated power of 5 MW, is a strategic decision driven by its alignment with the project's economic and environmental goals. This turbine model, part of Siemens Gamesa's onshore portfolio, is designed for medium wind sites, making it an ideal fit for Dakar's coastal wind conditions, due to its technical suitability. The capacity is optimized for wind speeds, maximizing energy capture with a rotor area of 16,513 square meters. It employs a geared technology approach with a three-stage gearbox (two planetary and one parallel) and a doubly-fed induction generator, ensuring high reliability and efficiency.

Economically, the SG 5.0-145 offers significant advantages that enhance the project's financial viability. Siemens Gamesa's focus on reducing the Levelized Cost of Energy (LCoE) through the Optima Flex technology allows for a tailored solution that optimizes energy production while minimizing costs. Furthermore, the turbine's design incorporates environmentally friendly features, such as noise reduction through DinoTails technology, minimizing its impact on local wildlife and communities near Dakar's coast *(https://www.windkraft-journal.de*).

Logistically, the SG 5.0-145 is well-suited for deployment in Dakar due to its modular and flexible design, which facilitates transportation, installation, and integration with the project's infrastructure. The turbine's adaptability to saline and dusty environments, as offered by optional kits, ensures durability in Dakar's coastal climate, reducing the risk of corrosion and extending operational life.

Figure 8 Siemens Gamesa wind turbine (model SG 5.0-145)

(Source: Siemens Gamesa)

The wind farm is planned to have a capacity of 45 MW and operate at a capacity factor of 41.7%. The number of turbines required is 9, each of a 5 MW capacity. The average wind speed for Dakar's coastal wind is 4.9 m/s.

The economic input of CAPEX and OPEX for a Wind Capacity of 45 MW is outlined below. The CAPEX includes turbine costs, transportation, foundations, connection, and installation with an estimate of €1,500/kW for onshore turbines. (Siemens Gamesa reports 2025). OPEX includes maintenance, repairs, and insurance, typically at €50 per kW annually *(www.irena.org)*. These parameters, sourced from the literature and technical reports, are implemented in our simulation model.

Reverse Osmosis for Desalination

The selection of the reverse osmosis (RO) technology for the desalination plant is a critical decision influenced by both economic and environmental factors. RO was chosen for its proven technical efficiency in producing high-quality fresh water from seawater, which in turn ensures the optimal operation of PEM electrolyzers. This process entails forcing seawater through a semi-permeable membrane under high pressure, effectively eliminating salts and impurities to create fresh water with low total content of dissolved solids*(www.lenntech.com)*.

Economically, reverse osmosis presents significant advantages that make it an ideal selection for the green hydrogen project. While the initial capital investment for RO plants can be considerable cost of membranes and high-pressure pumps, the operational costs are relatively low in comparison to alternative desalination techniques like thermal distillation. The technology also facilitates the incorporation of advanced pre-treatment and energy recovery systems, thereby enhancing efficiency and further reducing costs over time *(www.meco.com*).

From an environmental perspective, reverse osmosis supports the green hydrogen project's sustainability goals by minimizing ecological impact. Unlike thermal desalination methods that require substantial energy input and often depend on fossil fuels, RO can be efficiently powered by renewable energy sources such as wind, reducing greenhouse gas emissions. Furthermore, modern RO plants are designed to manage brine discharge responsibly, using diffusers to disperse concentrated salt water back into the ocean without harming Dakar's marine ecosystems *(https://www.meco.com*).

Several sources have concluded that green hydrogen production takes up a significant volume of freshwater resources (Beswick et al., 2021). Locating green hydrogen production in a coastal region like Dakar and making use of seawater reduces pressure on freshwater resources that are used for agriculture and wider consumption in the population.

Figure 9 *Reverse osmosis machine* (source: www.meco.com)

Technically, a 15 MW power capacity desalination plant to be installed to produce fresh water for the electrolyzer using reverse osmosis (RO), is designed to deliver a specific volume of fresh water per day, supporting the electrolyzer system in the Dakar project. Reverse osmosis systems consume 3 kWh per cubic meter of fresh water produced. The power allocation will be 35% of the total wind energy generated.

The CAPEX and OPEX for the desalination plant with a daily water processing capacity of 13.9 million gallons, which are projected. CAPEX, which includes transportation, connection, and installation, is estimated at 2.1 euros per gallon of water production capacity. OPEX covers maintenance and insurance, with a 5% CAPEX per gallon annually, amounting to the projected euros per gallon per year. This covers operational costs, equipment upkeep, and insurance to ensure the plant's reliability in the project (*The True Cost of Drinking Water: Understanding the Expenses of Reverse Osmosis Plants Gunnar 2024).*

Electrolysis through Proton Exchange Membrane Technology.

The selection of Proton Exchange Membrane (PEM) technology for electrolysis is driven by its technical superiority, economic viability, and environmental compatibility. Its exceptional technical efficiency and performance in hydrogen production make it an ideal fit for the project's goals. The use of a solid polymer electrolyte allows PEM electrolysers to operate at high current densities and pressures, resulting in a compact design and rapid response to wind energy inputs. This flexibility ensures optimal hydrogen output even when wind energy supply fluctuates, a critical factor for maintaining consistent production levels.PEM electrolysers produce high-purity hydrogen (up to 99.9%).

Economically, PEM technology offers significant advantages that support the project's feasibility despite its higher initial capital costs compared to traditional alkaline electrolysers. The compact size and high efficiency of PEM systems reduce the space and infrastructure requirements, lowering installation and land-use costs in Dakar's coastal region.

From an environmental standpoint, PEM aligns seamlessly with the green hydrogen project's sustainability objectives. PEM electrolysers produce hydrogen without carbon emissions during operation, supporting the global transition to clean energy and meeting Germany's demand for decarbonized fuels. The technology's high efficiency minimizes energy waste, reducing the overall environmental footprint of the production process. Moreover, the absence of liquid electrolytes, unlike in alkaline systems, eliminates the risk of chemical leaks (Stargate

Hydrogen), Dakar's marine ecosystems, and ensures compliance with environmental regulations, thereby enhancing the project's green credentials for international export

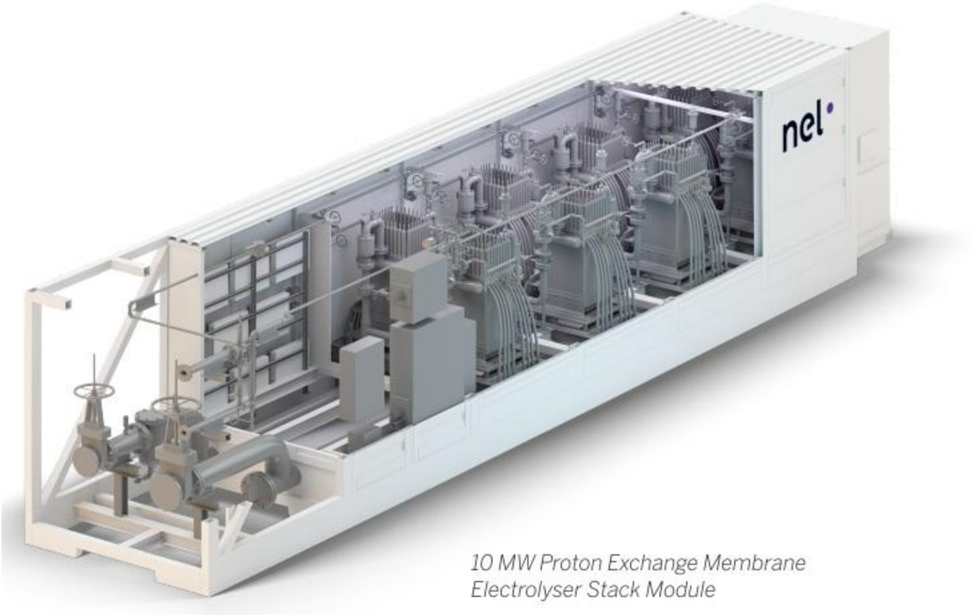

Figure 10 *: A 10 MW PEM electrolyser stack module from Nel Hydrogen*

Technically, the electrolyzer system with a 20 MW capacity to be installed uses Proton Exchange Membrane technology to produce green hydrogen. The PEM electrolyzers require 51.2 kWh of energy to produce 1 kg of hydrogen. This provides a more comprehensive assessment of the energy content, including latent heat from water vapor condensation, offering a conservative and realistic estimate of the hydrogen's potential energy output for industrial applications. The allocated power will be 65% of the total wind power generated. The system includes two units of 10 MW PEM (Nel Hydrogen modules). Each operates at 1.5–2.0 A/cm², with normal temperatures between 51 and 54°C. (nelhydrogen.com).

The CAPEX covers the PEM electrolyzer system, which consists of two 10 MW units. Transportation, connection, and installation costs are estimated at 2,503 euros per kW (Nel Hydrogen). OPEX includes maintenance and insurance, typically averaging 41 euros per kW yearly, resulting in a total annual OPEX that covers routine servicing, component replacements, and insurance to maintain the plant's operational efficiency(*observatory.clean-hydrogen.europa.eu*).

Pumping Pipes for Seawater to Desalination Plant

The water pipes form the critical infrastructure linking the abundant seawater resource to the reverse osmosis desalination process, which supplies fresh water to the PEM electrolyser. For optimal performance, high-density polyethylene (HDPE) pipes are recommended due to their durability, corrosion resistance, and lightweight properties, which are essential for handling seawater's saline content over long distances. HDPE pipes can withstand the harsh coastal environment of Dakar, where salt corrosion is a significant concern for traditional materials like steel (Bingo Pipes).

From an economic perspective, the choice of HDPE pipes and efficient pumping systems offers significant cost advantages over time. While the initial installation costs may be higher than those of conventional materials, the reduced maintenance and replacement frequency due to corrosion resistance leads to lower long-term operational expenses.

Environmentally, the recommended pumping pipe system is designed to minimize ecological impact, a key consideration given the project's focus on green hydrogen production. The use of non-toxic HDPE materials prevents the leaching of harmful chemicals into the marine environment, protecting Dakar's coastal ecosystem.

Logistically, the pumping pipe system must be strategically routed from the coastline to the desalination plant, typically located near the wind farm for energy efficiency. The recommended design includes a network of underground or submerged pipes to protect against storm surges and erosion, common along Dakar's coast due to its exposure to the Atlantic. The system should incorporate pressure regulators and check valves to prevent backflow and maintain consistent water pressure, enhancing operational reliability. (*www.bingopipes.com)*

Figure 11 *Water pumping pipes* (Source: Delta Irrigation)

Technically, these pipes offer a pressure rating of PN10 (10 bar) and a standard dimension ratio (SDR) of 11. The pipe diameter is sized for a flow rate of 2.53 m³/s, using a velocity of 1.5–2 m/s (industry standard for seawater). For a 1.75 m/s velocity and a discharge coefficient of 0.9. An area of 1,400 mm (1.4 m) HDPE pipe is selected for a safety margin, with a wall thickness of approximately 127 mm (www.bingopipes.com).

The CAPEX for transportation, connection, and installation is estimated at 100 euro/m for a 1,400 mm diameter, distributed in ten lines or rows, with each having 50 meters, resulting in a total length of 500 meters. OPEX for Pumping Pipes (HDPE) includes maintenance and insurance, typically 2% of the total CAPEX annually, covering routine inspections, corrosion prevention, and insurance premiums to ensure operational reliability in the Dakar project. (India HDPE deltairrigation)

Green Hydrogen Storage Tank

The recommended storage tanks for hydrogen are cryogenic hydrogen storage tanks, which offer compelling economic benefits that align with the Dakar project's objective of producing green hydrogen for export to Germany. These tanks store hydrogen in a liquid state at approximately -253°C, reducing its volume to about 1/800th of its gaseous form, which significantly decreases the number of storage units needed compared to high-pressure alternatives like carbon fiber-reinforced polymer (CFRP) tanks. Based on industry estimates from companies like Chart Industries, cryogenic storage tanks lower the initial capital expenditure and operational expenditure due to reduced maintenance and energy for compression, while improving the project's Levelized Cost of Hydrogen.

The economic advantages extend to logistics and export scalability, critical for the Dakar-to-Germany supply chain. Cryogenic tanks enable bulk storage and transport in insulated ISO containers, reducing the frequency of shipments. This optimization boosts the project's revenue potential, lowering the export tax rate. The durability of cryogenic tanks (20–30 years with proper insulation) reduces replacement costs over the project's 20-year lifetime. In Dakar's coastal environment, where corrosion-resistant materials like stainless steel or aluminium-lined tanks are viable, these tanks minimize maintenance, enhancing economic sustainability and improving the project's financial viability (*stargatehydrogen.com).*

Environmentally, cryogenic tanks also mitigate environmental risks associated with hydrogen leakage and resource use. The insulated design limits hydrogen permeation to less than 0.1% of the transported volume annually, minimizing the release of unburned hydrogen, a potent indirect greenhouse gas. (*stargatehydrogen.com).*. In Dakar's coastal ecosystem, where the NelHydrogen electrolysers produce 99.999% pure hydrogen, this containment ensures compliance with Germany's environmental standards, avoiding penalties. Furthermore, the utilisation of fewer cryogenic tanks reduces the carbon footprint of production and transport, estimated at 500–700 kg CO_2 per tank. Cryogenic hydrogen storage tanks are an excellent fit for the Dakar project due to their geographic and operational context. (*stargatehydrogen.com).*

Figure 12: *Liquid-Cryogenic hydrogen storage tanks* (Source: Linde Engineering)

Technically, the Cryogenic hydrogen storage tanks operate at -253°C and at pressures up to 850 kPa (123 psi), with a maximum pressure limit typically around 1035 kPa (150 psi). The vacuum, combined with multilayer insulation (MLI), minimizes heat transfer into the tank, reducing evaporation of the liquid hydrogen (H2 Hydrogen Tools portal). Each tank has a usable liquid hydrogen capacity of 3,040 kg, requiring 57 tanks monthly to store the hydrogen produced by the Nel-Hydrogen electrolyzers. The storage tank weighs 3,500. The outer diameter is 2 m, and the length including valves is 2.5 m., with a design life of 20 years, ensuring safe and efficient hydrogen storage for export to Germany.

Economically, the CAPEX includes the transportation, connection, and installation, estimated at 10,000 euros per tank to store H2 produced monthly. OPEX includes maintenance and insurance, typically 2% of CAPEX annually per tank, equating to 200 euros per tank per year, covering insulation checks, valve servicing, and insurance to ensure safe operation. (stargatehydrogen.com).

3.6:Validation and Scenario evaluation

To ensure accuracy, results were validated using published benchmarks from Siemens Gamesa (wind energy), MECO EDI water system (desalination), and Nel-Hydrogen (electrolyzer data).

Each of these elements represents a major subsystem or risk factor; therefore, the assessment shares equal analytical weight in the scenario testing without prioritizing one over another.

3.7: Projected Simulation Model Outputs

- ✓ Daily hydrogen production (kg)
- ✓ Senegal Economic revenue generated from hydrogen export
- ✓ Total energy share between Electrolysers and the water desalination plant
- ✓ CO2 emissions avoided in Germany (kg) through green hydrogen export
- ✓ Amount of Brine disposal for the desalination process.

The Levelized Cost of Hydrogen (LCOH) is used to determine the average cost to produce one kilogram of hydrogen over the lifetime of a project. It helps investors and decision-makers compare different hydrogen production technologies and assess their economic feasibility. Below is the formula that will be utilized to this variable:

$$LCOH = \frac{Annualized\ CAPEX + annual\ OPEX}{annual\ amount\ of\ GH2\ produced}$$

$$Annualized\ CAPEX = Total\ CAPEX\ * Annuity$$

$$Annuity = r * \frac{(1+r)^n}{(1+r)^n - 1}, \qquad r\ - depreciation\ rate$$

n -Project lifetime in years (Tanyi et al., 2024) ((Leiblein et al., 2021)

This chapter has provided a comprehensive overview of the methodologies employed to evaluate the economic and environmental implications of a green hydrogen plant in Dakar, Senegal, aimed at exporting hydrogen to Germany. Dakar's selection as the study area has proven to be strategically sound, given its geographical advantages, including access to seawater, consistent wind patterns, and proximity to a major port. These factors enhance the project's logistical efficiency, reducing costs and environmental impacts associated with long-distance shipping to Germany. The use of AnyLogic software has enabled a multimethod simulation approach, effectively modelling the interconnected processes of wind energy generation with key technologies, such as the Proton Exchange Membrane (PEM) electrolyser, reverse osmosis desalination, and high-pressure composite storage tanks, which have been justified through their technical efficiency, economic viability, and environmental sustainability. The PEM electrolyser's ability to produce high-purity hydrogen with renewable energy, the energy-efficient reverse osmosis process for desalination, and the durable, lightweight carbon fiber-reinforced polymer tanks for storage collectively ensure that the project aligns with global decarbonization goals while remaining economically competitive for export to Germany.

The methodologies and technological choices outlined in this chapter provide a solid framework for assessing the economic and environmental implications of green hydrogen production in Dakar. The use of AnyLogic has illuminated critical insights into system optimization, while the strategic selection of technologies and the study area ensures alignment with both local and global sustainability objectives. This chapter sets the stage for subsequent chapter in analysing and discussing, offering a foundation for evaluating the project's scalability, long-term economic benefits, and contributions to global energy transitions, particularly in supporting Germany’s demand for clean hydrogen.

4: Chapter 3: Results and discussion

The analysis assesses the economic feasibility, environmental sustainability, and technical reliability of this initiative, building on the methodology outlined in Chapter 3. The global shift toward renewable energy sources has positioned green hydrogen as a key element in decarbonizing industrial sectors, especially through production in regions rich in renewable resources. This chapter offers a comprehensive viability analysis of the proposed green hydrogen production project in Dakar, Senegal, designed to r display project quantities in daily, monthly, and yearly quantities using a desalination plant and electrolysers powered by wind energy. The main goal of this chapter is to determine whether the Dakar project can achieve a competitive Levelized Cost of Hydrogen (LCOH) while meeting environmental targets in the form of reduced CO_2 emissions . The chapter involves a detailed review of capital and operational costs (CAPEX and OPEX), as well as revenue potential for Senegal from a 10% export tax, and the use of cryogenic tanks for hydrogen storage. Organized into sections, the analysis begins with an economic evaluation, followed by an environmental assessment, a technical feasibility review, and a conclusion.

4.1: Economic Evaluation of Hydrogen

The economic evaluation of the Dakar green hydrogen project reveals a promising yet challenging financial landscape, underpinned by a Levelized Cost of Hydrogen (LCOH) of 9.97 euros/kg, calculated based on a total CAPEX of €158.86 million and an annual OPEX of €6.9 million. Based on a discount rate of 6% with an annuity of 0.0872 over a 20-year lifetime, this LCOH, derived from an annualized CAPEX & OPEX and divided by hydrogen production of 2,079,491 kg/year, indicates a cost structure that is competitive with global green hydrogen benchmarks (5–10 euros/kg). Revenues gained by the Senegal government through a 10 % export tax on gross sales amount to €2.73 million annually, supplemented by indirect income from jobs, estimated at 0.383 million per year, totalling € 3.11 million per year. However, the high CAPEX and OPEX, driven by desalination (€29.68 million CAPEX), renewable energy (wind CAPEX 67.5 million), and electrolyzer costs (€50.06 million CAPEX), highlight the need for cost optimization in the technologies. Additionally, the annual sales revenue is projected at €20.73 million, the project contributes €2.1 million per year in export taxes to Senegal, and generates €383,000 in indirect job revenue annually, supporting the creation of 45 to 100 professional jobs.

Additionally, the proximity of the LCOH to the upper limit of the global benchmarks demonstrates the project's technical and economic feasibility. Still, it may face pressures to reduce costs further through technological efficiencies, economies of scale, government subsidies, or policy incentives to ensure competitiveness in the global hydrogen market.

Table 2 : Revenue and Cost Metrics

Metrics	Value (€)	Unit	Comments
LCOH	9.97	€ per kg	Discount rate 6% Lifetime 20-year project
Annual Hydrogen Sales	20.73 million	€ per year	2,079,491 kg × 9.97 €/kg
Senegal Export Tax (10%)	2.1 million	€ per year	Direct revenues
Indirect Job Revenue (Jobs)	0.383 million	€ per year	45 - 100 professional jobs created

Table 3: Breakdown of total CAPEX (€158.86 million) across components.

Components	CAPEX (€M)	Annual OPEX (€M)	Characteristics
Wind Energy System	67.5 million	1.85 million	45 MW capacity
Desalination Plant	29.68 million	1.5 million	52447 m³/day (Reverse Osmosis)
Electrolysers	50.06 million	1 million	Nel-Hydrogen, 2x10 MW (Proton Exchange Membrane)
Pumping Pipe System	0.1 million	0.002 million	500 meters (10 rows with 50 meters each connecting from the seawater to the desalination plant) of high-density polyethylene (HDPE) pipe

Storage Tanks	0.57 million	0.0114 million	57 cryogenic liquid hydrogen storage tanks.Monthly shipping
Buildings	3 million	0.06 million	Construction of two buildings, one unit for electrolysers, one unit for desalination plants (Reverse osmosis)
Land	1.2 million	0.024	The land required for the installation of wind and the two buildings was 1,125,000 square meters.
Technologies and Battery Storage Installation + Training and Labour force	6.8 million	0.383 million	Expert Installation of technologies, a labour force training program, and ongoing monitoring, to produce green hydrogen.
Transportation (H2 Shipment)		2.1 million	Monthly shipments of green hydrogen produced

4.2: Percentage proportion of total CAPEX across components

The capital expenditure (CAPEX) analysis shows that the wind energy system makes up the largest part of the investment at 42.47%, followed by electrolysers at 31.50%, and the desalination plant at 18.68%, together accounting for over 92% of the total CAPEX. The other components, installation and training, buildings, land, storage tanks, and the pumping pipe system, collectively represent a small share of less than 8%, indicating that most of the capital investment is focused on the core renewable energy and hydrogen production infrastructure.

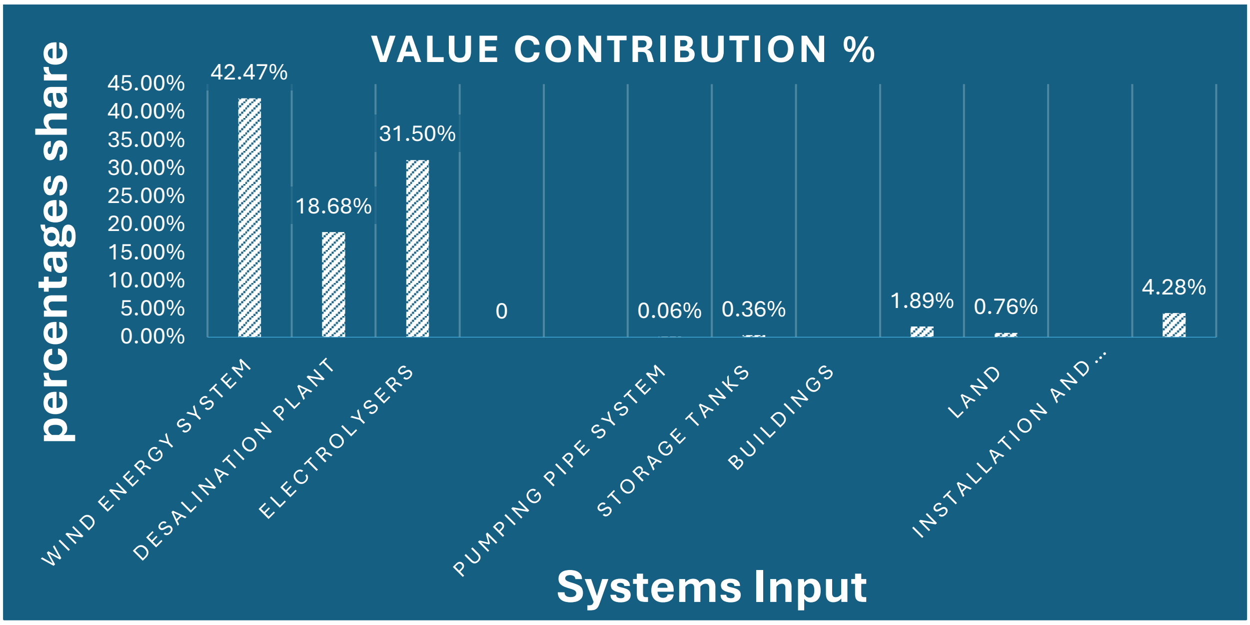

Figure 13: CAPEX breakdown by infrastructure component for the simulated model

4.3: Environmental Assessment

The environmental assessment of the Dakar green hydrogen project highlights significant ecological benefits and effective mitigation strategies for its export to Germany. The replacement of fossil fuel-based hydrogen in Germany's steel industry with green hydrogen production results in substantial CO_2 savings. This reduction supports Germany's CO_2 reduction target by 2030, enhancing the project's environmental credentials**.**

4.4: Environmental Impact Metrics

The simulation highlights the environmental benefits of replacing fossil fuel-based methods with hydrogen in the steel industry. For every 1 kilogram of hydrogen used, 25 kg of CO_2 will be saved (Albrecht, Uwe Ball, Michael Bünger et al., 2022). This has been projected in daily terms in the model and aggregated into yearly terms through the full runtime of the simulation. The graph is organized into three timeframes: daily, monthly, and yearly, each displaying the specific amount of CO_2 reduced by the substation of the hydrogen production pathway. Daily CO_2savings amount to 142,800 kilograms. Monthly, the reduction totals 4,284,650 kilograms, calculated by multiplying the daily savings by approximately 30 days. Annually, the total is 51,987,275 kilograms, obtained through the simulation's total runtime of 365 days . This data pertains to the German steel industry, where green hydrogen replaces a process that has an emissions factor of about 25 kg of CO_2 per kg of hydrogen. (Steel Watch. 2025).

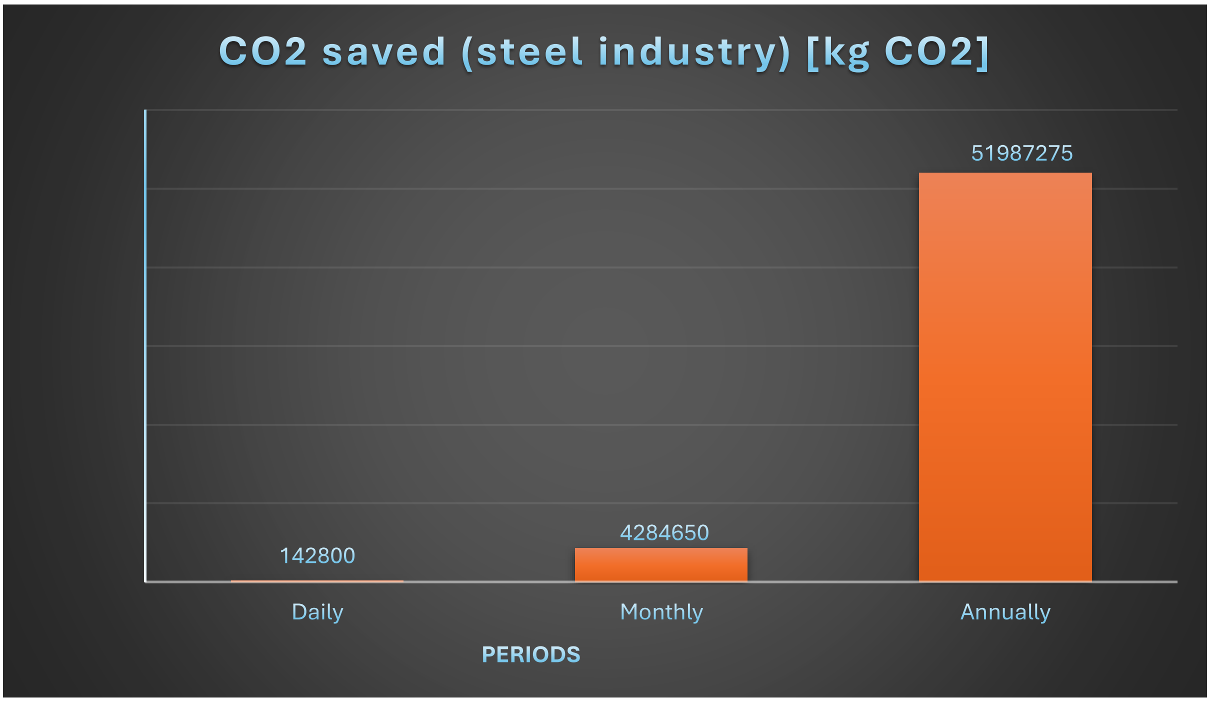

Figure 14 : Amount of CO_2 saved in German steel industry from using green hydrogen

4.5: Brine Discharge

The daily amount of water pumped from the seawater to the desalination process is estimated at 104,895 m³. This involves the MECO Water Systems machine, which produces 52,447 m³ of fresh water daily and generates 52,447 m³ of brine daily. According to (eaiwater.com) and (www.amtaorg.com), the recovery process yields 50% fresh water and 50% brine discharge. This brine is planned to be managed through a controlled disposal system by releasing it into the middle sea via a 2 km offshore diffuser pipeline, diluting it to below 2% salinity (from 7% in concentrated brine) to avoid harming Senegal's coastal ecosystem. It will be monitored by real-time sensors to ensure compliance with local environmental standards. In addition, regular environmental impact assessments will be conducted to evaluate the long-term effects of brine disposal, and adaptive management strategies will be implemented as needed to address any emerging ecological concerns. These measures, along with the cryogenic storage tanks' low permeation rate (0.1% annually), minimize ecological impacts and position the project as a sustainable operation.

4.6: Assessment of brine discharge

The simulation result outlines the brine discharge associated with the desalination process in green hydrogen production. On a daily basis, the system releases approximately 52,447.5 cubic meters (m³) of brine for 10 hours of operation. This daily discharge scales up to 1,153,834 m³ every month (22 working days), indicating the consistent and large-scale operation of the desalination units. Annually, the total brine discharge reaches a significant volume of 13,846,008 m^3. These figures highlight the environmental implications of such operations and underscore the need for sustainable brine management strategies to mitigate potential impacts on marine ecosystems.

4.7: Technical Assessment.

This section provides a detailed technical input assessment focusing on the 15 MW MECO reverse osmosis (RO) desalination process, which produces fresh water; the 20 MW Nel-Hydrogen Proton Exchange Membrane electrolyzer system for green hydrogen production; and the Siemens Gamesa 45 MW wind energy system, which powers these processes. The main goal of this technical assessment is to determine the operational feasibility of the project, ensuring that the water output from the reverse osmosis plant, the hydrogen output from the electrolysers, and the energy supplied by the wind system are all feasible. The section is divided into subsections that evaluate the performance of each component.

4.8: Technical input for the Wind energy

The table presents detailed technical inputs for a wind energy project. The wind farm consists of nine individual wind turbines, each with a rated capacity of 5 megawatts, resulting in a total installed capacity of 45 megawatts. The capacity factor, which represents the actual output as a percentage of the maximum possible output, is given as 41.7%, indicating the plant operates at nearly half of its full capacity on average due to varying wind conditions. The average wind speed at the site is 4.9 meters per second, which is a crucial parameter for determining the efficiency and viability of wind energy generation. Based on these factors, the total energy generated by the wind farm each day is estimated to be 450 megawatt-hours. This information highlights the scale of the project, its expected performance, and the influence of local wind conditions on energy output. These technical parameters are essential for assessing the economic and environmental benefits of the wind energy installation.

This section provides a detailed technical input assessment focusing on the 15 MW MECO reverse osmosis (RO) desalination process, which produces fresh water; the 20 MW Nel-Hydrogen Proton Exchange Membrane electrolyzer system for green hydrogen production; and the Siemens Gamesa 45 MW wind energy system, which powers these processes. The main goal of this technical assessment is to determine the operational feasibility of the project, ensuring that the water output from the reverse osmosis plant, the hydrogen output from the electrolysers, and the energy supplied by the wind system are all feasible. The section is divided into subsections that evaluate the performance of each component.

Table 4: Wind Technical Input

Parameters	Value base
Total wind turbines	9
Capacity per turbine	5 MW
Total capacity installed	45 MW
Capacity factor	41.7%
Wind speeds	4.9 m/s
Energy generated per day	450 MWh

4.9: Projection of energy-generating

The graph shows an estimate of energy generation over different periods for the wind energy system. On a daily basis, the system is expected to produce 450 megawatt-hours of electricity. When this daily output is projected over a month, the total energy generated reaches 13,500 megawatt-hours, demonstrating the capacity for sustained production. Over the year, the annual energy generation is estimated at 164,250 megawatt-hours. These values, derived from multiplying the total capacity installed, the time of operation, and the capacity factor, and presented in megawatt-hours, highlight the significant contribution of the wind energy system to the overall electricity supply and reflect its performance over short and long operational periods.

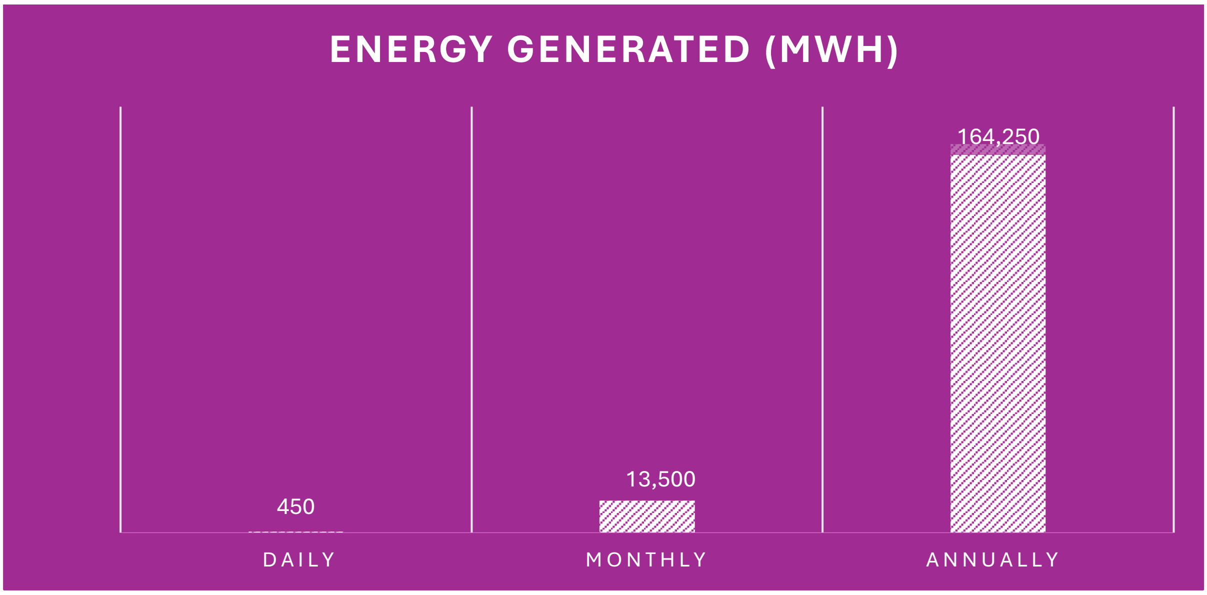

Figure 15: Energy generated in MWhs in the simulated model

4.10: Technical input for the Electrolyser

The table shows the technical input requirements for a 20-megawatt (MW) electrolyzer system. The PEM electrolysis process uses 51.2 kWhs to output 1 kg of hydrogen. the total energy consumption or output is calculated at 292.5 megawatt-hours (MWh). This figure is obtained by multiplying the total energy generated from wind per day, 450 MWh, by the 65% allocation for hydrogen production, resulting in surplus energy that can be stored in a lithium battery for later use in case of energy intermittencies. This emphasizes the system's significant energy demand and output potential, highlighting its ability to support large-scale hydrogen production during extended operation. Producing one kilogram of hydrogen requires nine liters of water. to support this level of production, the system requires approximately 52,447.5 liters of water per day. This water demand reflects the essential role of water as a raw material in the electrolysis process, where it is split into hydrogen and oxygen. Efficient water management is therefore critical to the sustainable operation of this hydrogen production facility.

Table 5: Technical input for the Electrolyser

Parameters	Value base
Capacity install	20 MW
PEM electrolyser energy use	51.2 kWh/kg
Energy shares for operation	292.5 MWh
Water needed per kg of hydrogen	9 liters
Water needed per day	52,447.5 liters

4.11:Projection of Green Hydrogen Production

The graph outlines the estimated production levels of green hydrogen across different periods. Daily, the system is expected to generate approximately 5,712 kilograms of hydrogen. When scaled to a monthly estimate, this production reaches around 171,386 kilograms. Over the course of a year, the total estimated hydrogen production amounts to 2,079,491 kilograms. These values reflect a consistent and large-scale hydrogen output, underscoring the project's capacity to contribute significantly to renewable energy supply through green hydrogen generation.

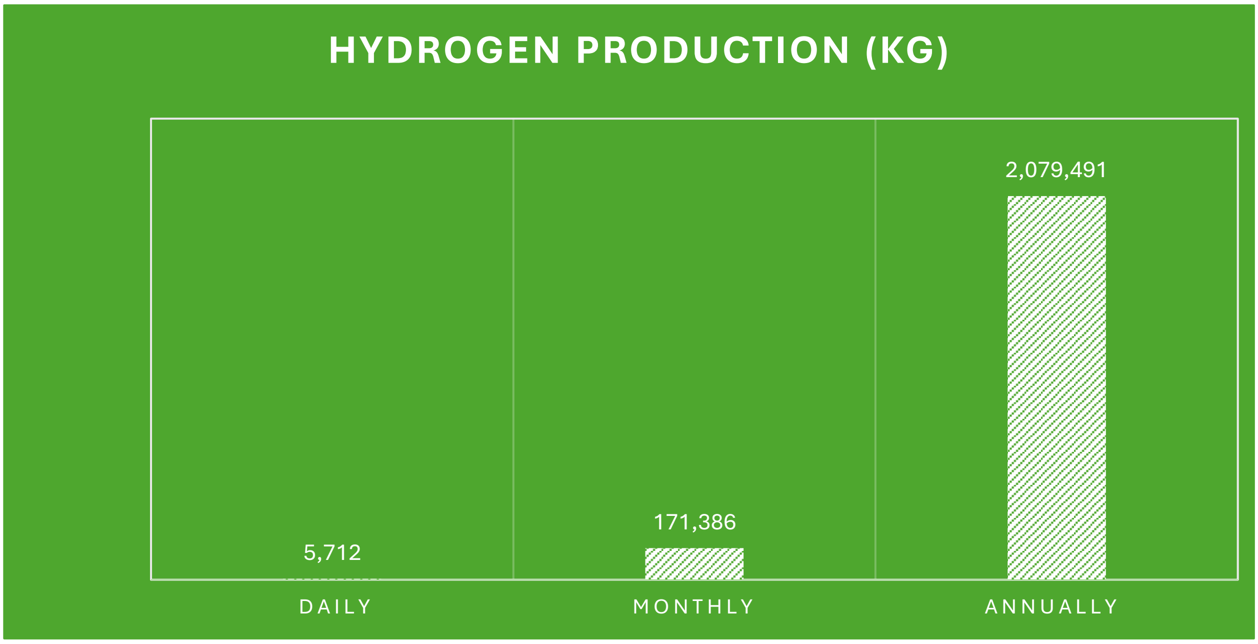

Figure 16 : Hydrogen Production in kilograms from the simulated model

4.12:Technical input for the reverse osmosis desalination plants

The table provides key technical parameters for a reverse osmosis (RO) desalination plant with an attachment of the pipes, pumping water from the sea to the desalination plant. The plant is designed with an installed capacity of 15 megawatts (MW), indicating the maximum electrical power it can utilize during operation. The RO system is characterized by an energy consumption rate of 3 kilowatt-hours per cubic meter (kWh/m³) of water produced, which is typical for efficient modern desalination processes. Over a standard 10-hour operational period, the total energy allocated for the plant is 157.5 megawatt-hours (MWh). This figure is derived by multiplying the total energy generated from wind per day, 450 MWh, by the 35% allocation of the desalination plant, reflecting the energy used for desalinating water.

Table 6: Technical input for the reverse osmosis

Capacity	RO Systems consumption per freshwater produced.	Energy used for 10 hours of operation.
15 MW	3 kWh/m³	157.5 MWh

4.13: Output of Freshwater

The graph estimates freshwater processing volumes at the desalination plant over various periods. The plant is expected to process 52,447.5 cubic meters of freshwater daily. When these daily amounts are summed over a month (22 working days), the total significantly increases to 1,153,845 cubic meters, showing the plant's strong capacity for continuous operation. Extending this to a year, the total freshwater processed reaches 13,846,140 cubic meters. These figures, expressed in cubic meters (m^3), clearly demonstrate the plant's potential output and its ability to supply large quantities of freshwater to meet ongoing demand.

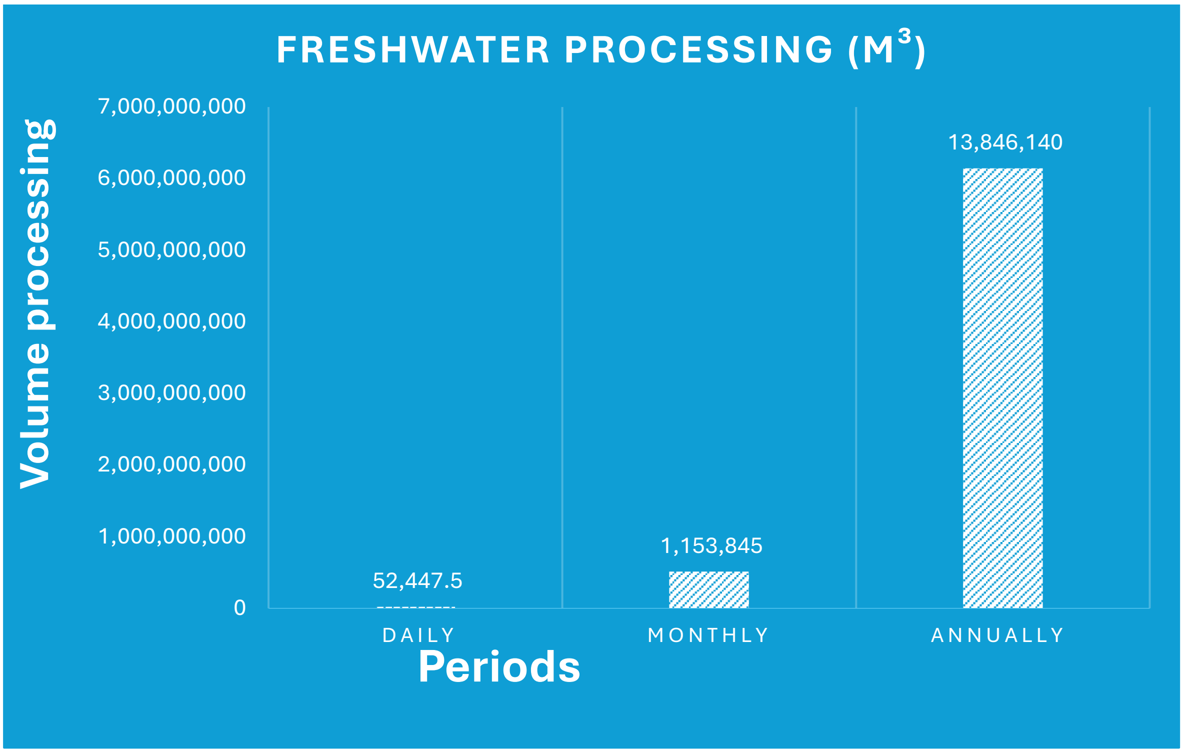

Figure 17: Desalinated water in m^3 in the simulated model

4.14: Positioning Dakar as a competitive green hydrogen export hub

The cost of the Levelized Cost of Hydrogen (LCOH) in this study is considered competitive primarily because it falls within the 5–10 USD/kg range that the International Renewable Energy Agency (IRENA, 2020) and the International Energy Agency (IEA, 2022) project as the global benchmark for green hydrogen.

Grey hydrogen produced via steam methane reforming (SMR) is significantly cheaper, typically in the range of 2–5 USD/kg (IRENA, 2022). This gap highlights that, under purely market conditions, green hydrogen is not yet cost-competitive with grey hydrogen. However, cost parity can be achieved politically through carbon pricing, subsidies, and regulatory mechanisms such as the EU's Carbon Border Adjustment Mechanism (European Commission, 2020), which are explicitly designed to internalize the carbon cost of fossil-based hydrogen

It is also important to recognize that hydrogen is not the only decarbonization option. In many sectors, direct electrification via renewables may remain more efficient and cost-effective than hydrogen (IEA, 2021). However, in hard-to-abate sectors such as steel, shipping, and fertilizer production, hydrogen is indispensable (BNEF, 2020).

Senegal benefits from high wind resource availability, as demonstrated by projects such as the Taiba N'Diaye wind farm, which enables low-cost renewable electricity generation, a critical factor since electricity accounts for the largest share of hydrogen production costs.

The integration of desalination systems ensures a reliable water supply without substantially raising costs, due to advances in reverse osmosis technology. Moreover, the results support the argument that Dakar could emerge not only as a regional renewable energy hub but also as a credible supplier for Germany's import-driven hydrogen market, provided that supportive policies and infrastructure investments are implemented. Thus, the study not only validates earlier global assessments of cost-competitiveness but also fills a knowledge gap by demonstrating how water-scarce regions can achieve viable hydrogen export through desalination integration.

Additionally, the export dimension strengthens competitiveness, given Germany's ambitious hydrogen import targets under its National Hydrogen Strategy, Dakar's proximity compared to Middle Eastern suppliers reduces transport and logistics costs. Collectively, these factors explain why the modeled LCOH in this study is competitive relative to international benchmarks and why Dakar presents a favorable case for green hydrogen exports.

4.15: Infrastructure Planning Analysis

The infrastructure for the electrolyser units and the desalination plant is clearly illustrated through both 2D and 3D visualizations (figures 19,20, and 21). The 2D site plan provides a top-down view, revealing the logical arrangement of each facility component: water is first drawn from the intake near the shoreline and directed to the desalination plant, which is strategically located close to large storage tanks for easy handling of both raw and processed water. Adjacent to the desalination plant, the electrolysis block sits centrally, allowing efficient transfer of purified water into the electrolyser units for hydrogen and oxygen production.

Separate storage tanks are designated for the hydrogen production, while water pipelines and connections ensure safe retrieval of seawater for the desalination plant. The shipping bay and storage area are positioned for convenient access, enabling straightforward loading and distribution of hydrogen for export.

Moving to the 3D renderings, these images provide a clear view of the site's physical scale and how it fits within the environment. The buildings feature clean, practical architectural designs, allowing enough space for operations and maintenance. The desalination and electrolysis facilities look sturdy and industrial, with cylindrical tanks for hydrogen storage nearby. The layout minimizes transport distances, helping to decrease energy losses and improve efficiency. Being close to the coast means the water intake pipeline is short, and wind turbines in the background highlight the renewable energy source for the facility. The 3D views also show infrastructure such as access roads, parking areas, and shipping lanes, which are vital for smooth logistics and staff movement. The landscape design, including green open spaces and organized circulation, enhances safety and makes operations easier. The wind turbines further emphasize the integration of green energy into hydrogen production. The combination of 2D and 3D visuals illustrates a well-organized, efficient, and environmentally conscious approach to siting and building the electrolyzer and desalination plant infrastructure.

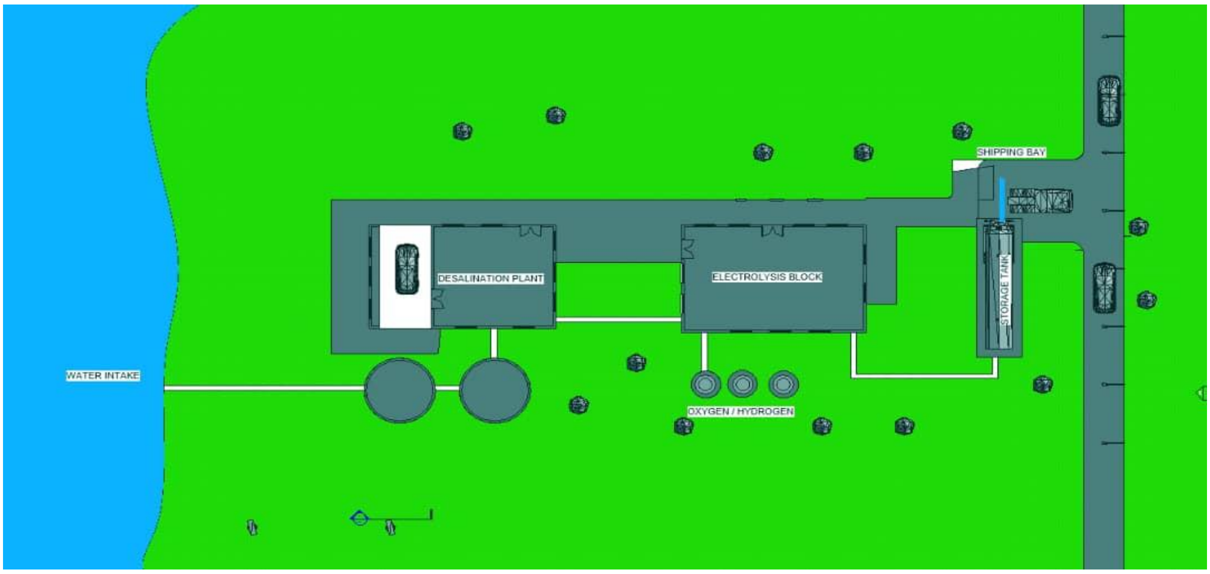

Figure 18: 2D building plan view (own rendering in Revit Software)

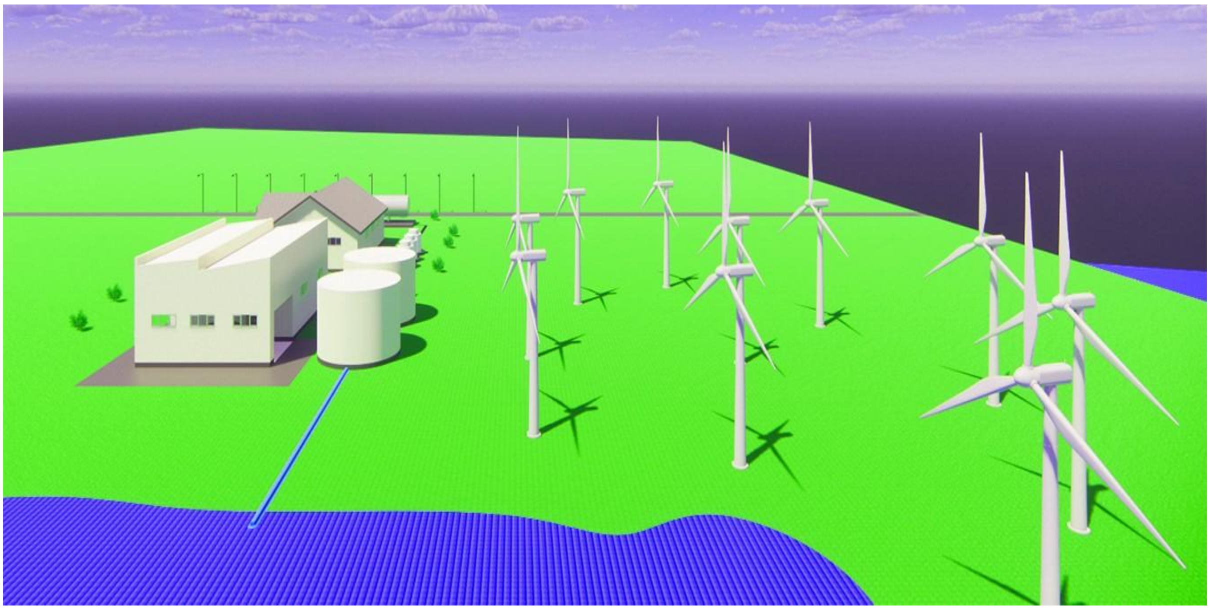

Figure 19: 3D back building plan view (own rendering in Revit Software)

Figure 20: *3D front building plan view (own rendering)*

The Dakar green hydrogen project demonstrates strong feasibility from a technical, environmental, and economic perspective. The project showcases a comprehensive "cradle-to-gate" hydrogen production approach, spanning from seawater intake and desalination to hydrogen production through electrolysis powered by wind energy, and finally, to storage and export. The evaluation reveals a Levelized Cost of Hydrogen (LCOH) of 9.97 euros/kg, competitive within the global range of 5–10 € /kg. This integrated value chain is supported by a robust infrastructure layout and innovative technologies.

With a total installed capacity of 45 MW of wind energy generating approximately 164,250 MWh annually, the system provides more than enough power to sustain operations. The electrolyser system, with an allocation of 292.5 MWh for operation and storage over a 10-hour shift, uses 65% of the total wind energy, leaving 35% available for the desalination process. This allocation allows the desalination plant to produce roughly 52,447 m^3 of freshwater daily. While approximately 51,412.5 liters of water per day are needed for hydrogen production, the volume of freshwater generated slightly exceeds this requirement, indicating a substantial surplus that can be stored and redirected to local communities, enhancing water resilience in the region.

The next section of the discussion will delve into a comprehensive focus on the thesis's overall conclusion themes, recommendations, and a forward-looking perspective on the broader impact on sustainable development goals.

4.16: Conclusion and Perspectives

Conclusion

Integrating green hydrogen production, desalination, and renewable energy, especially wind power, offers a promising solution to water scarcity, energy transition, and climate change challenges. The thesis fills an important gap, specifically the lack of prior studies on similar green hydrogen projects in West Africa that combine models of wind energy, desalination, and hydrogen export infrastructure. It provides a pioneering analysis tailored to the region's unique context. Despite Germany's interest in African hydrogen (e.g., Scholz's 2022 visit to Senegal), the thesis's originality lies in offering a framework to assess economic viability, environmental impact, and technical feasibility in this understudied area. Case studies such as the Dolphyn project in the UK, Hyphen in Namibia, an Algerian desalination project, and Senegal's Taiba N'Diaye wind farm demonstrate the feasibility and economic potential of combining desalination with electrolysis powered by renewable sources in the region.

The study emphasizes the importance of policy frameworks, such as the ECOWAS Green Hydrogen Strategy, in facilitating large-scale deployment through institutional support, financing, and regional collaboration. It also outlines the socio-economic and environmental benefits of such projects, including job creation, carbon reduction, and resource resilience, while addressing challenges like infrastructure deficits, brine disposal, and regulatory barriers.

A detailed overview of the methodologies and technologies employed and the strategic selection of Dakar as the study area, the use of AnyLogic simulation software, and the implementation of technologies such as Proton Exchange Membrane electrolysis, reverse osmosis desalination, and cryogenic hydrogen storage tanks have been justified based on technical efficiency, economic viability, and environmental sustainability. By simulating the interconnected processes of wind energy generation and hydrogen production, the study has established a solid foundation for assessing the economic and environmental impacts of green hydrogen production in Dakar. The methodologies and technological choices outlined in the research offer insights into system optimization and ensure alignment with both local and global sustainability goals.

The comprehensive analysis of the economic, environmental, and technical aspects of the proposed green hydrogen project in Dakar, Senegal, highlights the project's promising feasibility. The Levelized Cost of Hydrogen (LCOH) competes with global benchmarks, which demonstrates that the project could become a significant export revenue stream for Senegal. The detailed assessment of capital expenditure (CAPEX) and operational costs (OPEX) underscores the financial landscape, emphasizing the need for cost optimization and technological efficiencies. The environmental assessment demonstrates significant CO_2 savings through the production of green hydrogen, supporting Germany's decarbonization goals. The technical evaluation of wind energy, electrolysis, and desalination systems indicates operational feasibility and scalability, with ample energy generation and freshwater processing capacities. The infrastructure planning analysis, visualized through 2D and 3D renderings, illustrates a well-organized and environmentally conscious layout for the facilities, emphasizing efficiency and sustainability. The project's holistic approach, from seawater intake to hydrogen export, showcases a robust value chain supported by innovative technologies and infrastructure.

4.17:Key Themes

Integrated Sustainability: The idea of integrated sustainability is key to the green hydrogen project in Dakar, as it combines three vital areas: renewable energy production, freshwater generation through desalination, and climate change mitigation. By using wind energy to power desalination and electrolysis, the system runs entirely on clean energy, removing greenhouse gas emissions linked to fossil fuel-based hydrogen production. Additionally, the desalinated water not only supports the electrolyzer but also offers spillover benefits for the local water supply, illustrating a co-benefit model that promotes both environmental protection and social development. This integrated approach fosters economic growth through green industrial activity while respecting ecological limits, aligning with multiple Sustainable Development Goals.

International Partnership: This project highlights the importance of international cooperation in tackling global climate and energy issues. The partnership between Senegal and Germany, where Senegal provides the geographic and renewable resource advantages and Germany offers technology and financing, demonstrates a mutually beneficial model of collaboration. This exchange not only speeds up energy transition efforts worldwide but also strengthens diplomatic and economic relations between the two countries.

Innovation in resource-scarce environments: The deployment of desalination-powered hydrogen production in Dakar marks a breakthrough in applying advanced technology to address resource limitations. Coastal arid regions like Dakar often face freshwater shortages, which hinder many industrial processes, including green hydrogen production. By integrating seawater desalination with renewable-powered electrolysis, this project shows how innovation can overcome natural constraints and open new development opportunities. The modular and scalable nature of this solution makes it highly replicable in similar environments across Africa, the Middle East, and other coastal zones, paving the way for wider adoption of green hydrogen technologies in the Global South.

4.18: Forward-Looking Perspective & Sustainable Development Goal (SDG)

A critical examination of the limitations of the selected approach is essential. First, the economic modeling relies on secondary data, rather than site-specific field measurements, which introduces uncertainty in CAPEX, OPEX, and efficiency assumptions. Second, the simulation assumes stable renewable energy input and does not fully account for intermittencies or potential grid integration challenges, which could raise costs or reduce hydrogen output. Third, the environmental assessment, while quantifying avoided CO_2 emissions, only accounts for green hydrogen replacing fossil fuels in the steel industry and the impacts of large-scale desalination plants in the discharge of brine. Finally, the policy analysis assumes Germany's hydrogen demand and supportive frameworks will remain stable, yet geopolitical or market shifts could alter export prospects.

SDG 7 (Affordable and Clean Energy): The Dakar green hydrogen project directly advances the objective of SDG 7 by facilitating the large-scale deployment of renewable energy technologies. By converting wind-powered electricity into hydrogen through electrolysis, the project not only diversifies Senegal's natural resources portfolio but also contributes to making clean energy. This transition helps to reduce dependence on fossil fuels and enhances energy sovereignty.

SDG 6 (Clean Water and Sanitation): Although the project's primary goal is hydrogen production, its integration with desalination systems yields an important co-benefit aligned with SDG 6. The reverse osmosis desalination technology used to supply freshwater for electrolysis also generates surplus potable water. This excess can be redirected to serve local communities, thereby addressing water scarcity challenges in coastal Dakar and improving long-term water resilience.

SDG 8 (Decent Work and Economic Growth): The construction, operation, and maintenance of wind farms, desalination units, electrolysers, and export facilities create a diverse range of skilled and semi-skilled employment opportunities. From engineering and technical jobs to logistics and environmental management roles, the project supports inclusive economic development. Moreover, through capacity-building initiatives, it promotes knowledge-based employment, thereby enhancing local productivity and aligning with the objectives of SDG 8.

SDG 13 (Climate Action): By replacing fossil-based hydrogen and contributing to decarbonization in sectors such as steel production, the project significantly reduces carbon dioxide emissions. This aligns directly with SDG 13 by supporting climate mitigation through cleaner industrial processes and the expansion of low-carbon energy infrastructure. The project's contribution to global emission reduction targets reinforces its role as a climate-smart investment**.**

SDG 17 (Partnerships for the Goals): This initiative exemplifies the principles of SDG 17 through its cross-border collaboration between Senegal and Germany. The project demonstrates how joint ventures, knowledge exchange, and financial commitments from the Global North can support clean energy transitions in the Global South. These partnerships not only accelerate technology deployment but also establish frameworks for long-term cooperation in sustainable development and climate resilience.

While the current analysis thoroughly explores the economic, technical, and environmental dimensions of green hydrogen production in Dakar, a comprehensive understanding of the project's long-term viability also necessitates a deeper exploration of its social implications. Future studies should investigate how local communities perceive and interact with the project, especially in terms of land use, water access, and employment distribution. Understanding gender dynamics, equity in job creation, community acceptance, and potential displacement effects is critical to ensuring the project is socially inclusive and ethically grounded. Additionally, social studies could help uncover potential conflicts, cultural considerations, and mechanisms for stakeholder participation, all of which are essential for fostering long-term local support and sustainability. These insights would strengthen policy frameworks and guide socially responsible implementation, aligning the project more fully with just transition principles and Sustainable Development Goals (particularly SDG 5 on gender equality and SDG 10 on reduced inequalities).

4.19: Recommendations

Policy Incentives: To enhance the financial viability and long-term sustainability of the Dakar green hydrogen export project, it is strongly recommended that both Senegal and Germany establish binding long-term hydrogen purchase agreements. Such contracts would create revenue certainty and reduce investor risk, thereby attracting private capital. Additionally, fiscal incentives, including tax holidays, import duty exemptions on renewable energy equipment, and production subsidies, should be instituted to lower upfront and operational costs. These policy tools would improve the project's return on investment and make it more competitive in the global hydrogen market.

Capacity Building: The success and longevity of this complex green hydrogen infrastructure depend heavily on the availability of skilled human capital. Therefore, targeted capacity-building initiatives must be implemented, focusing on technical education and vocational training for local engineers, technicians, and operators. Establishing partnerships with academic institutions and international hydrogen technology providers can facilitate knowledge transfer. In the long run, this will ensure local ownership, reduce reliance on foreign expertise, and foster a sustainable green technology workforce in Senegal

Sustainable Water Management: Given that the project involves large-scale seawater desalination, environmental stewardship is essential. The government and stakeholders must mandate continuous environmental monitoring of brine discharge and its effects on marine biodiversity. This includes setting regulatory thresholds for salinity, temperature, and chemical additives in the discharged brine. Developing mitigation measures, such as brine dilution systems or discharge dispersal modeling, will help minimize ecological degradation and support the project's compliance with international environmental standards

Cost Reduction Strategies: To drive down the Levelized Cost of Hydrogen (LCOH), innovation should be actively supported in both electrolysis and desalination technologies. This may include adopting next-generation high-efficiency PEM electrolyzers, integrating variable renewable energy sources, and deploying energy recovery devices in the desalination process. Public and private sector investment in research and development, pilot projects, and digital solutions can help identify scalable improvements that reduce capital and operational expenses over time, making hydrogen exports more affordable**.**

Carbon Trading Mechanism: Senegal has an opportunity to further capitalize on the environmental benefits of green hydrogen by participating in global carbon markets. By quantifying the emissions avoided through renewable hydrogen production (compared to conventional hydrogen or fossil fuel usage), the project can generate verified carbon credits. These credits can be sold under mechanisms such as the Voluntary Carbon Market or Article 6 of the Paris Agreement, providing an additional revenue stream and enhancing the economic case for investment**.**

Bibliography

Abasolo Farfán, I., Bonacic Castro, C., Garrido Lazo, R., Fernández Gil, A., San Martin

Albrecht, U., Ball, M., Bünger, U., Kutz, C., & Michalski, J. (2022). Emissionsfreie Stahlerzeugung – Metastudie zu den technischen, technologischen und wirtschaftlichen Parametern für die Umstellung der deutschen Stahlindustrie auf eine emissionsarme Stahlproduktion auf Basis von grünem Wasserstoff. *Deutscher Wasserstoff Und Brennstoffzellen-Verband (DWV)*. Retrieved from www.lbst.de

Hormazábal, M., Rodríguez Machuca, P., Serafini, D., Rodríguez Soto, A., Mena-Carrasco, M., Valdes, J., & Masip Macia, Y. (2024). Socio-environmental and technical factors assessment of photovoltaic hydrogen production in Antofagasta, Chile.

Al-Mutaz, I. S., & Al-Ahmed, M. I. (1989). Evaluation of solar powered desalination processes. In *Desalination* (Vol. 73).

Al-Zahrani, A., Orfi, J., Al-Suhaibani, Z., Salim, B., & Al-Ansary, H. (2012). Thermodynamic analysis of a Reverse Osmosis desalination unit with energy recovery system.

Andrianne, J., & Alardin, F. (2004). Desalination site selection on North-African coasts.

Basiony, M. G., Nada, S., Mori, S., & Hassan, H. (2025). 4E valuation of standalone hybrid renewable energies system for building freshwater and electricity demand using green hydrogen yield and water desalination.

Beswick, R. R., Oliveira, A. M., & Yan, Y. (2021). Does the Green Hydrogen Economy Have a Water Problem?

Birhanu, M. K., Tsai, M. C., Chen, C. T., Kahsay, A. W., Zeleke, T. S., Ibrahim, K. B., Huang, C. J., Liao, Y. F., Su, W. N., & Hwang, B. J. (2020). Electrocatalytic reduction of carbon dioxide on gold–copper bimetallic nanoparticles:

Borgomeo, E., Mortazavi-Naeini, M., Hall, J. W., & Guillod, B. P. (2018). Risk, Robustness and Water Resources Planning Under Uncertainty

Borshchev, A., Karpov, Y., & Kharitonov, V. (2002). Distributed simulation of hybrid systems with AnyLogic and HLA. In *Future Generation Computer Systems* (Vol. 18).

Bhattacharya, S., & Kammen, D. (2023). greener is cheaper: an example from offshore wind farms. pp 30–46.

Blohm, M., & Dettner, F. (2023). Green hydrogen production: Integrating environmental and social criteria to ensure sustainability.

Cammalleri, C., Naumann, G., Mentaschi, L., Formetta, G., Forzieri, G., Gosling, S., Bisselink, B., Roo, De A., & Feyen, L. (2020). Global warming and drought impacts in the EU.

Caldera, U., & Breyer, C. (2017). Learning Curve for Seawater Reverse Osmosis Desalination Plants:

Clean Hydrogen Partnership. (2024). Electrolyser Cost. Retrieved from https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/production-trade-and-cost/electrolyser-cost

Dagnachew, A. G., & Solf, S. (2024). The Green Hydrogen Dilemma The risks, trade-offs, and co-benefits of a green hydrogen economy in low-and middle-income countries
Dakar to Hamburg by Air freight, Cargo ship or Road - Fluent Cargo. Retrieved June 6, 2025, from https://www.fluentcargo.com/routes/dakar-sn/hamburg-de

De Roo, A., Trichakis, I., Bisselink, B., Gelati, E., Pistocchi, A., & Gawlik, B. (2021). The Water-Energy-Food-Ecosystem Nexus in the Mediterranean:

Desalination - European Commission. Retrieved June 10, 2025, from https://blue-economy-observatory.ec.europa.eu/eu-blue-economy-sectors/desalination_en

Ecowas green hydrogen policy and strategy framework. Retrieved June 6, 2025 from www.ecreee.orgk

Electrolyser cost | European Hydrogen Observatory. Retrieved May 3, 2025, from https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/production-trade-and-cost/electrolyser-cost

Elsaid, K., Sayed, E. T., Abdelkareem, M. A., Baroutaji, A., & Olabi, A. G. (2020). Environmental impact of desalination processes: Mitigation and control strategies

Elabbar, M. M., & Elmabrouk, F. A. (2005). Environmental impact assessment for desalination plants in Libya. Case study: Benghazi North and Tobrouk desalination plants.

Elewa, M. M., el Batouti, M., & Al-Harby, N. F. (2023). A Comparison of Capacitive Deionization and Membrane Capacitive Deionization Using Novel Fabricated Ion Exchange Membranes.

Elimelech, M., & Phillip, W. A. (2011). The Future of Seawater Desalination: Energy, Technology, and the Environment (Vol. 333)

Elimelech, M., & Phillip, W. A. (2011). The future of seawater desalination: Energy, technology, and the environment.

Faroon, M., ALSaad, Z., Albadran, F., & Ahmed, L. (2023). Review on Technology-Based on Reverse Osmosis. Anbar Journal of Engineering Sciences, 14(1), 89–97.

Faraz, M. I. (2024). Strategic analysis of wind energy potential and optimal turbine selection in Al-Jouf, Saudi Arabia.

Feo-García, J., Pulido-Alonso, A., Florido-Betancor, A., & Florido-Suárez, N. R. (2024). Cost Studies of Reverse Osmosis Desalination Plants

From Stathelle to Sfax for Safe Drinking Water | Pipelife. Retrieved July 5, 2025, from https://www.pipelife.com/service/news-and-projects/2023/from-stathelle-to-sfax-for-safe-drinking-water.html

Gilau, A. M., & Small, M. J. (2008a). Designing cost-effective seawater reverse osmosis system under optimal energy options

Gérardin, M., & Ferrière, S. (2025). Decarbonising steel and other base metals : let ' s send the right signals LA NOTE D ' ANALYSE, (January).

Green hydrogen and steel decarbonisation: what matters from a climate lens? What needs demystifying? Retrieved July 5, 2025, from https://rmi.org/wp content/uploads/2020/01/hydrogen_insight_brief.pdf.

Greenlee, L. F., Lawler, D. F., Freeman, B. D., Marrot, B., & Moulin, P. (2009). Reverse osmosis desalination: Water sources, technology, and today's challenges.

Grommes, E.-M., & Stefanie Könen-Sagui, Dipl.-G. (2018). Links between Renewable Energies and Employment in Senegal.

Haven, M., & Wales, S. Dolphyn Hydrogen and Our Hydrogen Production Trials. Retrieved July 5, 2025, from www.dolphynhydrogen.com

High-density polyethelyne (HDPE) pipe for Massive Desalination Plant project-Henan Bingo Pipeline Co., Ltd. Retrieved July 10, 2025, from https://www.bingopipes.com/high-density-polyethelyne-pipe-for-massive-desalination-plant-project.html

Hubert, M., Peterson, D., Miller, E., Vickers, J., Mow DOE, R., Klembara, M., & Satyapal, S. (2022). DOE Hydrogen Program Record 24005: Clean Hydrogen Production Cost Scenarios with PEM Electrolyzer Technology.

Hydrogen calculator | OGE. Retrieved July 15, 2025, from https://oge.net/en/hydrogen/hydrogen-calculator

Hydrogen: a renewable energy perspective. (2019). *International Renewable Energy Agency*.

Hydrogen liquefaction, storage, transport, and application of liquid hydrogen. Retrieved July 15, 2025, from https://doi.org/10.5445/IR/1000155199

Hyphen: Project for green hydrogen in Namibia. Retrieved June 5, 2025, from https://enertrag.com/projects-show-cases/hydrogen-projects/hyphen-project-for-green-hydrogen-in-namibia

Jiménez-Arias, D., Sierra, S. M., García-Machado, F. J., García-García, A. L., Borges, A. A., & Luis, J. C. (2022). Exploring the agricultural reutilisation of desalination reject brine from reverse osmosis technology.

Jones, E., Qadir, M., van Vliet, M. T. H., Smakhtin, V., & Kang, S. mu. (2019). The state of desalination and brine production: A global outlook.

Kakavand, A., Sayadi, S., Tsatsaronis, G., & Behbahaninia, A. (2023). Techno-economic assessment of green hydrogen and ammonia production from wind and solar energy in Iran.

Karagiannis, I. C., & Soldatos, P. G. (2008). Water desalination cost literature: review and assessment.

Land Required for a Wind Farm - What Landowners Should Know. Retrieved July 6, 2025, from https://lumifyenergy.com/blog/land-required-for-a-wind-farm/

Lazarus, M., Diallo, S., & Sokona, Y. (1993). uirc•ub 4 energy and environment scenarios for senegal.

Leiblein, J., Bär, K., Mörs, F., Hotz, C., & Graf, F. (2021). Techno-Economic Analysis of Green Hydrogen Production from Solar Energy in MENA and Transport to Central Europe

Lee, C. H., Ho, H. J., Chen, W. S., & Iizuka, A. (2024). Total Resource Circulation of Desalination Brine: A Review. In Advanced Sustainable Systems (Vol. 8).

Liquid Hydrogen: A choice for Efficient Energy Storage and Transport. Retrieved July 6, 2025, from https://stargatehydrogen.com/blog/liquid-hydrogen/

Maatallah, T., Alimi, S. el, Dahmouni, A. W., & Nasrallah, S. ben. (2013). Wind power assessment and evaluation of electricity generation in the Gulf of Tunis,

Mokshin, V. v., Kirpichnikov, A. P., & Soiko, A. I. (2019). Simulation and optimization of the cargo terminal in the AnyLogic environment. *Journal of Physics:*

Meharban, F., Tang, X., Yang, S., Wu, X., Lin, C., Tan, L., Hu, W., Zhou, D., Li, J., & Li, X. (2025). Harnessing direct seawater electrolysis for a sustainable offshore Hydrogen future.

Niang, S. A. A., Gueye, A., Drame, M. S., Ba, A., Sarr, A., Nebon, B., Ndiaye, S. O., Niang, D. N., Dioum, A., & Talla, K. (2024). Analysis of wind resources in Senegal using 100-meter wind data from ERA5 reanalysis.

Orfi, J., Sherif, R., & AlFaleh, M. (2025). Conventional and Emerging Desalination Technologies: Review and Comparative Study from a Sustainability Perspective.

Ovadia, Y. S., Gefel, D., Aharoni, D., Turkot, S., Fytlovich, S., & Troen, A. M. (2016). Can desalinated seawater contribute to iodine-deficiency disorders?

Palchevskyi, B. A., Krestyanpol, O. A., & Yu Krestyanpol, L. (2020). the use of anylogic system for modelling a flexible automated packing system in training engineering students.

Park, G. L., Schäfer, A. I., & Richards, B. S. (2012). The effect of intermittent operation on a wind-powered membrane system for brackish water desalination.

Peinke, J., Barth, S., Böttcher, F., Heinemann, D., & Lange, B. (2004). Turbulence, a challenging problem for wind energy

PEM Electrolysers vs. Alkaline Electrolysers. Retrieved May 5, 2025, from https://stargatehydrogen.com/blog/pem-electrolysers/

Personal, M., Archive, R., & Kohnert, D. (2024). M P RA Transition of power in Senegal.

Pharmaceutical EDI Water Purification Systems | RO Skid. Retrieved June 10, 2025, from https://www.meco.com/product/biopharmaceutical-packaged-reverse-osmosis-edi/

Pistocchi, A., Bleninger, T., Breyer, C., Caldera, U., Dorati, C., Ganora, D., Millán, M. M., Paton, C., Poullis, D., Herrero, F. S., Sapiano, M., Semiat, R., Sommariva, C., Yuece, S., & Zaragoza, G. (2020). Can seawater desalination be a win-win fix to our water cycle?

Ray, S. S., Chen, S. S., Sangeetha, D., Chang, H. M., Thanh, C. N. D., Le, Q. H., & Ku, H. M. (2018). Developments in forward osmosis and membrane distillation for desalination of waters.

Report, B. (2024). Net-Zero Pathways for European Steel.

Reilly, J., Poudel, R., Krishnan, V., Anderson, B., Rane, J., Baring-Gould, I., & Clark, C. (2022). Hybrid Distributed Wind and Battery Energy Storage Systems.

Saïd Ba, A. (2022). The energy policy of the Republic of Senegal. Evaluation and perspectives. Retrieved June 10, 2025, from https://hal.science/hal-01956187v1

Saleh, L., Zaabi, M. al, & Mezher, T. (2019). Estimating the social carbon costs from power and desalination productions in UAE.

Sarr, S., & Fall, S. (2022). Just energy transitions and partnerships in Africa: A Senegal case study.

Stolte, M., Minuto, F. D., Perol, A., Bindi, M., & Lanzini, A. (2025). Optimisation of green hydrogen production for hard-to-abate industries: An Italian case study considering national incentives

Shepherd, A., Roberts, S., Sünnenberg, G., Lovett, A., & Hastings, A. F. S. (2021). Scotland’s onshore wind energy generation, impact on natural capital & satisfying no-nuclear energy policy.

Siemens Gamesa, Uni Aalborg und Projektpartnerunternehmen forschen daran Offshore-Windkraftanlagen kostengünstiger zu machen | Windkraft-Journal.. Retrieved May 6, 2025, from https://www.windkraft-journal.de

Sola, I., Sáez, C. A., & Sánchez-Lizaso, J. L. (2021). Evaluating environmental and socio-economic requirements for improving desalination development.

Stehly, T., Duffy, P., & Mulas Hernando, D. (2023). Cost of Wind Energy Review.

Taïba Ndiaye (Senegal) - Wind farms. Retrieved May 6, 2025, from https://www.thewindpower.net/windfarm_en_37870_taiba-ndiaye.php

Taiba N'diaye Wind Energy project - Aera Group. (n.d.). Retrieved May 6, 2025, from https://aera-group.fr/project/support-senegals-first-utility-scale-wind-farm/

The Taiba N'Diaye Wind Farm in Senegal: Renewable Energy for Whom? (2023).Retrieved May 6, 2025, from www.re-course.org.

Trieb, F., & Müller-Steinhagen, H. (2008). Concentrating solar power for seawater desalination in MENA region.

Tanyi, R. J., Mensah, L. D., Ntiamoah, A., Quansah, D. A., & Adaramola, M. S. (2024). Techno-economic assessment of hydrogen production in Ghana through PV electrolysis and biomass gasification

Tu, W. H., Zhao, Y., Chan, W. P., & Lisak, G. (2024). Reclaimed seawater discharge – Desalination brine treatment and resource recovery system.

What Is The Cost-Estimation Of A Reverse Osmosis(RO) Plant.. Retrieved July 4, 2025, from https://www.commercialroplant.com/what-is-the-cost-estimation-of-a-reverse-osmosisro-plant/

Where and how to buy land in Senegal - JIWALL.. Retrieved June 5, 2025, from https://jiwall.com/en/acheter-une-maison-en/where-and-how-to-buy-land-in-senegal/

Wind Costs. Retrieved June 8, 2025, from https://www.irena.org/Data/View-data-by-topic/Costs/Wind-Cos

Youm, I., Sarr, J., Sall, M., Ndiaye, A., & Kane, M. M. (2005). Analysis of wind data and wind energy potential along the northern coast of Senegal.

Zhang, Y., Wang, Y., & Wu, L. (2012). Research on Demand-driven Leagile Supply Chain Operation Model: A Simulation Based on AnyLogic in System Engineering

Appendix

LCOH Calculation

LCOH Formula:

$$\text{LCOH} = \frac{\text{Annualized CAPEX} + \text{Annual OPEX}}{\text{Annual Hydrogen Production (kg)}}$$

Where:

$$\text{Annualized CAPEX} = \text{Total CAPEX} \times \text{Annuity Factor}$$

$$\text{Annuity Factor} = \frac{r(1+r)^n}{(1+r)^n - 1}$$

Step 1: Input Values

- **CAPEX** = €158,860,000
- **OPEX (Annual)** = €6,888,466
- **CRF / interest rate (r)** = 6% = 0.06
- **Lifetime (n)** = 20 years
- **Hydrogen Production** = 2,079,491 kg/year

Step 2: Calculate Annuity Factor (CRF)

$$\text{Annuity Factor} = \frac{0.06(1+0.06)^{20}}{(1+0.06)^{20}-1} = \frac{0.06(3.207)}{3.207-1} = \frac{0.1924}{2.207} \approx 0.0872$$

Step 3: Calculate Annualized CAPEX

$$\text{Annualized CAPEX} = €158,860,000 \times 0.0872 \approx €13,855,392$$

Step 4: Calculate LCOH

$$\text{LCOH} = \frac{13,855,392 + 6,888,466}{2,079,491} \approx \frac{20,743,858}{2,079,491} \approx \mathbf{€9.97/kg\ H_2}$$
