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Business model for hydrogen exports from Senegal to Hamburg, Germany

Presented the (15/07/2025) by:

Mouhamadou War

Major Supervisor	Co-Supervisor
Prof. Assane Beye	Msc Abraham Josaphat
Prof. Peter Letmathe	Miflinso Yehouenou

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DEDICATION

To my father, my mother, my siblings, and my entire family, my friends, and fellow students, whose unwavering support, love, and encouragement have been the foundation of all my successes. To my teachers and mentors since Ecole12, through Lycée Banque Islamique, Sine Saloum El Hadji Ibrahima Niass University, CEFER, and WASCAL. And to all those who believe in a more sustainable and equitable future, I dedicate this work with gratitude and love. I dedicate this work with deep gratitude to my supervisors, Msc Abraham Josaphat Miflinso Yehouenou, Prof Assane Beye, and Prof Peter Letmathe, whose insightful guidance, unwavering support, and constructive feedback were instrumental throughout this research.

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Acronyms and abbreviations

- **ARENA** Australian Renewable Energy Agency
- **BMBF** Bundesministerium für Bildung und Forschung
- **BMC** Business Model Canvas
- **BMI** Business model innovation
- **CO2** Carbon dioxide
- **CCS** Carbon Capture and Storage
- **DC** Direct current
- **CAPEX** Capital expenditure
- **EU** European Union
- **ECOWAS** Economic Community of West African States**.**
- **EHB** European Hydrogen Backbone
- **GHG** Greenhouse gases
- **H_2O** Water
- **H2** Hydrogen
- **OH^-** Hydroxide ions
- **ICS** Industrie chimique du Senegal
- **IRR** Internal Rate of Return
- **IEA** International Energy Agency
- **IPCC** Intergovernmental Panel on Climate Change
- **IPCC** Intergovernmental Panel on Climate Change
- **JETP** Just Energy Transition Partnership
- **NWR** Net Water Requirement
- **NPV** Net Present Value
- **$O2^-$** Oxygen ions
- **OPEX** Operational expenditures
- **NHS** National Hydrogen Strategy
- **NZTC** Net Zero Technology Center
- **PEM** Proton exchange membrane
- **SOE** solid oxide electrolysis

- **SASCAL** Southern African Science Service Centre for Climate Change and Adaptive Land Management
- **ROI** Return on Investment
- **ROE** Return on Equity
- **UA** African Union
- **UK** United Kingdom
- **RES** Renewable Energy Sources
- **WASCAL** West African Science Service Centre on Climate Change and Adapted Land Use
- **CFADS** Cash Flow Available for Debt Service
- **DS** Debt Service
- **DSCR** Debt Service Coverage Ratio
- **PSE** Programme Senegal Emergent

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Abstract

In the context of global decarbonization, green hydrogen has emerged as a key solution for hard-to-abate sectors, including shipping and heavy industry. Senegal, rich in solar and wind resources, offers a promising opportunity for the production and supply of green hydrogen. Germany is interested in importing green hydrogen from renewable-rich countries. This thesis designs and evaluates a business model based on investment in emission reduction for exporting green hydrogen from Senegal to Germany, using a mixed-methods approach and Osterwalder's Business Model Canvas (BMC). The value proposition is high-purity hydrogen, with oxygen as a by-product, enabling industrial decarbonization and local economic development. This hydrogen targets customers, including the German and Senegal industries. It is delivered through maritime shipping and supported by customer relationships, emphasising reliability, sustainability certification, and long-term collaboration. Delivering this value relies on key resources, including solar and wind plants, water, hydrogen production and export infrastructure, supporting activities such as power generation, hydrogen production, storage, and transport. These activities are coordinated through partnerships with government, financial institutions, and technology companies like Siemens Energy, enhancing feasibility and reducing risk. The cost structure consists of CAPEX and OPEX, aligned with revenue from hydrogen sales, with potential income from oxygen and carbon pricing. Financial analysis shows a base-case NPV of USD 69.24 million, IRR of 12%, and ROI of 53.12%, but sensitivity analysis reveals that lower hydrogen prices, absence of O_2 sales, or missing carbon pricing could reduce profitability. The project has a payback period of 16 years in the base scenario, which may challenge investors, although 2030 and 2050 horizons show improving ROE and competitiveness. By linking all nine BMC components, the study demonstrates that the project is feasible and commercially promising; however, it faces risks that require mitigation. Strategic partnerships, supportive policies, and adaptive planning are essential to position Senegal as a key player in the global hydrogen economy.

.**Keywords:** green hydrogen, business model canvas, Senegal and Germany

Business model for Hydrogen exports from Senegal to Hamburg, Germany

Résumé

Dans le contexte de la décarbonation mondiale, l'hydrogène vert s'est imposé comme une solution clé pour les secteurs difficiles à réduire, notamment le transport maritime et l'industrie lourde. Le Sénégal, riche en ressources solaires et éoliennes, offre un potentiel prometteur pour la production et l'approvisionnement en hydrogène vert. L'Allemagne souhaite importer de l'hydrogène vert en provenance de pays riches en énergies renouvelables. Cette thèse conçoit et évalue un modèle économique basé sur l'investissement dans la réduction des émissions pour l'exportation d'hydrogène vert du Sénégal vers l'Allemagne, en utilisant une approche mixte et le Business Model Canvas d'Osterwalder (BMC). La proposition de valeur est un hydrogène de haute pureté, avec de l'oxygène comme sous-produit, favorisant la décarbonation industrielle et le développement économique local. Cet hydrogène cible des clients, notamment les industries allemandes et sénégalaises. Il est livré par voie maritime et soutenu par des relations clients, privilégiant la fiabilité, la certification de durabilité et une collaboration à long terme. La création de cette valeur repose sur des ressources clés, notamment des centrales solaires et éoliennes, l'eau, la production d'hydrogène et les infrastructures d'exportation, ainsi que sur des activités de soutien telles que la production d'électricité, la production, le stockage et le transport d'hydrogène. Ces activités sont coordonnées par le biais de partenariats avec le gouvernement, les institutions financières et les entreprises technologiques comme Siemens Energy, ce qui améliore la faisabilité et réduit les risques. La structure des coûts comprend les CAPEX et les OPEX, alignés sur les revenus des ventes d'hydrogène, avec des revenus potentiels provenant de la tarification de l'oxygène et du carbone. L'analyse financière montre une VAN de base de 69,24 millions USD, un TRI de 12 % et un retour sur investissement de 53,12 %, mais une analyse de sensibilité révèle que la baisse des prix de l'hydrogène, l'absence de ventes d'O_2 ou l'absence de tarification du carbone pourraient réduire la rentabilité. Le projet a une période de retour sur investissement de 16 ans dans le scénario de base, ce qui peut poser un défi aux investisseurs, bien que les horizons 2030 et 2050 montrent une amélioration du ROE et de la compétitivité. En reliant les neuf composantes du BMC, l'étude montre que le projet est réalisable et commercialement prometteur, mais qu'il est confronté à des risques nécessitant des atténuations. Des partenariats stratégiques, des politiques de soutien et une planification adaptative sont essentiels pour positionner le Sénégal comme un acteur clé de l'économie mondiale de l'hydrogène.

Mots-clés: Hydrogène vert, business model canvas, Senegal, and Germany

Mouhamadou War

Introduction

1. Background and Context

For decades, global energy demand has steadily increased due to population growth and industrialisation(Stancu et al., 2025). Most of this energy consumption is derived from fossil fuels, leading to substantial greenhouse gas emissions. This causes environmental damage and accelerates climate change(Hof et al., 2017). This trend is supported by numerous scientific studies, including those of the IPCC, which confirm that most of the warming observed in recent decades is directly linked to human activities(Stancu et al., 2025).In this concerning context, the international community committed in 2015 to take measures to limit global warming to well below 2°C. It also pledged to pursue efforts to keep it below 1.5°C by drastically reducing greenhouse gas emissions(UNFCCC, 2016).

In light of this situation, transitioning to clean and sustainable energy sources is essential. This transition mainly relies on renewable sources such as solar and wind power. However, due to their intermittent nature, solutions for adaptable energy carriers and long-term energy storage are necessary. Green hydrogen and its derivatives are crucial for decarbonising sectors that are difficult to electrify, such as heavy industry and long-distance transportation. Green hydrogen, generated through the electrolysis of water using renewable electricity, is emerging as a promising solution (IRENA, 2023).

The Russian gas crisis has reinforced the urgency of green hydrogen adoption, coupled with the surge in gas prices, which has accelerated Europe's transition to alternative energy sources and strengthened its role in energy security(Jaller-Makarewicz & Flora, 2022). The European Council is discussing the imminent development of an EU-wide hydrogen infrastructure, which will rely on pipelines that depend on neighbouring countries(European Commission, 2022). The first hydrogen trains in Germany are part of several pilot projects designed to demonstrate the benefits of hydrogen(IEA, 2021). To achieve its carbon neutrality targets by 2045, Europe, especially Germany, has emphasised the importance of hydrogen. As a global leader in climate action, Germany has set ambitious goals for its transition to a green economy. To meet domestic demand and support industrial decarbonisation, Germany aims to import substantial quantities of green hydrogen as part of its National Hydrogen Strategy. The strategy emphasises the importance of international cooperation and highlights hydrogen's role in decarbonising the industry, transport, and energy sectors (Affairs, Federal Ministry for Economic Affairs (BMWK, 2023).

Building on this, the five northern German states are united by their political commitment to establishing a hydrogen economy, owing to their highly favourable local conditions, unique in Germany (Ministries of Economics and Transport of the North German, 2019). As Michael Westhagemann, Director of the Authority for Business, Transport and Innovation, stated: "*Hydrogen offers great opportunities for Hamburg, a major industrial and transport hub in the north, to further strengthen the economic capacity and quality of life in our city. With the growing demand for green hydrogen in Hamburg, we can contribute to scale effects from which the entire energy region of northern Germany can benefit."* Hamburg, a major industrial and logistics hub in northern Germany, plays a vital role in this effort. However, its high urban density limits its ability to produce renewable energy locally. Therefore, Hamburg must rely on global collaborations to secure sustainable sources of green hydrogen(Ministries of Economics and Transport of the North German, 2019).

Senegal has significant potential in renewable energy resources, including solar, wind, and biomass. Its coastal location provides access to seawater. This favourable setting creates opportunities for the development of green hydrogen. Simultaneously, the Senegalese government affirms its ambition to become a regional energy hub through the Senegal Vision 2050. As part of its inclusive growth strategy, Senegal views green hydrogen as a potential opportunity for economic diversification(Kachi et al., 2023). With its resources, Senegal could produce green hydrogen and export it to other nations, such as Germany(Ude et al., 2024).

Exporting green hydrogen could serve as a lever for structural transformation, facilitating a sustainable economic model. However, realising this potential requires an understanding of international market dynamics, supportive policies, and the technical and logistical requirements to foster mutually beneficial cooperation. These renewable energy and water resources, its stable political situation, and its strategic access to the sea position Senegal well within the international green hydrogen sector. For the export of hydrogen from Senegal to Germany, establishing a robust Business model is essential. This approach necessitates meticulous coordination across the key dimensions of this strategy.

2. Problem statement

The high consumption of fossil fuels such as oil, gas, and coal, which are limited and finite resources, contributes to greenhouse gas emissions into the atmosphere(IRENA, 2021). These emissions contribute to climate change, affecting many countries across Africa, Europe, and globally. Faced with the climate emergency and the need for energy security, green hydrogen presents a potential solution to decarbonise all sectors and achieve carbon neutrality.

Africa, endowed with immense potential in renewable resources, has been recognised through initiatives like H2Atlas-Africa, which demonstrate the continent's capacity to become a major player in the global hydrogen economy(Dr Solomon Agbo, 2020; ECREEE ECOWAS, 2023). Germany, like many countries in the Global North, aims to secure its clean energy supplies as part of its strategy to achieve carbon neutrality. As a key player in the energy transition, Germany has developed strategies to incorporate green hydrogen into its energy systems (Affairs, Federal Ministry for Economic Affairs (BMWK), 2023). To satisfy its domestic green hydrogen demand, the nation faces a production challenge due to the limited potential of renewable resources such as solar energy. As a result, Germany relies heavily on hydrogen imports from regions rich in renewable resources, particularly Africa, such as Senegal (Affairs, Federal Ministry for Economic Affairs (BMWK), 2023).

However, realising this opportunity requires more than assessments of Africa's technical resource potential. It also depends on supportive policy and regulatory frameworks, large-scale infrastructure investment, and international partnerships to ensure that hydrogen production and export can materialise sustainably. For Germany and other countries in the Global North aiming to import hydrogen from Africa, the development of a robust business model is critical. Such models help assess economic viability, define partnerships and trade channels, and ensure value creation, in line with the Business Model Canvas framework and recent analyses of hydrogen value chains(Ahmad et al., 2024; Egli et al., 2025a; Terlouw et al., 2022a).

Hydrogen research is growing, but studies on business models for exports from Africa are still rare(IEA, 2022; Imasiku et al., 2025). Most focus on technical feasibility and policy ambitions, without linking production, transport, and export in a clear framework(Fasihi & Breyer, 2020; Mukelabai et al., 2022). This gap leaves policymakers and investors with little guidance on risks, cooperation, or trade design. This study addresses that gap by using the Business Model Canvas for the Senegal-Germany hydrogen trade. Senegal, with a good renewable energy potential, provides a suitable case. By mapping value chains, partnerships, and financial viability, the research offers a structured model that can guide future hydrogen export projects.

3. Main objective

This thesis aims to design and evaluate a business model that facilitates the production and export of green hydrogen from Senegal to Hamburg, Germany, using Osterwalder's Business Model Canvas.

4. Research question

- How can the BMC of Osterwalder be applied to design a profitable business model for exporting green hydrogen from Senegal to Germany (Hamburg)?
- Which factors ensure the competitiveness of H2 export from Senegal to Germany?
- What policy recommendations can favour the implementation of the business model?

5. Scope of the thesis

This study focuses on the business model for hydrogen exports from Senegal to Germany. It will design and evaluate a model for green hydrogen production in Senegal, from production to export to the Hamburg port in Germany. The hydrogen will be produced using electricity generated from solar and wind power plants to be installed in Senegal, and water will be purchased from the national company Sones. It employs the Osterwalder model to assess the production and export of green hydrogen from Senegal to Germany, utilising the Business Model Canvas. The analysis will outline the key elements of the export-oriented business model. It will identify how the company, through stakeholders in Senegal and Germany, can produce, store, and transport green hydrogen to Germany by ship. Although the focus remains on export, the study will briefly examine the potential of hydrogen to meet local industry demand in Senegal. Additionally, the study will identify suppliers of renewable energy equipment, electrolysers, and storage. Through this process, costs will be analysed, capital expenditures (Capex) and operational expenditures (Opex) will be identified, and the value chain will be examined, focusing on the production of green hydrogen and its export, to assess the economic benefits for Senegal, including job creation and local access to energy. The study will focus on the value chain from production to transport in the Hamburg port, Germany, excluding distribution and end use. It will not address the environmental impact assessment or the social impact of the model. It will simply formulate some general policy recommendations to make this model viable.

Chapter I: Literature Review

This chapter aims to establish the theoretical and contextual foundations necessary to develop a business model for exporting green hydrogen between Senegal and Germany, utilising the Business Model Canvas framework. It is organised into five sections: first, it examines the theoretical foundations of economic models; then, it explores their application to the energy sector. It is followed by an overview of the principles of green hydrogen production, the strategic and political context and finally, the gaps identified in the literature.

1. Theoretical Foundations of Business Models

1.1 Business Model Concept

The concept of business models has been in use for centuries, but its formal application in academic discourse began in the mid-1990s, mainly due to the rise of the Internet. With the emergence of digital transformation and new markets, the use of the term increased significantly between 1995 and 2000, and this trend continued through to 2010 and beyond (Zott et al., 2011).

Despite the popularity of the term ‘business model’, there are several ways to define it based on its description, representation, architecture, framework, and more. It has been defined in various ways to reflect its multifaceted nature. According to Timmers (1998), a business model is an architecture that describes the flows of products, services, and information, outlining the roles of different commercial players, their potential advantages, and their sources of revenue. Building on this view, Amit & Zott (2001) describe the business model as the content, structure, and governance of transactions that create value by exploiting commercial opportunities. Shafer et al. (2005) define the business model as a tool that illustrates the fundamental logic of the company, used to translate strategy into concrete decisions. This definition focuses on the strategic aspect of the organisation. According to Osterwalder et al. (2005), the business model is a theoretical instrument composed of elements, properties, and their interrelationships, providing a simplified representation and explanation of a company's strategy. Later, Zott & Amit (2010) refined this definition, presenting the business model as a system of interdependent activities that extend beyond the boundaries of a single organisation, emphasising its systemic and networked nature. Osterwalder et al. (2010) further defined the business model as a tool that helps organisations capture, understand, design, analyse, and modify their business logic.

The variety of these definitions facilitates the development of more integrative models. Osterwalder et al. (2010) illustrate this evolution well by offering a systemic vision through the Business Model Canvas (BMC), which is composed of nine interdependent blocks: value proposition, customers, channels, partners, resources, revenues, costs, and others. This approach presents a clear, visual, and adaptable interpretation of entrepreneurial logic, including in emerging sectors such as green hydrogen. Other authors, such as Chesbrough (2006), emphasise the strategic role of the economic model in open innovation, highlighting the importance of external interactions in generating new sources of value.

A notable difference between these authors concerns the integration of strategy within business models. Osterwalder & Pigneur (2011) appear to see the business model as an operational structure organised around nine blocks, while Chesbrough (2006) focuses more on the strategic aspect, particularly in open innovation contexts. Barquet et al. (2013) thus emphasise that strategy and the business model are two distinct but interconnected entities. A good strategy can effectively guide the design of the business model.

In this study, we utilise the tool proposed by Osterwalder et al. (2010) as a reference model for developing a business model dedicated to green hydrogen production and export. This choice is motivated by the clarity, visual simplicity, and widespread use of the BMC in academic and professional fields. This model helps identify the key components necessary for the project's feasibility. It is particularly suitable for evaluating the economic viability of a complex project such as exporting green hydrogen from Senegal to Germany.

1.2 Business Model Innovation

Business model innovation has become a research area that increasingly focuses on how companies adapt or transform their models to gain a competitive advantage in the market. According to Mitchell & Coles (2003), the ability to innovate in the field of business models can help an organisation to be more resilient to environmental changes and stay competitive. Business model innovation allows companies to consider new parameters that influence local or even international markets. Foss & Saebi (2017) provide an in-depth analysis of the subject, highlighting that BMI involves changes in the configuration of business models by incorporating new aspects to address challenges or meet diversification needs.

The concept is studied to understand and facilitate the analysis and planning of transformations from one business model to another. These research aspects demonstrate that business model innovation involves modifying a company's model configuration, either by altering specific elements or by adopting a new model entirely. For example, the triple-layer business model reveals how some companies initially focused on technical and economic aspects have started to innovate by including social and environmental dimensions. These models enable participation in solving environmental challenges and promoting sustainable development.

Market innovation can target various dimensions through specific parameters: the content of the offer, its modalities, the target audience, and the reasons it creates value. This enables a broad spectrum of changes, ranging from innovating revenue models to collaborating with new partners. Najafi-Tavani et al. (2023) and Raphael Amit and Christoph Zott (2021) examine how innovation in economic business models can enhance export performance, enabling companies to adapt to international markets. They demonstrate that organisational learning and resource-based capabilities, such as skills and knowledge development, are key to this process, supporting the success of hydrogen business models. These capabilities play a decisive role in competitiveness within international markets. In this study, the principles of business model innovation are applied to the context of green hydrogen exports from Senegal to Germany. The research focuses on designing a business model that enhances competitiveness and adaptability in international markets. Innovation is operationalised by examining key elements of the business model, such as value propositions, partnerships, revenue streams, and trade channels, while incorporating economic feasibility through CAPEX, OPEX, and financial analysis. This integrated approach, consistent with insights from Foss & Saebi (2017), allows the study to propose a business model that is responsive to market demands and capable of supporting successful hydrogen exports.

Based on the theoretical foundations of the business model concept, it is relevant to explore its implementation in specific sectors such as energy, particularly in emerging hydrogen markets.

2. Business Model for Energy Sectors

Most research on hydrogen business models concentrates on production and utilisation across various sectors, such as transportation(Särnbratt et al., 2023). Roland Berger (2023) highlights that by 2030, the green hydrogen market will be led by large-scale projects aimed at exporting hydrogen products to countries with significant energy import needs, such as Germany or Japan.

To support this growing market, Zhao et al. (2023) propose a theoretical approach that addresses issues at multiple levels to ensure profitability for all involved parties and to accelerate infrastructure development through a study on economic models for hydrogen refuelling stations.

A complementary study by Frontier Economics (2020), commissioned by the UK Department for Business, Energy and Industrial Strategy (BEIS, 2020), categorises business models into four broad types for the large-scale production of low-carbon hydrogen in the UK. It proposes models such as contractual payments to producers, regulatory performance models, end-user subsidies to lower costs for consumers, and supply obligation schemes that mandate minimum hydrogen consumption in specific sectors. These models aim to reduce costs, protect consumers and taxpayers, and implement policies that support the adoption of hydrogen in industrial sectors, thereby mitigating investment risks and stimulating growth.

L. Zhang et al. (2023) suggest a unified framework that integrates clean energy production, hydrogen energy systems (HES), and transmission networks. This framework promotes cost-effective and sustainable integration of hydrogen. It assesses hydrogen needs across different sectors. The study's results indicate that hydrogen produced from renewable energy sources is a promising long-term energy storage solution. L. Zhang et al. (2023) analyse the Swedish hydrogen transport market, targeting producers, station operators, and heavy-duty vehicle manufacturers. Although these models are adaptable, they remain fragile due to technological immaturity, the lack of regulatory standards, and uncertainty in demand. The viability of these stations depends on subsidies and strong partnerships to promote low-carbon mobility. As the market is still emerging and economically uncertain, the sector will require subsidies for renewable investments.

Yang et al. (2024a) propose three innovative approaches to close the cost gap between green and fossil hydrogen in their study on hydrogen credit-subsidised business models. The first is the Investment for Emission Reduction (IER) model, which involves investing in green hydrogen projects, selling hydrogen to customers, and leveraging carbon markets where high fossil fuel users must buy credits, making hydrogen a valuable tool for emission. This model focuses on revenue sharing from carbon credits that are avoided. The second is the Hydrogen Credit Investment, which enables a company to invest in green hydrogen projects, acquire carbon credits, and resell them to users for a revenue stream. The third, Profit Sharing, distributes ownership of H2 credits among producers, transporters, and users to foster collaboration and shared incentives for decarbonisation.

Deloitte (2023) emphasises the need to develop business models to address what it calls the “systemic first-mover dilemma” in hydrogen markets. This article highlights five key areas of uncertainty: demand, regulation, technology, infrastructure, and collaboration, and proposes business models to mitigate these risks. These include “take-or-pay” contracts that secure revenues for hydrogen producers, insurance and reinsurance mechanisms to reduce risks associated with projects in emerging markets, and the use of “book-and-claim” systems that separate physical delivery from emissions reporting.

After examining the application of economic models in the energy sector, including hydrogen, it is now appropriate to focus on the concept of its production.

3. Green hydrogen production concept

Hydrogen is an abundant element that can be extracted from many sources where it is chemically bonded to various organic and inorganic compounds. Water (H_2O), composed of two hydrogen atoms and one oxygen atom, is an example. Hydrogen can be produced by splitting water through electrolysis**,** a process that uses electricity to separate water molecules into hydrogen and oxygen(Ahmad et al., 2024; Terlouw et al., 2022a). If the energy used for electrolysis comes from renewable sources, hydrogen production is clean and referred to as green hydrogen**.** Hydrogen can be produced from fossil fuels or renewable energy. Depending on its production technology, energy source, and environmental impact, hydrogen is classified into different colour shades, namely blue, grey, brown, black, and green(Noussan et al., 2020; Shiva Kumar & Lim, 2022).

Green hydrogen is considered the cleanest energy resource with the highest gravimetric energy density (142 $MJ \cdot kg^{-1}$)(Agaton et al., 2022). It is produced through electrochemical processes that utilise electricity from renewable energy sources to split water into hydrogen and oxygen. These processes are exothermic and require 242 kJ/mol of energy to split water into H_2 and O_2 gases (Ahmad et al., 2024). Among the various electrochemical hydrogen production technologies, water electrolysis is the most widely used method. This method provides a near-zero carbon footprint production route, without carbon capture and storage (CCS). Electrolysis units are the most commonly used systems for generating high-purity hydrogen. Moreover, the safety impacts associated with this technology are very low due to the possible distance between the power source and the electrolyser(Ahmad et al., 2024).

During the water-splitting process, a specific amount of direct current (DC) must be applied to the electrodes, which are separated by an aqueous electrolyte with high ionic conductivity(Karayel et al., 2023). At the anode, water molecules are oxidised, producing oxygen gas and either hydroxide ions (OH^-) in alkaline electrolysis, protons (H^+) in proton exchange membrane (PEM) electrolysis, or oxygen ions (O^{2-}) in solid oxide electrolysis (SOE). The ions produced at the anode migrate through the electrolyte to the cathode. At the cathode, the ions are reduced, forming hydrogen gas(Al-Shara et al., 2021; L. Zhang et al., 2024).

The following equation illustrates the overall reaction:

$$H_2O + \text{electricity} \rightarrow H_2 + {}^{1}/_{2}\, O_2 + \text{heat}$$

The above reaction (equation (1)) requires a theoretical thermodynamic voltage of 1.23 V. There are three main electrolysis technologies: SOEC, PEMEC, and AEC, classified according to their operating temperature and the type of electrolyte used.

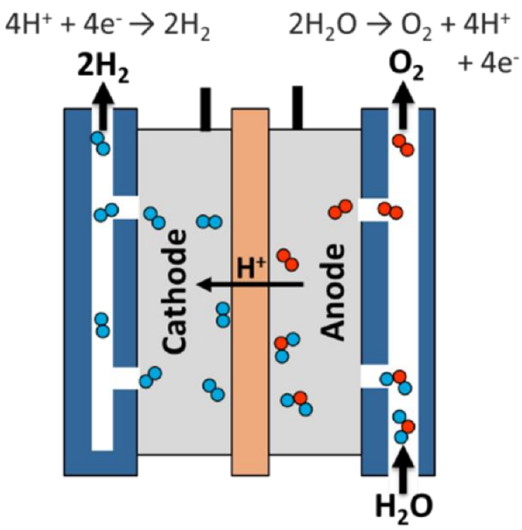

*Figure 1:*Water Electrolysis via Proton Exchange Membrane Technology

Source:*(US.Department of energy, 2025)*

The green hydrogen produced by these electrolysers can be stored in liquid, solid, or gaseous form. It can also be transported by various means, including buses, trains, ships, and pipelines, across regions. Although green hydrogen production technologies are now well established, their deployment across countries largely depends on the political and strategic framework. The following section, therefore, examines the political and strategic context at different scales.

4. Policy and Strategy Context

4.1 Senegal’s Emerging Hydrogen Strategy

Many countries around the world have implemented policies or initiatives to promote the production of green hydrogen. Some nations have already developed national green hydrogen strategies, while others are in the early stages or have not yet begun. Among these countries in the initiative phase, most collaborate at the regional organisational level to better understand this emerging field. Senegal, a nation rich in renewable resources, participates in this approach by working within Ecowas or with other organisations to advance green hydrogen. The country is still in the initial phase in this sector, but it aims to play a significant role. Within ECOWAS, numerous studies have been carried out, with Senegal's involvement, to highlight the wealth of green hydrogen resources in West Africa and support their development.

Within the framework of the ECOWAS regional policy on green hydrogen, ECREEE ECOWAS (2023) projects that sub-Saharan Africa has a technical potential of 1,923 EJ, alongside declining production costs expected by 2040. The hydrogen potential of the entire ECOWAS region is estimated at around 165,000 TWh/year, which is sufficient to meet the region's demand. The H2Atlas findings indicate significant low-cost production potential that goes well beyond regional energy needs and paves the way for export to the global market. They demonstrate that the development of green hydrogen in the region has strong potential for local job creation. With a significant role for green hydrogen in its 2050 vision, ECOWAS is also working to strengthen research and adaptation capacities to climate change (ECREEE ECOWAS, 2023). The African Union supports this vision through its Agenda 2063, which advocates for sustainable development, renewable energy, and industrialisation(AU, 2015). It also benefits from renewable energy production costs that are among the lowest in the world, particularly thanks to photovoltaic solar energy. All these achievements by the organisation are also reflected in Senegal, which can be regarded as a future producer of green hydrogen.

The country has vast land suitable for producing green hydrogen. Additionally, it possesses enormous potential in renewable energy, especially solar, with an average sunshine of more than 5.8 kWh/m²/day, and wind, with a potential of approximately 6.61 m/s (Apfel, 2022; Ministère de l'énergie, du pétrole, 2025). The country has experienced a 23% growth in renewable energy since 2017 and aims to increase its total installed capacity by 40% by 2030. Wind and solar energy have been expanding since 2017, reaching a 23% share of electricity generation in 2021(IEA, 2023). Following the signing of a Just Energy Transition Partnership (JETP) with partners such as Germany, the ambition was raised to 40% renewable energy in the total installed capacity by 2030 (Federal Ministry for Economic Cooperation and Development (BMZ), 2023).

In addition to these energy resources, Senegal has significant potential in water resources due to its several underground water tables rich in freshwater, rivers such as the Senegal River and the Gambia River, and other rivers. It also has access to the Atlantic Ocean in several parts of its territory(Faye & Gomis, 2021; USAID, 2021). These resources, combined with desalination processes, enable the country to meet its water needs and respond to the increasing demand for clean energy.

With its strong solar and wind resources, Senegal is well-positioned to develop sufficient green hydrogen production to meet local needs and potentially supply export markets such as Germany. According to Table 3 of Green Hydrogen Production Assessment of ECOWAS, Senegal stands out for its renewable energies, its water availability and its ports, placing it among the most advanced countries in the region for the production of green hydrogen.(ECREEE ECOWAS, 2023).H_2 Atlas, will go further by analysing the socio-economic performance of the country using three composite indicators. The results reveal a positive current and future performance of the energy and electricity sectors, strong export potential, quality infrastructure, and a highly favourable ecopolitical framework(H2Atlas-Africa project, 2025). The current government of Senegal has strengthened these initiatives in their programme book, emphasising support for the production and valorisation of renewable energies through projects like Power-to-X(Pr, 2024).

4.2 German Hydrogen Strategy

Germany aims to decarbonise these sectors by replacing fossil fuels with green hydrogen. However, it faces potential limitations in renewable energy sources, such as solar power, to produce the green hydrogen needed to meet all these demands. Therefore, in June 2020, it developed a national strategy for the production and import of green hydrogen. This energy carrier is considered a key solution for hard-to-decarbonise sectors in order to achieve climate neutrality by 2045(Bukowski, 2024; Moll et al., 2023).

To meet its climate targets, Germany needs to speed up the expansion of hydrogen considerably. This strategy was updated in 2023, covering the period from 2023 to 2030. The German National Hydrogen Strategy, launched in 2020 and revised in 2023, reflects the country's ambition to become a global leader in green hydrogen by fostering domestic innovation while securing international partnerships to meet its increasing demand. It aims to address two main priorities of the federal government: ensuring energy security by reducing reliance on imported natural gas and promoting decarbonisation to achieve climate neutrality by 2045(Bukowski, 2024; Moll et al., 2023). The strategy establishes ambitious goals for domestic production and infrastructure development. Production capacity in Germany is estimated to be 5 GW by 2030, according to the NHS, and could reach 10 GW(Affairs, Federal Ministry for Economic Affairs (BMWK, 2023). This capacity remains limited, given the national strategy's ambitious goals, which have led Germany to seek international partnerships for importing green hydrogen.

According to the NWR, hydrogen demand is estimated at 95-130 TWh, of which 50-70% would be supplied by imports (German Federal Ministry of Economic Affairs & Energy, 2020), and by 2045, this demand could reach 360-500 TWh, with 200 TWh coming from imported hydrogen derivatives. The NWR recommends extending the import strategy beyond 2030 to 2035-2040 by establishing a transparent phase model for imports, infrastructure, and regulation (Wasssertoffrat, 2024). In this context, Germany prioritises partnerships with states that have abundant and low-cost renewable energy potential, which can be utilised to produce green hydrogen cost-effectively.

The import strategy recognises that hydrogen is crucial for maintaining the competitiveness of the energy sector. The primary sources of hydrogen demand are expected to come from sectors such as transportation, electricity companies, and industries including steel, chemicals, and petrochemicals. Hydrogen demand also originates from sectors such as maritime transport, heavy logistics, and heating (German Federal Ministry of Economic Affairs & Energy, 2020). However, the industrial sector is expected to account for a large portion of the demand for hydrogen, estimated at around 45 TWh, and its derivatives at over 10 TWh by 2030 (Affairs, Federal Ministry for Economic Affairs (BMWK), 2023; Bukowski, 2024).

To meet all these demands, Germany must consider several key parameters. Among these, Germany is actively involved in the research and development of green hydrogen capacities and skills, with funding for programmes such as WASCAL and SASCAL. Additionally, Germany has launched initiatives to support long-term green hydrogen import contracts and to assist partner countries in developing their infrastructure. In 2022, Germany introduced the G7 Green Hydrogen Pact and co-founded the Green Hydrogen Catalogue to support global efforts for green hydrogen. This action is supported by federal government initiatives to assist companies in their transition to green hydrogen. Such strong measures have prompted companies like ThyssenKrupp and Salzgitter to incorporate green hydrogen into their energy consumption, making their industrial processes more environmentally friendly(Seithümmer et al., 2024).

4.3 International Collaboration in Green Hydrogen Trade

Although many countries around the world are beginning to take an interest in green hydrogen and are moving towards a global market, some have significant production potential, while others lack this capacity. Countries with deficits in green hydrogen to meet their needs will likely import it from nations with high production capacity, thereby creating an international green hydrogen market. Consequently, international trade in this product could play an important role in balancing supply and demand.

Hydrogen presents a unique opportunity for countries to decarbonise their sectors. Over the past decade, several green hydrogen export initiatives and projects have been launched worldwide. Initiatives such as the European Hydrogen Backbone aim to connect European regions with high demand to hydrogen production via pipelines. To establish this green hydrogen backbone, the European Union is collaborating with many countries, particularly those in North Africa, such as Morocco. The European Hydrogen Backbone (EHB) aims to develop cross-border infrastructure by constructing a 38,000 km pipeline network across Europe by 2040. This infrastructure will link hydrogen production facilities to demand centres, ensuring a reliable supply and making large-scale hydrogen more economical(Mielich et al., 2025).

This is in addition to the interest of some European countries in importing green hydrogen. With BMBF funding of €1.7 million, scientists and economists studied the feasibility of creating a green hydrogen supply chain between Australia and Germany in 2020. The BMBF and the Australian Renewable Energy Agency (ARENA) launched the HyGATE project in February 2022 to import hydrogen and export climate protection technologies (ARENA, 2023). Building on a research and technology partnership, Canada and Germany are collaborating on various green hydrogen projects. The BMBF has funded four joint projects. Additionally, ten projects aimed at strengthening German-Canadian hydrogen research networks have received funding since 2020, with SMEs from both countries participating in these initiatives. In August 2022, the two countries signed a hydrogen agreement, with the first hydrogen deliveries from Canada to Germany planned for 2025 (The National Research Council of Canada (NRC), 2023). A new development agreement was signed to create the world's first liquid hydrogen import corridor, connecting the port of Duqm (Oman) with the port of Amsterdam (Netherlands) and German logistics platforms, including Duisburg (Alsir,2025).

In April 2025, Namibia launched the HyIron project, Africa's first zero-emission iron plant, producing green iron from renewable hydrogen with support from the EU, Germany, and the Netherlands under the Global Gateway. The project is expected to reduce CO_2 emissions and create thousands of jobs (Directorate General for International Partnerships (DG INTPA), 2025). The UK's Net Zero Technology Centre (NZTC) and Germany's Cruh21 published the Green Hydrogen Export Environment report, outlining plans to export 35 TWh of hydrogen from Scotland to Germany by 2030 without a pipeline, and expand to 94 TWh by 2045 with pipeline infrastructure(Ana Almaida, 2024). In Egypt, a €7 billion partnership with France was established to build a green hydrogen and ammonia complex in Ras Shokeir, positioning the country as a regional energy hub (MENA, 2025). Nigeria, through collaboration with Germany, is focusing on scientific and academic innovation to develop its green energy sector and participate in the global hydrogen market (Federal Foreign Office, 2021).

There are also other projects worldwide, such as those in Mauritania and various other countries. All these initiatives play a vital role in strengthening the global green hydrogen market and its development. Despite the establishment of policy and strategic frameworks, several uncertainties and limitations remain regarding the practical realisation of large-scale green hydrogen projects.

The following section highlights these gaps to better identify the challenges to be addressed and ensure the viability of the proposed model.

5. Gaps and limitations in the literature

The demand for green hydrogen to decarbonise high-emission sectors is growing rapidly. In response, many countries are developing strategies for the production, import, or export of hydrogen. However, studies focus on technical feasibility, production processes, and national policies, without exploring concrete business structures in detail(Fasihi & Breyer, 2020; Mukelabai et al., 2022).

Institutional cooperation mechanisms, such as government-facilitated partnerships and strategic alignment between exporting and importing countries, are essential for transcontinental hydrogen projects but are often underdeveloped, leaving investors without guidance on operational, financial, and political integration(Scholvin & Kalvelage, 2025).

In Africa, most research focuses on renewable energy potential and policy ambitions rather than comprehensive business strategies(IEA, 2022; The WORLD BANK, 2023). Although some techno-economic assessments provide cost estimates and resource mapping in sub-Saharan Africa, they do not propose structured business models that integrate production, transportation, and export (Winkler et al., 2025). This lack of integration poses a significant risk to investors and may hinder sustainable market development.

Furthermore, the Business Model Canvas (BMC) remains largely underutilised in the African green hydrogen sector (Imasiku et al., 2025). Existing studies focus on technical feasibility without analysing the interdependencies between key actors, revenue sources, cost structures, and value propositions, which are essential elements for designing viable hydrogen export projects. For example, the Megaton Moon project in Mauritania illustrates a phased public-private partnership (PPP) approach to developing green hydrogen production (Greengo Energy, 2023). However, no structured BMC application has been established to guide decision-making, stakeholder engagement, and financial viability, reflecting a general lack of integrated business models in sub-Saharan Africa.

Thus, despite Senegal's recognised potential as a green hydrogen producer and exporter, no study has proposed a comprehensive BMC framework to guide project design, investment decisions, and value chain integration(IEA, 2022; The WORLD BANK, 2023). This gap exposes projects to economic and social risks and limits their ability to align with political and market realities. This research aims to fill this gap by developing a business model adapted to Senegal, integrating production and export to Germany using BMC. It thus directly addresses the lack of structured and practical business models identified in the current literature.

Based on the literature review’s identification of key themes and research gaps, this study now outlines the methodology used to address these gaps and explore the research questions further.

Chapter II: Methodology

This chapter outlines the methodological foundations of this study, which was used to develop an economic model for exporting green hydrogen from Senegal to Germany. It systematically describes the study area, the methodological tools employed, and the methods used for data collection and analysis. It provides an overview of the Business Model Canvas applied, as well as the approach taken to model the project. It concludes with a general depiction of the value chain.

1. Study Area

This thesis develops and evaluates the business model for exporting green hydrogen from Senegal to Germany via the port of Hamburg. Within the scope of the thesis, the hypothetic Senegalese company will produce green hydrogen and sell a significant portion in Germany. Senegal, located in West Africa, has an area of approximately 196,722 km² and a population of 18,126,390 inhabitants (ANSD, 2024). The country has substantial potential in renewable energy, particularly solar and wind, thanks to its abundant sunshine and the regularity of its winds in certain regions. With this potential, Senegal aims to meet its national energy needs and also become a regional player, potentially even an energy exporter (IEA, 2023). These renewable resources offer Senegal the opportunity to produce green hydrogen for local use and for export to countries such as Germany.

The site chosen for production is the commune of Diass, due to its potential in solar and wind resources, with an average solar irradiation (high irradiance solar: 6.53 kWh/m2/day, Min irradiance solar: 4.93 kWh/m2/day) and average wind speeds (high wind speed:7.16 m/s, Min Wind speed:3.92 m/s), the availability of the Sones network, and existing infrastructure like road, solar power plant, and others (Nasa, 2025; Ndiaye et al., 2025). It is also located approximately 53 km from Dakar Port, facilitating the transportation of the product, as well as near the port of Ndayane, which is currently under construction and is scheduled for completion in 2027 (DIALLO, 2024).

Germany, with its ambition to reduce emissions in various sectors, represents a significant market for the hypothetic Senegalese company. This aim is followed by a national strategy for the production of hydrogen and its import to countries with high potential and at competitive prices. It is one of the most active countries on the market, with an import strategy that accounts for more than 50% of its national demand(Affairs, Federal Ministry for Economic(BMWK), 2023). Germany is seeking strategic partnerships for the import of green hydrogen to decarbonise its sector and achieve carbon neutrality by 2050. Senegal, with its strategic geographical position on the Atlantic coast and political stability, offers a solution for Germany to participate in the decarbonization process. With green hydrogen, Senegal and Germany could strengthen their bilateral cooperation in the energy sector and play a crucial role in the decarbonization of both countries and the world at large.

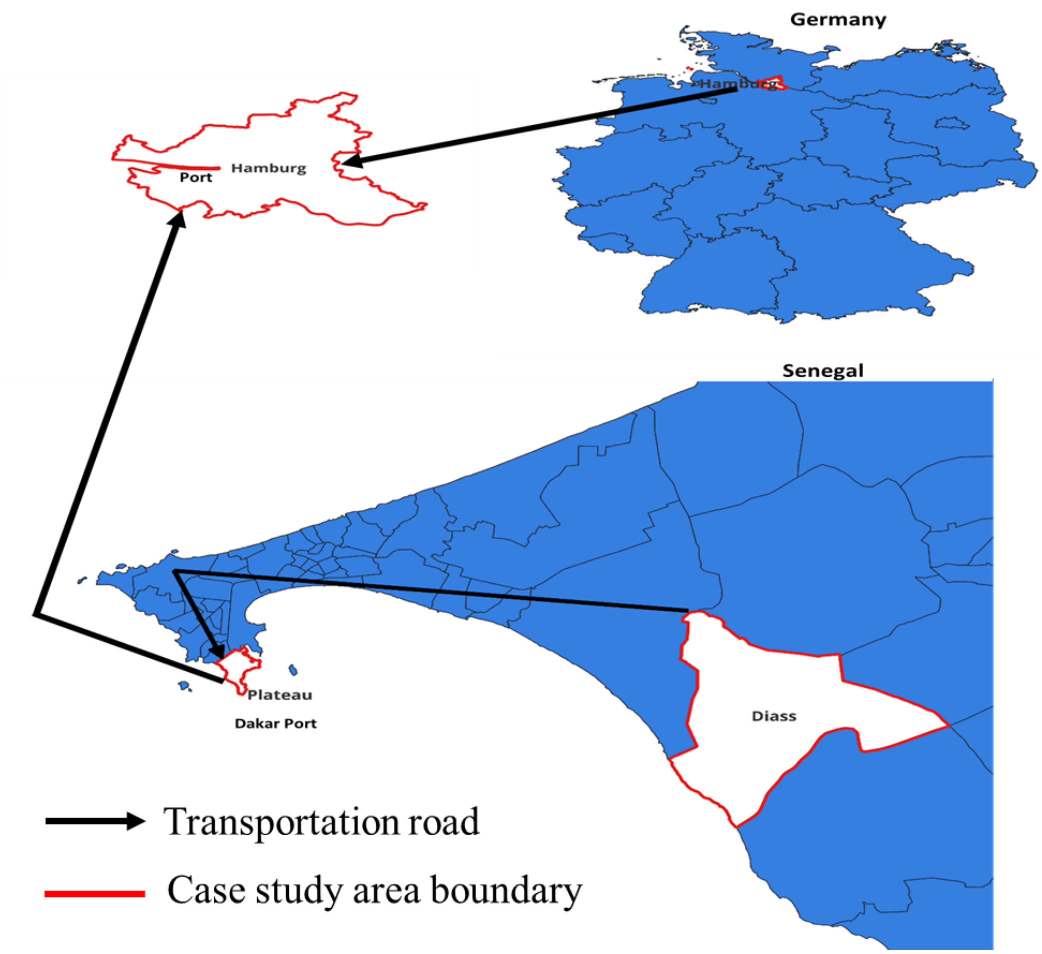

Figure 2:Study aera Map

***Source**: Own figure*

2. Methodology

This study adopts a mixed-method approach combining qualitative and quantitative techniques to design a sustainable business model using the Osterwalder Business Model Canvas (BMC) as a framework. The methodology integrates literature research, financial modelling, and business model analysis to address the research questions. The process begins with a literature review to gather relevant data. Some of this data is used to support the review itself, while other quantitative data informs the development of a financial model. A comprehensive financial model was developed to perform the technical and economic evaluation of the hydrogen export system. The model, implemented using Excel, incorporates detailed cost, revenue, and operational assumptions to calculate key financial indicators such as NPV, IRR, ROI, and payback. This model integrates capital expenditures (CAPEX), operational expenditures (OPEX), and revenue streams to provide a comprehensive view of the financial aspects of the hydrogen export project. A sensitivity analysis was performed to assess how variations in key parameters, such as hydrogen price, equipment costs, and the discount rate, could affect the financial viability of the export project. By combining the results of the BMC and the financial analysis, the study offers a comprehensive assessment of the economic and strategic feasibility of exporting green hydrogen from Senegal to Germany.

3. Business Model Canvas Overview

3.1 Business Model Canvas as an Analytical Framework

The Business Model Canvas is a strategic management tool that provides a structured framework for visualising, analysing, and developing business models (Oliveira & Ferreira, 2011). Designed by Osterwalder and Pigneur, it helps organisations, managers, and entrepreneurs to structure their projects effectively. It provides a structured methodology for analysing, designing, and optimising a business model, helping companies to visualise how they create, deliver, and capture value(Osterwalder & Pigneur, 2011).

The business model canvas helps to identify opportunities, assess risks, and develop a strategy for financial and operational success while focusing on nine key elements: customer segments, value proposition, distribution channels, customer relationships, revenue streams, key resources, key activities, key partnerships, and cost structure(Osterwalder et al., 2010).

Using the BMC will enable the visualisation of the strategic and economic aspects of the green hydrogen export project by evaluating the value chain, understanding the stakeholders involved, and ensuring the project's financial viability. Green hydrogen is a rapidly evolving sector with uncertainties. The BMC will also enable the identification of opportunities in the German and Senegalese markets, anticipating logistical and technological challenges, while defining strategies aligned with the customer's needs. It also enables making informed decisions by selecting the right market segments and establishing key partnerships to secure the project. The BMC also enables presenting a clear and attractive economic model to investors by showcasing a coherent and achievable plan.

3.2 Building Blocks of the BMC

- **Key partnerships**

The building block "Key Partnerships" represents the network of partners, suppliers, collaborators, and other external entities necessary for the business model to function correctly. Companies enter into partnerships to optimise operations, reduce risks, or acquire essential resources. Key partners refer to external companies, suppliers, subcontractors, or parties that the company needs to carry out or implement its key activities and create value for customers (Osterwalder et al., 2010).

- **Key resources**

The key resources building block describes the most important assets required for a business model to function correctly. These resources enable a company to deliver value, reach markets, maintain customer relationships, and generate revenue. They vary depending on the business model and can be physical, financial, intellectual, or human. They play a crucial role in the company's production activities and competitiveness(Osterwalder et al., 2010).

- **Key activities**

The Key Activities block outlines the most important actions a company must perform to make its business model successful. These actions are essential for creating and delivering a value proposition, reaching markets, maintaining customer relationships, and generating revenue(Osterwalder et al., 2010).

- **Value proposition**

The value proposition encompasses all the products and services a company offers to meet its customers' needs and expectations. This component is essential for clarifying the product and making the offering more attractive. The value proposition is the reason customers choose one company over another. It solves a customer problem or satisfies a customer need(Osterwalder et al., 2010).

- **Distribution channels**

A commercial channel refers to how a company delivers its value proposition to its customers. It includes the distribution of its products and services, as well as the interactions established with its various customer segments to convey the value proposition(Osterwalder et al., 2010).

- **Customer segments**

The "Customer Segments" building block defines the different groups of people or organisations that a company wants to reach and serve. This part of the BMC model is essential for any business model development because a company cannot function without its customers. Identifying these segments is important for understanding market needs and satisfying customers. To better satisfy customers, it is beneficial to group them into segments based on similar needs or behaviours (Osterwalder et al., 2010).

- **Customer Relationship**

The "Customer Relations" describes the types of relationships a company establishes with specific customer segments. This section examines how the company should define the type of relationship it wishes to establish with each customer segment. In this context, relationships can be strategic and may be accompanied by a long-term or short-term contract, partnerships, co-development, or other arrangements. These relationships play a crucial role in the company's growth, expansion, and sustainability, contributing to increased sales volumes and market share. This relationship must foster trust, traceability, and transparency (Osterwalder et al., 2010).

- **Cost structure**

The cost structure outlines all expenses involved in operating a business model, including the main costs incurred in its execution. These costs can be calculated more easily once key resources, key activities, and key partnerships are identified (Osterwalder et al., 2010).

- **Revenue streams**

The revenue stream block represents the income generated by a company from each customer segment. It involves determining the value that customers are willing to pay for. Each stream can follow various pricing mechanisms. This block is essential for a company to maximise shareholder wealth(Osterwalder et al., 2010).

Table 1:Osterwalder BMC block

Keys Partners	**Keys Activities**	**Value Proposition**	**Customer relationships**	**Customer Segments**
	Keys resources		**Channels**	
Costs Structure		**Revenue Streams**		

Source: *(Osterwalder et al., 2010)*

4. Data collection

Data collection for this master's thesis primarily relies on secondary sources, including scientific articles, government reports, institutional publications, and policy documents from Senegal and Germany. For the literature review, academic databases such as Google Scholar, Elicit, and Scopus were used to collect relevant sources. The data collected for the thesis includes both qualitative and quantitative information. Quantitative data, including hydrogen prices, investment costs, interest rates, and discount rates, were gathered to calculate costs and revenues. Qualitative data were collected from relevant policy documents, government strategies, and expert studies on green hydrogen, solar, and wind energy. To facilitate the analysis, a financial model was developed to organise and estimate project costs, incorporating CAPEX and OPEX calculations and testing different scenarios.

Key assumptions and parameters

Table 2:Solar and Wind data

Cost type	**Unit**	**Value**	**Reference**
Solar plant Capex	$/kW	600	*(Nizami et al., 2022)*
Solar PV Opex	$/kW	9	*(Nizami et al., 2022)*
The capacity factor of solar	%	20.5	*(IRENA, 2024)*
Wind Onshore Capex	$/kW	1191	*(Allington & Cannone, 2024)*
Wind Onshore Opex	% Capex	2	*(Allington & Cannone, 2024)*
Capacity factor of wind	%	27-37	*(IRENA, 2024)*
Lifespan of Solar Plant	years	25	*(Allington & Cannone, 2024)*
Lifetime of a Wind turbine	years	25	*(Allington & Cannone, 2024)*

Table 3: Electrolyser data

Cost type	Unit	Value	Reference
PEM Electrolyser Capex	$/kW	1100	*(Nizami et al., 2022)*
PEM Electrolyser Opex	% Capex	1.32	*(Nizami et al., 2022)*
Water required	l/kg H_2	9	*(Silhorko-Eurowater, 2022)*
Water price Sones	Francs Cfa /m3 USD/m3	878,35 1.5	*(Quotidien, 2022)*
Stack Replacement Cost	$/kW	420	*(Bhandari & Shah, 2021)*
System efficiency PEM	%	75	*(H-TEC SYSTEMS, 2023)*
Lifetime stack	hours	60,000	*(Fraunhofer ISE, 2021)*
Electricity	kWh/kg H_2	53	*(H-TEC SYSTEMS, 2023)*
PEM electrolyser lifetime	years	25	(Kotowicz et al., 2024a)

Table 4: Compressor and liquefaction data

Cost type	Unit	Value	Reference
H_2 compressor capex	€/kW	2440	(Terlouw et al., 2022b)
H_2 Compressor OPEX	% Compressor CAPEX	4	(Terlouw et al., 2022b)
Compressor Power requirements, installed	kWh/kg H_2	2.2	*(The Linde Group, 2022)*
H_2 Compressor Lifetime	years	10	(Terlouw et al., 2022b)
Energy consumption for water treatment	kWh/m 3	0.79	*(Y. Zhang et al., 2018)*
Energy required for H_2 liquefaction	kWh/kg	13–15	*(Geng & Sun, 2023)*
Cost purification system	% Of electrolyser capex	1-2	*(Fraunhofer ISE, 2021)*

Table 5: Storage data

Cost type	Value	Unit	Reference
H_2 Storage CAPEX	€/kgH_2	460	(Terlouw et al., 2022b)
H_2 Storage OPEX	% Of Storage CAPEX	1	(Terlouw et al., 2022b)
O_2 Storage capex	$/m3	40.09	*(Sollai et al., 2023)*
O_2 Storage Opex	% Of Capex	3	*(Sollai et al., 2023)*
O_2 Storage lifespan	years	20-25	*(Lorenzo Cotula et al.,2022)*
H_2 Storage Lifetime	years	20	(Terlouw et al., 2022b)

Table 6: Logistics and cost data

Cost type	Unit	Value	Reference
Insurance, local taxes and fees	% Of the CAPEX	1	*(Collodi et al., 2017)*
H_2 Price Germany	€ per kg to USD per kg (exchange rate 17/08/2025)	8 -10 to 9.35-11.69	*(Winterbourne, 2024)*
Shipping Distance from Dakar port to Hamburg port	km	5,249.42	*(Sea-distances, n.d.)*
Shipping Cost	USD/kg	1-2	*(Sophanna, 2024)*
Oxygen price	USD/tonne	75 to 100	*(Sollai et al., 2023)*
Carbon price	USD/tonne	50	*(Carbon commentary, 2020)*
Cost of transporting compressed gaseous hydrogen gas tanks	USD/kg	0.1-1	*(Sophanna, 2024)* *(Hydrogen Council, 2021)*
CO_2 emission from transport of H_2 by Ship	kg CO_2 eq. per tonne kilometer for freight ship and tank	0.00198	*(Yusuf Bicer a, b,*, 2017)*
CO_2 emission from transport of H_2 by truck	CO_2/tkm	52.7	*(Simon Suzan, 2021)*
Carbon content from gray hydrogen	kgCO_2/kg H_2	9	*(Schlissel et al., 2022)*
Discount rate	%	5	(Kotowicz et al., 2024a)
Electrolyser operating hours	hours	4500	*(Proost, 2020)* *(CONNAISSANCE DES ÉNERGIES, 2024)*
Project lifetime	years	25	*Author*

5. Data processing and analysis

The collected data were processed and analysed using a combination of qualitative assessment and quantitative modelling techniques to evaluate the financial feasibility and strategic viability of green hydrogen exports from Senegal to Germany. The qualitative data were analysed thematically and integrated with quantitative findings to provide a contextual understanding of the project. The quantitative model enabled the calculation of financial indicators by applying a 5% discount rate over a 25-year project lifespan. It integrated key financial formulas, including net present value (NPV), internal rate of return (IRR), return on investment (ROI), and payback period calculations, to evaluate the project's financial performance.

5.1 Financial Modelling Approach

The financial modelling approach applied in this study was designed to calculate and evaluate the financial feasibility of the green hydrogen export project. It organises the data, including technical parameters such as annual renewable energy production, electrolyser sizing, water consumption, CAPEX, and OPEX, to calculate key financial indicators like NPV, IRR, ROI, ROE, and payback period. Assumptions such as a 25-year project lifespan, a 5% discount rate, linear equipment depreciation, and cost projections for 2030 and 2050 were incorporated. This approach also enables sensitivity analysis, highlighting the parameters that have the greatest impact on project profitability and allowing for anticipation of risks and areas for improvement.

5.2 Financial Indicators for Project Evaluation

To evaluate the financial feasibility and strategic viability of the green hydrogen export project, a set of key financial indicators is employed. These indicators provide insights into profitability, investment attractiveness, and risk, supporting informed decision-making and ensuring that the project contributes to a sustainable business model. Each indicator is applied to assess different aspects of project performance, from long-term value creation to operational efficiency(Delapedra-Silva et al., 2022).

5.2.1 Net Present Value

NPV is a financial metric that evaluates a project's profitability by comparing the expected future cash flows to the initial investment, discounted to present value using a specific discount rate(Delapedra-Silva et al., 2022).

NPV Formula:

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{\mathrm{Ct}}{(1+\mathrm{r})} - \mathrm{C0}$$

Where:

- Ct = Cash inflow at year *t*

- C0 = Initial investment (CAPEX)
- r = Discount rate
- t = Year
- n = Project lifetime in years

5.2.2 Interest rate of return

The internal rate of return (IRR) is a metric used to assess renewable energy and hydrogen projects with NPV. It is expressed as the interest rate at which the project's NPV is zero. The IRR formula is based on setting the net present value (NPV) of all future cash flows to zero(Delapedra-Silva et al., 2022).

IRR Formula:

$$0 = \sum_{i=0}^{N} CFi(1 + IRR)^{-i}$$

5.2.3 Return on Investment

The ROI, defined as the annual cost savings over the invested capital or as the average yearly net profit over the invested capital, is also a standard criterion used for analysing the economic viability of RES projects(Delapedra-Silva et al., 2022).

Formula:

$$ROI = \frac{Annual\ Return}{Investment} \times 100$$

5.2.4 Return on Equity

Return on equity (ROE) is an indicator used to measure the profitability of a project or company in relation to the equity invested by shareholders (or owners). It demonstrates the effectiveness of equity in generating profits(Delapedra-Silva et al., 2022).

Formula:

$$\mathrm{ROE} = \frac{\text{Net income}}{\text{Equity}} \times 100$$

5.2.5 Payback period

The payback period is a measure that indicates how long it takes to recover the investment in a project. It is a simple and commonly used metric to evaluate the risk and liquidity of an investment(Delapedra-Silva et al., 2022).

Formula:

$$\text{Payback Period} = \frac{\text{Initial Investment}}{\text{Annual net cash inflow}}$$

5.2.6 Debt Service Coverage Ratio (DSCR)

The debt service coverage ratio (DSCR) is a key financial indicator that measures a project's ability to generate sufficient net operating income to cover its debt obligations, thereby assessing the bankability of projects (DeChesare, 2025; Tomlinson, 2021).

Formula:

$$\text{DSCR} = \frac{\text{CFADS}}{\text{DS}}$$

5.2.7 Learning Curve Model or Wright's Law

The Learning Curve Model describes how the unit cost or time to produce a good decreases systematically as cumulative production increases, due to the gains in experience and efficiency improvements(Revinova et al., 2023).

Formula:

$$\text{Cn} = \text{C0} \times \left(\frac{\text{Qn}}{\text{Q0}}\right)^{\log 2(1-\text{LR})}$$

6. Selected Business Model Approach

The Investment for Emission Reduction (IER) business model was chosen for this thesis as it directly links financial returns to measurable reductions in greenhouse gas emissions, aligning with the decarbonization objectives of Senegal and Germany(Yang et al. 2024a).In this model, the company invests in green hydrogen projects and generates revenue by selling hydrogen to customers(Yang et al. 2024a).

From a strategic perspective, the IER model integrates carbon markets, where companies with high fossil fuel energy consumption must purchase carbon credits, making green hydrogen a valuable asset for emission reduction(Yang et al. 2024a). This creates a dual benefit: customers reduce their fossil fuel dependency and achieve regulatory compliance under mechanisms such as the EU Green Deal and CBAM, while the company generates financial returns.

7. Value chain of the project

This research outlines a complete value chain for exporting green hydrogen from Senegal to Germany. It begins with electricity generation from solar and wind energy, supported by water supply from Sones, enabling hydrogen and oxygen production through electrolysis. The gases are stored in tanks, with part of the hydrogen and all oxygen supplied locally in Senegal, while the remaining hydrogen is exported to Hamburg, Germany. This framework allows the identification of economic model components while considering the project's technical and logistical requirements.

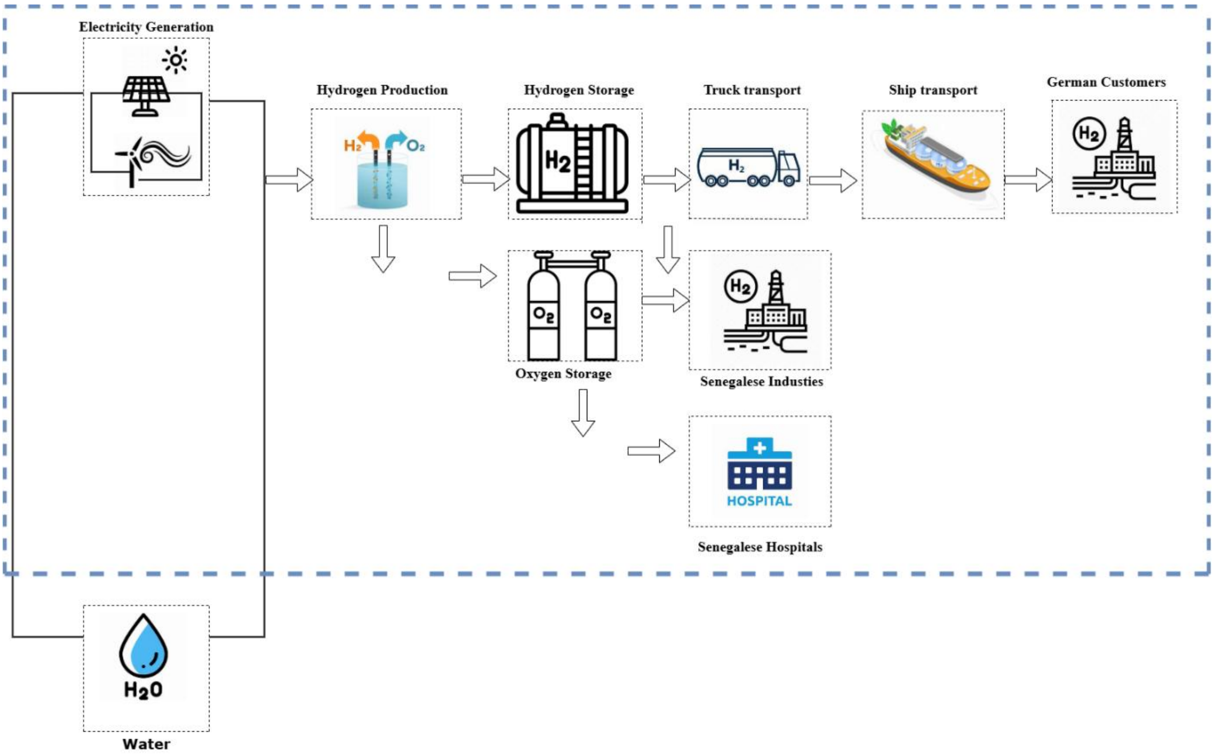

Figure 3:Value chain of the green hydrogen project

***Source**: Own figure*

Having outlined the methodological approach and analytical framework, the following chapter presents the main results obtained.

Chapter III: Results and Discussion

This chapter presents the main results of the study, focusing on the feasibility and strategic viability of exporting green hydrogen from Senegal to Germany. It is organised into sections that outline the project results, provide a sensitivity analysis of critical parameters, and conclude with a discussion of the implications for sustainable business strategy.

1. Results of the Business Model Canvas

This section presents the main findings related to the 9 components of the BMC. It begins with a description of the outcomes for each part of the Business Model Canvas. It begins by identifying key partners, key resources and key activities along the hydrogen value chain, from project planning, permitting, and infrastructure development in Senegal to storage, liquefaction, and maritime transportation of green hydrogen to Hamburg, Germany. It also highlights the other components of the BMC, such as the value proposition and customer segments.

1.1 Keys Partners

The success of the green hydrogen export business model depends on a strong ecosystem of strategic partnerships that encompasses the entire project value chain. This relies on the company's robust relationships with stakeholders in both Senegal and Germany. This has been achieved by identifying key partners across the complete hydrogen value chain, from project planning, permitting, and infrastructure development in Senegal, to storage, liquefaction, and maritime transportation of green hydrogen to Hamburg, Germany. These key partners include:

1.1.1 Project planning & construction permits

The planning and construction phase is vital to the project's success. It must build strong partnerships to ensure the technical, regulatory, and social feasibility of the project. The company needs to collaborate with the Ministry of Petroleum and Energy for regulatory approval and energy policy alignment, the Ministry of the Environment for environmental permits, and local municipalities for land-use authorisations and community integration. It must form partnerships with consulting firms specialising in solar and wind power for feasibility studies, environmental and social impact assessments, and site design. Collaborating with universities and vocational training centres is crucial for mobilising and training local human resources and ensuring the availability of qualified workers. For construction and installation, SolaireDirect, a subsidiary of Engie, has been chosen for the installation and construction of the solar plant due to its expertise and experience in executing large-scale projects. The company must also engage with development finance institutions and climate funds to unlock capital before construction and help mitigate project risks. Cooperation with local communities and civil society organisations is equally essential for building trust, ensuring social acceptance of the operation, and preventing land conflicts. These partners provide the institutional, technical, and human support necessary to transition the project from concept to viable construction.

1.1.2 Renewable Energy Technology Suppliers and Developers

- **Solar Energy plant**

As part of the project's development, renewable energy technology suppliers play a key role in providing and installing the equipment necessary to generate green electricity, a fundamental pillar of the electrolysis process. A vital project requires reliable partners. Kama Solaire and Solektra International, major players in the deployment of photovoltaic solar energy in Senegal and West Africa, have been selected to supply photovoltaic panels, inverters, and mounting systems. Solektra has partnered with Sunna Design to launch the first solar streetlight assembly plant in Africa, with a production capacity of 30,000 units per year(Johnson, 2017). For electrical wiring, connections and protection devices, Cofisec and Eiffage Senegal were selected due to their recognised expertise in this field. Eiffage notably carried out major works for SENELEC, including the construction of transmission lines and 225 kV substations(EIFFAGE, 2018). The company also co-developed the Ten Merina photovoltaic solar park of 30 MW (EIFFAGE, 2024).TSE (Touba Solar Energy) and Senstock are distinguished by their specialisation in transformers and grid integration. They have technical expertise adapted to the local context, essential to guarantee the stability of solar connections in Senegal. These players can therefore be selected as strategic partners for the supply of transformers, switching equipment, and grid integration components.

- **Wind Energy plant**

Wind, like solar, is one of the key pillars of the project for supplying electricity to the electrolyser. This highlights the importance of strategically selecting partners to ensure they have the appropriate equipment for the project's conditions. For wind power generation equipment, Vestas was chosen for its recognised technological expertise and extensive experience in design, installation, and maintenance. Vestas offers the latest generation of turbines, such as the V236-15.0 MW, which provide optimal energy efficiency and high power outputs. It has an installed capacity of 100 GW across more than 39 countries(Matt Copeman, 2024; Vestas, 2025). The company is also the supplier of the Taïba power plant, which is already operational in Senegal, providing a solution tailored to Senegalese conditions.

1.1.3 Hydrogen production suppliers

For the successful implementation and proper operation of the electrolyser, establishing a strong partnership with companies involved in manufacturing equipment for this phase is essential. Among these potential partners, Siemens Energy was selected for its cutting-edge technology and innovative solutions, such as PEM, which are adapted for harnessing the volatile energy produced from wind and solar power. Thanks to their high efficiency and power density, their PEMs produce high-quality gas with minimal maintenance requirements. A key partner based in Germany, Siemens, manufactures PEM electrolysers designed for the planned production capacities. This supply will facilitate the production of high-quality hydrogen(Gathmann, 2023; Siemens, 2025). Such a partnership could benefit from a transfer of knowledge and strengthen the project's credibility with international donors and government institutions.

Besides water electrolysis, additional equipment is vital to ensure product quality and safe export to Germany, thereby ensuring the project's success. Ultrapure water is crucial for maintaining water quality. A partnership with the German company EnviroFALK has been identified to provide expertise and equipment for producing ultrapure water in Senegal, which is vital for the performance and longevity of electrolysers. Their expertise will ensure a reliable supply of filtered water, thereby limiting electrolyser corrosion and extending its lifespan. Once the hydrogen is produced, it can be compressed for storage and transport. A company like Linde Engineering (Germany) could supply the compressor. Linde Engineering offers advanced solutions with high-pressure hydrogen compressors, storage, and liquefaction systems. To export green hydrogen to Germany, it must be liquefied to reduce its volume and facilitate its long-distance maritime transport. Linde is recognised as a manufacturer of advanced hydrogen liquefaction technologies. This partner could design modular units adapted to the project's capabilities. Linde Engineering (Germany) could be a reliable partner to meet these requirements.

1.1.4 Storage

For efficient and reliable export of hydrogen to Germany, once green hydrogen is produced, compressed, or liquefied, it must be temporarily stored. In this context, we have identified a trusted partner, a large company in this field. Linde is a leading supplier of cryogenic tanks, offering standard designs of the highest quality alongside customised solutions to meet customer needs. They have supplied over 20,000 cryogenic tanks for liquefied gases, demonstrating their extensive experience in this field (Linde Engineering, 2025). A partnership with this supplier would ensure secure and certified storage that complies with regulations.

1.1.5 Transport of H2 to Hamburg

Green hydrogen must be transported to customers by truck and ship. Forming partnerships with these carriers is crucial for the project's success. For road transport, Total Energie was chosen due to its existing logistics infrastructure, truck fleet, and expertise in fuel distribution. For maritime transport, Kawasaki Heavy Industries was selected due to its expertise in liquefied hydrogen carrier vessels. For example, the Suiso Frontier, the world's first liquefied hydrogen carrier, benefited from Kawasaki Heavy Industries' technical expertise (HESC, 2025). This logistics system requires extremely high safety standards to prevent losses and incidents, and it relies on partnerships with operators experienced in the cryogenic transport of liquefied gases.

1.2 Key resources

1.2.1 Project planning & construction permits

The success of the green hydrogen export model depends on a set of key resources. During the project planning and construction phase, several essential resources are needed to move the green hydrogen project from concept to realisation. Project planning is the initial step to ensure the project is technically feasible. A vital resource for this phase is obtaining construction permits, which are crucial for access to land, infrastructure, and regulatory security. These permits serve as an important institutional resource for legal compliance and also indicate government support. Securing land access for solar and wind farms requires a permit application. The project also requires qualified human capital, including engineers, technicians, project managers with expertise in infrastructure development, environmental specialists, and personnel to design, operate, and maintain complex infrastructure. Additionally, environmental licences are necessary to show compliance with standards, and simulation software such as Homer and PVSYST facilitate project studies. Access to financial capital through equity, concessional loans, and climate finance is crucial for mitigating risks associated with initial investments and covering high upfront costs. These resources are fundamental for implementing technical and administrative activities across the hydrogen value chain.

1.2.2 Renewable Energy Production

- **Solar Plant**

Solar energy production relies on essential resources to ensure proper functioning and performance. These include photovoltaic solar panels that convert solar energy into electricity, inverters to convert direct current into alternating current, and transformers to regulate system voltage levels. Additionally, wiring and connectors, regulators, and mounting structures for the solar panels are necessary. WISE (meteorological and irradiation sensor equipment) is also vital for monitoring environmental conditions. Switchgear and protective devices maintain electrical safety and control the system. Lastly, lightning protection systems, grounding equipment, fencing, physical security infrastructure, and monitoring and control units are critical for tracking performance and identifying faults. These resources are fundamental for solar infrastructure.

- **Wind plant**

Wind power generation requires substantial resources for operating the Wind Plant. These include wind turbines, transformers, switchgear, cabling, and control systems. These technical and logistical resources are vital for establishing a reliable wind power system that ensures a supply of renewable electricity.

1.2.3 Green hydrogen production

The green hydrogen production phase requires a set of essential technological and infrastructural resources. PEM electrolysers are crucial for splitting water into hydrogen and oxygen using renewable electricity. This process demands water purified through water purification, and compressors are necessary to pressurise the hydrogen gas. Liquefaction plants are necessary to convert hydrogen into a liquid form, thereby reducing its volume and facilitating long-distance transport. The production system also relies on control units, safety and monitoring systems, and cooling systems. Collectively, these resources establish a low-carbon, efficient, and scalable system for producing green hydrogen, suitable for international export.

1.2.4 Storage

The resources required for hydrogen storage include systems such as high-pressure tanks or cryogenic containers, which are essential for safely storing hydrogen prior to export. This technology requires specialised cryogenic equipment and the storage of hydrogen or oxygen.

1.2.5 Hydrogen Transport

The primary resources for hydrogen transportation include high-pressure hydrogen transport trucks, which are suitable for short distances. Shipping liquid hydrogen by tanker is necessary for international export to Germany. These vessels require port facilities equipped with cryogenic storage tanks, loading arms, and hydrogen safety systems.

1.3 Key activities

1.3.1 Project planning & construction permits

Project planning and construction involve a series of activities crucial for their successful execution. Key steps include conducting a technical feasibility study to assess the availability of solar and wind resources, as well as procedures for site selection and acquisition. It also entails evaluating economic and environmental feasibility. Furthermore, it encompasses the design and construction of facilities and infrastructure, along with liaison with relevant authorities to obtain permits and licences. Moreover, mobilising and training human resources through capacity-building programmes for engineers and technicians is essential to developing a skilled workforce. The acquisition of land for the project, infrastructure development, and engaging local communities are also fundamental. Finally, securing seed funding and launching community engagement activities are vital for establishing an inclusive and sustainable project from its start-up phase.

1.3.2 Renewable Energy Production

- **Solar**

The implementation of a solar power plant involves a series of activities. These include the assembly and installation of mounting structures, followed by the installation of panels, wiring, and DC electrical connectors. The energy generated will be converted into alternating current (AC) by the installed inverters. Transformers are integrated to ensure an appropriate voltage for downstream applications, such as hydrogen production. Energy production cannot occur without prior protection of the entire installation against hazards such as lightning. Therefore, protection systems, switching devices, and fences are installed to ensure safety. The system also requires remote performance monitoring. In addition to installation and integration, operation and maintenance are essential activities to ensure the system's performance throughout the project. Preventive maintenance involves regular cleaning of photovoltaic panels, inspecting electrical connections, monitoring electrical devices, and replacing components as needed. Corrective maintenance is performed in the event of issues. All these maintenance activities help extend the operational life of the solar power plant.

- **Wind**

The construction of a wind farm for the project involves key activities to ensure proper operation. These activities include assembling and mounting the wind turbines, such as installing blades, nacelles, and towers designed for efficient wind energy capture. Electrical work involves installing cabling, switchgear, grounding systems, and transformer substations to ensure the safe and stable transmission of electricity. Additionally, integrating control, monitoring, and data acquisition (SCADA) systems allows for continuous oversight of wind speed, turbine performance, and total production. Once the system is commissioned, grid testing and synchronisation verify its compatibility with local energy infrastructure. After installation, routine maintenance and safety inspections are carried out regularly to guarantee reliability and reinforce protective measures such as fencing and lightning rods. Each of these activities is essential to converting wind energy into usable power in a safe, scalable, and efficient way.

1.3.3 Hydrogen production

The activities involved in producing green hydrogen include supplying ultrapure water, providing power to the water electrolyser, and managing and operating the electrolysers. This also encompasses hydrogen treatment through compression or liquefaction, as well as the installation and maintenance of cooling systems. Additionally, it involves installing control units, security and monitoring systems, and cooling systems.

1.3.4 Storage

Key hydrogen storage activities include designing storage systems, selecting compatible materials, installing high-pressure or cryogenic tanks, setting up monitoring and safety systems, and performing regular maintenance to ensure safe and efficient containment.

1.3.5 Hydrogen transport from Port Dakar to Hamburg port

Key activities in hydrogen transportation include selecting the suitable method for transporting the product, ensuring the product's safety, integrating leak monitoring and detection systems, complying with transportation regulations, and maintaining infrastructure for safe and efficient delivery.

1.4 Value proposition

This thesis proposes high-purity green hydrogen for Senegalese consumers and its export to German markets. It also supplies oxygen as a valuable by-product to Senegalese industries, while supporting national decarbonization efforts, thereby generating local socio-economic and environmental benefits.

1.5 Channels

For the effective marketing of hydrogen from Senegal to Germany, it is vital to establish distribution channels suited to the market. Transporting the product to customers is also crucial. The hydrogen will be moved by truck from the production site to the port of Dakar. This mode of truck transport is preferred for its flexibility over short distances and its lower cost compared to pipelines and trains. From this port, the hydrogen will be shipped to Hamburg. These ships are specialised for transporting liquefied hydrogen. Due to the long distance, ship transport is the preferred method for moving hydrogen from Senegal to Germany. Besides logistics, the company's communication channels with customers are equally important. Online platforms can facilitate connections between the company and its customers. These channels ensure the reliable and traceable delivery of valuable resources from Senegal to Germany.

1.6 Customer segments

The green hydrogen export project to Germany targets customers in the German industrial and transport sectors, as well as clients in Senegal. These potential customers include large companies actively seeking green hydrogen at competitive prices to decarbonise their industries. On the German side, two key segments include prospective customers who are members of the Hydrogen Hamburg network. This network unites industrial players located in the major competitiveness cluster in northern Germany. It brings together manufacturers, infrastructure developers, and policymakers with the goal of reducing fossil fuel use by promoting the use of green hydrogen. Within this network, two specific customers have been identified: ArcelorMittal, a steel producer transitioning from carbon-intensive processes to hydrogen-based methods, and the Hamburg Port Authority, a logistics operator at the Port of Hamburg aiming to decarbonise its heavy-duty vehicle fleet using hydrogen fuel. These partners represent sectors with high demand that are difficult to decarbonise but are actively seeking clean alternatives. In Senegal, the selected client is ICS, a local fertiliser producer considered a potential major national buyer. By using green hydrogen to produce low-carbon ammonia, ICS supports national food security while reducing emissions from a key industrial sector. Besides exports to Germany, the project facilitates local value addition by selling hydrogen to Senegalese industries and oxygen to hospitals. These oxygen customers could include hospitals and industries in Senegal. The oxygen can also be utilised by sectors such as welding and metalwork. This local value addition encourages the creation of national added value, promotes green industrialisation, and bolsters the project's social and institutional acceptability.

1.7 Customer Relationship

To promote market stability and build investor confidence in exporting green hydrogen from Senegal to Germany, the project prioritises long-term contracts with German and Senegalese customers for the sale of hydrogen and oxygen. Additionally, these contracts often have a duration of 10 to 20 years, which reduces market risks and secures revenues(Crouch, 2021). To reinforce these relationships, it would be beneficial to include strategic partnerships with German stakeholders to co-invest in production, transport, or conversion infrastructure. Regular environmental compliance reports and technical guarantees will help foster trust, ensuring that green hydrogen meets German standards for purity and complies with European regulations. Ongoing, transparent communication regarding performance will further strengthen long-term customer relationships. This structured approach enhances Senegal's reputation as a hydrogen-exporting nation and supports Germany's efforts to diversify its clean energy sources through stable and cooperative partnerships.

1.8 Revenue

The main source of revenue for the project will primarily come from selling green hydrogen to German customers at 8 USD/kg and to Senegalese customers at 5 USD/kg. In addition to hydrogen sales, revenue will also be generated from the sale of oxygen. This oxygen can be supplied to Senegalese hospitals and industries at 88 USD/tonne, thereby supporting oxygen provision to hospitals. By accessing both the German and Senegalese markets, the project ensures diverse and resilient revenue streams. A further significant part of the expected revenue will derive from carbon credits at 50 USD/tonne from German clients. Collectively, these mechanisms enhance the economic sustainability of Senegal's hydrogen export strategy.

1.9 Cost structure

High initial capital expenditures and long-term operating costs mainly determine the cost structure of the green hydrogen export project. The main CAPEX includes the development of a solar and wind power plant, electrolysers for hydrogen production, compressors, a hydrogen liquefaction system, and storage tanks. OPEX include routine maintenance of the renewable energy systems, maintenance of the ultrapure water electrolysers, labor costs, water consumption, insurance and miscellaneous, as well as expenses related to the transportation of hydrogen by truck to the port of Dakar and by ship to Hamburg, and other expenses such as land costs, staffing and transportation, certificates, administrative and regulatory fees, etc. These elements highlight a strategic investment approach that, despite high costs, is essential to guarantee export profitability, local socio-economic benefits, and a sustainable hydrogen value chain aligned with international and climate-conscious market demands.

Figure 4 presents the share of the capex of each component used to calculate the total capex.

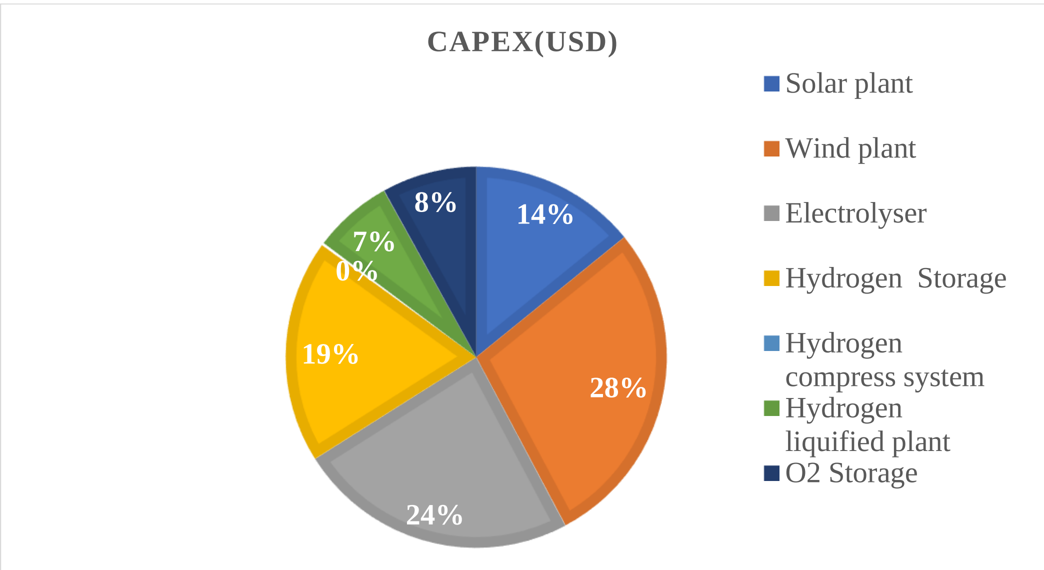

Figure 4:Share of Capital Expenditures

Source: Own figure

Figure 5 represents the share of the Opex of each component used to calculate the total Opex.

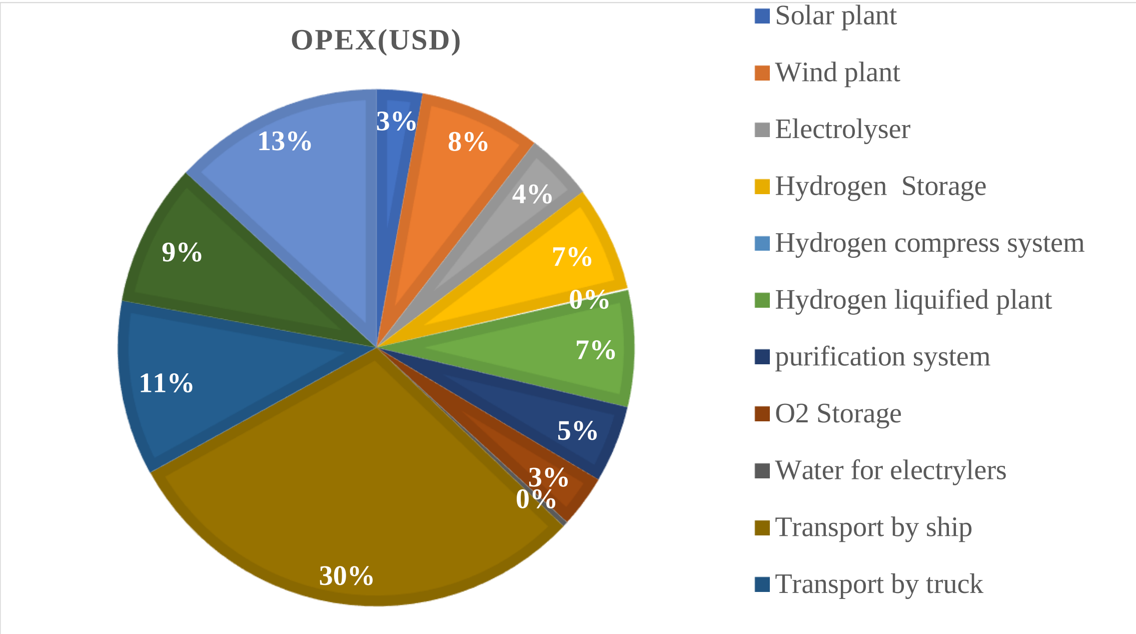

Figure 5:Share of operational expenditures

Source: Own figure

Figure 6 represents the share of the total Capex and cumulative Opex of the project over the 25-year project lifetime.

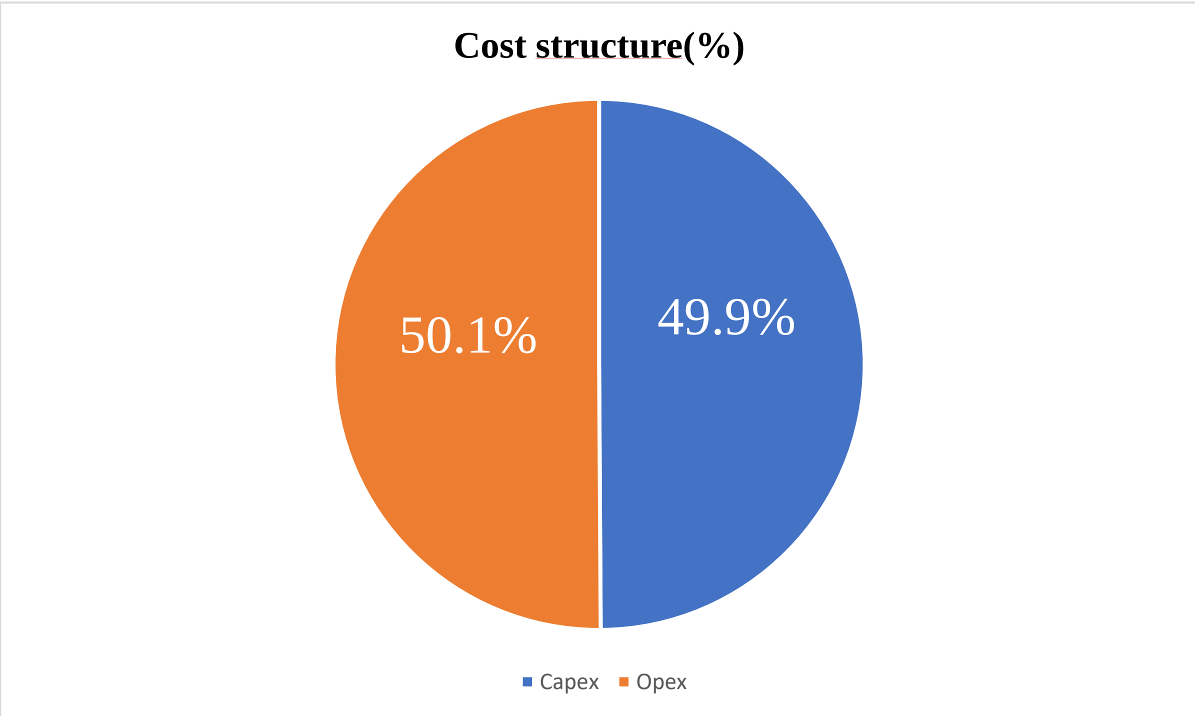

Figure 6:Share of Cost Structure

Source: Own figure

Business model for Hydrogen exports from Senegal to Hamburg, Germany

Table 7: Business model canvas, hydrogen export from Senegal to Germany

<table>
<tr>
<td rowspan="2"><u>Keys Partners</u>

-Senegal Government (Ministry of Petroleum and Energy, the Ministry of the Environment, and local municipalities, Sones)

- Technology companies, technology suppliers (Solar and Wind, electrolyser and liquefaction suppliers, storage)

-Financial institutions (green banks, EU donors)

- Port authorities (Dakar and Hamburg)

- Logistics companies (truck and maritime shipping operators)

-Construction and installation enterprise.</td>
<td><u>Keys Activities</u>

- Project planning and construction permit

- Renewable electricity production (PV & wind)

- Hydrogen production, compressor, and liquefaction.

- Storage of hydrogen

- Hydrogen transport

- Sales of the products</td>
<td rowspan="2"><u>Value Proposition</u>

- High-purity of green hydrogen

- oxygen as a valuable by-product

- Cost-competitive product

- Contribution to decarbonisation sectors for German customers</td>
<td><u>Customer relationships</u>

-long-term contract with customers from Germany and Senegal

-strategic partnerships with German stakeholders to co-invest in production, transport, or conversion infrastructure.

-Regular environmental compliance reports and technical guarantees

-Continuous and transparent communication between the enterprise and customers</td>
<td rowspan="2"><u>Customer Segments</u>

<u>For Hydrogen</u>

-German industry customer: ArcelorMittal

-German transportation customer: Hamburg Port Authority

-Senegalese industry customer: ICS

For Oxygen

-Senegalese industries and oxygen to hospitals</td>
</tr>
<tr>
<td><u>Keys resources</u>

- Solar and wind infrastructure

- Electrolysers</td>
<td><u>Channels</u>

-Delivery by truck to the Port of Dakar, then ship to the Port of Hamburg.

-Online platforms</td>
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</table>

<table>
<tr>
<td></td>
<td>- Water Purification, compression, and liquefaction system

- H_2 storage tanks

- Land and environmental permits

- Labour, Financial capital, and investment

- Access Water

- Software and monitoring systems</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td colspan="3"><u>Costs Structure</u>

- CAPEX: solar and wind plant, electrolysis, liquefaction, storage, compressors.

- OPEX: maintenance, personnel, logistics, water consumption, insurance and miscellaneous, transportation of hydrogen by truck to the port of Dakar and by ship to Hamburg, and other expenses such as administrative and regulatory fees.</td>
<td colspan="2"><u>Revenue Streams</u>

-Sale of green hydrogen to German customers at 8 USD/kg and to the Senegalese customer at 5 USD/kg.

-Sale of oxygen to Senegalese hospitals and industries at 88 USD/tonne.

-Revenue will come from carbon credits at 50 USD/tonne</td>
</tr>
</table>

Source: *Own table*

2. Financial Feasibility Analysis

This section provides the feasibility analysis of the project, divided into two parts. The first part emphasises key financial indicators to assess the project's profitability and attractiveness for investment. In contrast, the second part involves a sensitivity analysis to examine how critical parameters might evolve and impact the project.

2.1 Key Financial Performance Indicators (KPIs)

- **Net present value (NPV)**

The NPV calculation indicates a value of USD 69.24 million, highlighting the high profitability of the project over its 25-year lifespan.

- **Interest rate of return (IRR)**

The results indicate an Internal Rate of Return (IRR) of 12%, which exceeds the project's cost of capital of 5%, suggesting that the project is financially attractive.

- **Return on Investment (ROI)**

The project shows a return on investment (ROI) of 53.12%, showing that the total net profit represents a significant gain compared to the initial capital invested. This result underlines the financial attractiveness of the project and strengthens its ability to attract support from the public and private sectors.

- **Payback period**

The payback period is estimated at 16 years 1 month, indicating that the initial investment in the project will be fully recovered over this period. This result is due to significant investment costs.

- **Return on Equity**

Assuming 65% of the total investment is financed by debt, the result shows a Return on equity (ROE) of -110.25%. This result indicates a significant loss for equity investors, highlighting that the project is not financially attractive in this scenario. The negative ROE shows that shareholders would face reductions in the value of their invested capital.

2.2 Sensitivity analysis

Sensitivity analysis is a vital component in evaluating the financial robustness and resilience of investment projects under different economic scenarios. This section examines how key financial performance indicators, including net present value (NPV), internal rate of return (IRR), return on investment (ROI), return on equity (ROE), and payback period, respond to fluctuations in critical input parameters. These parameters include estimates of hydrogen export prices, capital expenditures (CAPEX), operating expenditures (OPEX) for 2030 and 2050, discount rates, and the inclusion or exclusion of by-product revenues (from oxygen and carbon sales).

Scenarios and Assumptions

- Base scenario (2025): The base scenario represents the standard configuration of the project on which all other calculated variants are based.
- Forecast 2030: Assume hydrogen export price, Capex, and Opex based on market expectations for the year 2030.
- Forecast 2050: Assume hydrogen export price, Capex, and Opex based on market expectations for the year 2050
- Hydrogen Export Prices Decreasing Over Time: This scenario tests a conservative trend in hydrogen price reduction over the period 2025–2050, with the price adjusted annually.
- Without Oxygen and Carbon Revenue: Excludes all by-product revenue streams, focusing only on hydrogen sales.
- Without Carbon Price: Excludes revenue from carbon pricing mechanisms while keeping oxygen revenue.
- Without Oxygen Revenue: Excludes only oxygen sales, maintaining carbon price revenue.
- Discount Rate +1%: Increases the discount rate by 1 percentage point to reflect higher perceived risk or financing costs.
- Discount Rate -1%: Decreases the discount rate by 1 percentage point to reflect lower risk or improved financing terms.

2.2.1 Sensitivity analysis Capex and revenue base case, forecast 2030, and forecast 2050

To reflect the changing nature of the market and technological progress, the sensitivity study examines the development of capital expenditure (CAPEX) and revenue assumptions across three-time frame scenarios: a baseline scenario (2025), a medium-term outlook (2030), and a long-term projection (2050). These projections consider expected cost reductions from technological advancements and infrastructure growth, as well as the potential decline in hydrogen export prices caused by increased global supply and market competition.

- **Capex variations**

Figure 7 represents the variations in capital expenditure (Capex) under the base case, 2030 projection, and 2050 projection scenarios.

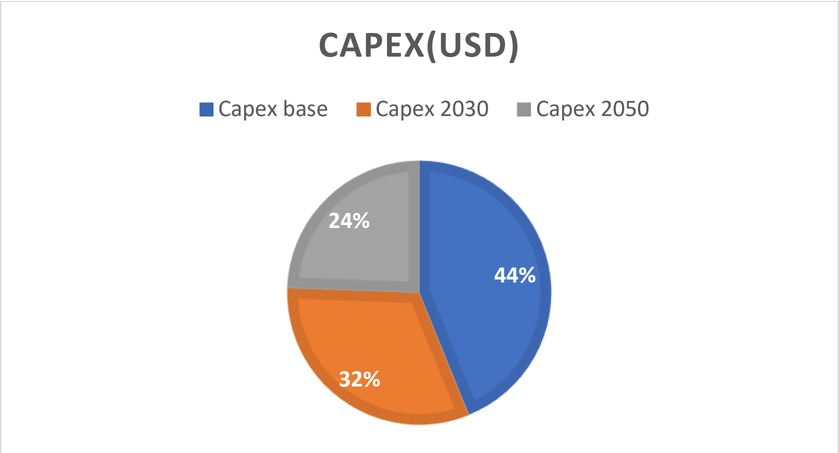

Figure 7:Capital Expenditure (CAPEX) Estimates for Green Hydrogen Project Base Case (2025), 2030, and 2050 Scenarios

Source: Own figure

Sensitivity analysis on Capital expenditure (Capex) variations reveals that the lower the construction cost, the better the project's financial performance. At the baseline level of capital expenditure, the project yields a return of 44%. By 2030, planned costs are expected to be reduced to 32%, and by 2050, to 24%. This reduction, a 20% difference compared to the baseline assumption for 2050, and 12% compared to the baseline for 2030, is due to a decrease in component costs.

- **Revenue variations**

Figure 8 represents the variations of the revenue under the scenario of base case, projection 2030 and 2050.

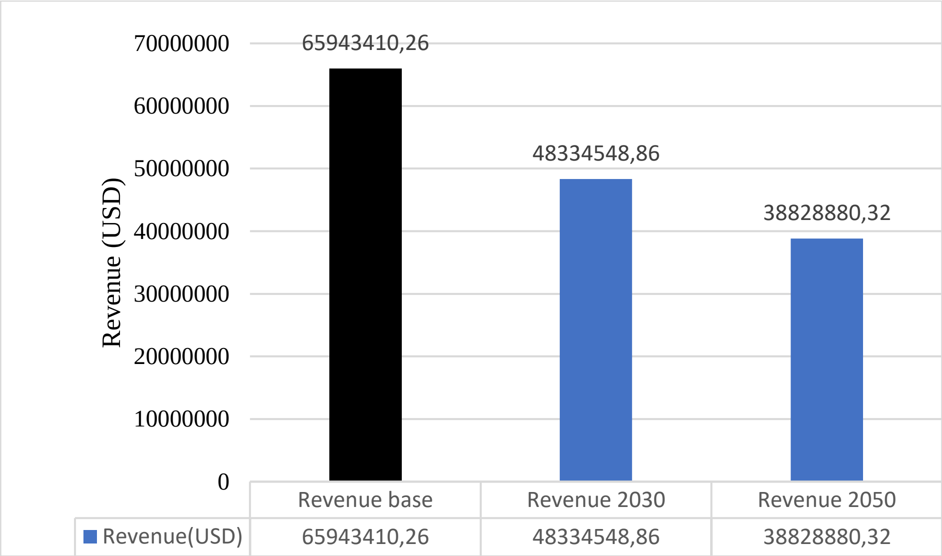

Figure 8: Variations of revenue

Source: Own figure

The sensitivity analysis indicates that as hydrogen prices decrease over time, the project's revenues decline from $65.94 million in the base case of 2025 to $48.35 million in the 2030 projection and to $38.82 million in the 2050 projection. The price reduction affects the project, resulting in a revenue decline under these assumptions

2.2.2 Sensitivity Analysis of Key Financial Indicators

Table 8 presents the key financial performance indicators (NPV, IRR, ROI, ROE, and Payback Period) under various scenarios.

Table 8: Result of sensitivity analysis

Scenario	NPV	IRR	ROI	ROE	Payback period
Base scenario (2025)	69,240,432	12%	53.12%	-110.25%	16 years 1 month
Forecast (2030)	58,712,223	12%	60.25%	94.70%	19 years 1month
Forecast (2050)	64,335,929	15%	74.30%	122.55%	17 years 1 month

Hydrogen Export Prices Decreasing Over Time	-92,367,776	-7%	-28.03%	-270.83%	22 years
Without O2 Sells and carbon price	-47,543,070	1%	4.26%	-206.93%	19 years 9 months
Without a carbon price	29,765,574	8%	36.6%	-144.18%	17 years 3 months
Without O2 sells	-8,068,211	4%	20.78%	-175.25%	18 years 6 months
Discount rate +1%	53,304,177	12%	53.12%	-110.25%	16 years 1 month
Discount rate -1%	88,634,654	12%	53.12%	-110.25%	16 years 1 month

- **Sensitivity Analysis Results (NPV)**

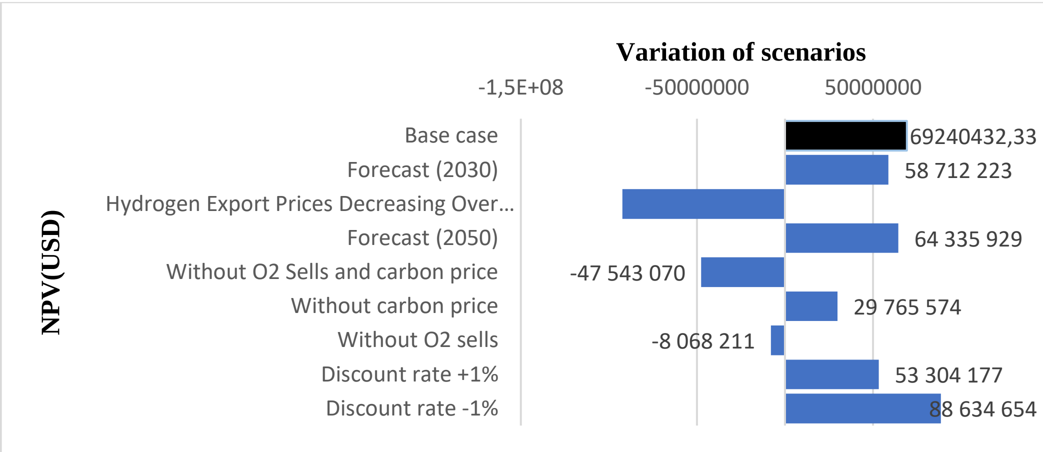

Figure 9:Variations of NPV

Source: Own figure

The analysis of the first scenarios shows that the project remains financially viable in most cases, with a positive NPV. In the base scenario (2025), the result shows an NPV of USD 69.24 million, representing a favourable outcome. By 2030, the NPV decreases to USD 58,71 million, indicating a reduction of profitability compared to the base scenario, emphasising the effect of declining market prices on the project's long-term value. In the long-term forecast for 2050, the NPV rises again to USD 64,33 million, reflecting a partial recovery. However, if hydrogen export prices decline over time (2025–2050), the project shows an NPV of -92,367,776. This negative value shows that falling export prices could make the project unprofitable, highlighting the need for stable prices. The graph also reveals that excluding oxygen and carbon credit revenues from the base scenario results in a negative NPV (-47.54 million USD). Even excluding oxygen alone results in a negative figure (-8.06 million USD), whereas the scenario that excludes only the carbon price remains positive (29.76 million USD). In the scenario of removing oxygen and carbon pricing, the project becomes unprofitable without these essential revenue streams. The NPV rises with a lower discount rate, confirming the project's long-term worth under favourable financing conditions. The value of the project is susceptible to revenue composition; monetising co-products is vital to maintaining viability.

- **Sensitivity Analysis Results (IRR)**

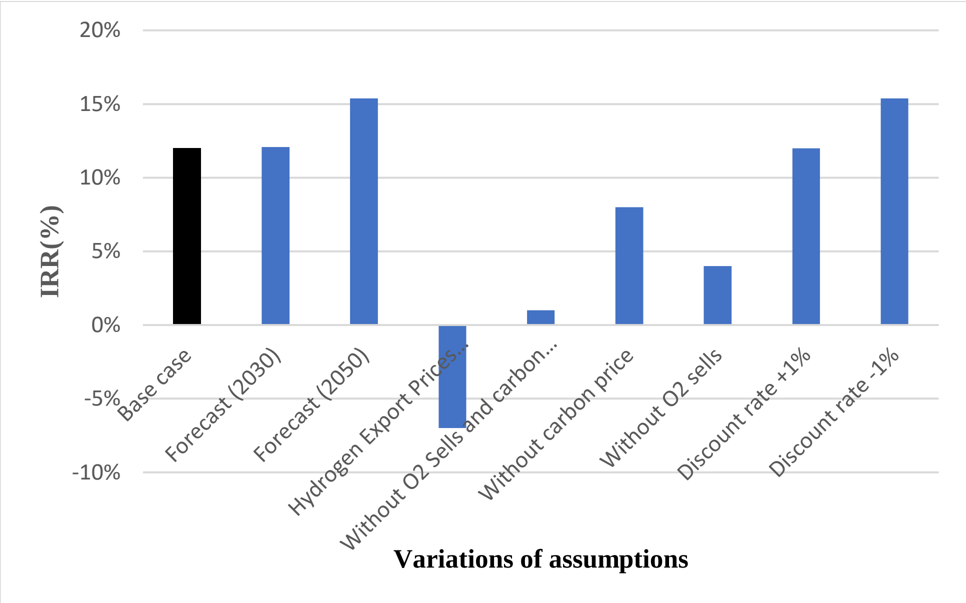

Figure 10:Variations of IRR

Source: Own figure

Like the NPV, the IRR is highly sensitive to the price of hydrogen and capital expenditures. The results of the internal rate of return (IRR) offer a clear overview of the project's investment dynamics under different future scenarios. The forecast for 2030 remains steady at 12%, while the long-term projection for 2050 increases to 15%, reflecting the expected improvement in cash flows and long-term project profitability. However, if hydrogen prices decrease more than anticipated, the IRR drops to –7%, indicating that the project would no longer be financially viable. The impact of co-product revenue streams is particularly crucial. Without O2 and carbon price revenue, the IRR sharply falls to 1%, showing the project's viability is compromised. Similarly, ignoring the carbon price lowers the IRR to 8%, while excluding oxygen revenues results in an IRR of 4% compared to the baseline scenario, making the project only marginally profitable. Overall, the findings suggest that the project's financial viability heavily relies on carbon pricing and the monetisation of co-products like oxygen, with declining hydrogen prices representing the greatest risk to long-term profitability.

• Sensitivity Analysis Results (ROE)

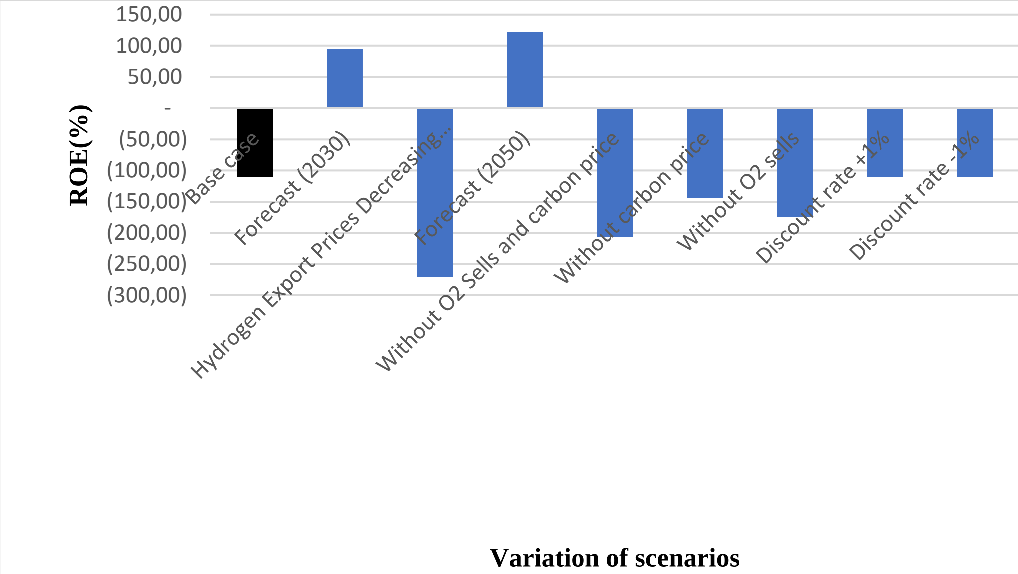

Figure 11:Variations of ROE

Source: Own figure

The sensitivity analysis shows that the project has a return on equity (ROE) of -110.25% in the reference scenario for 2025 due to high initial capital expenditures and limited revenues generated during the early phases of hydrogen production. In 2030, the ROE improves significantly to 94.70%, reflecting the project's increasing profitability through operational efficiency and the recovery of part of the CAPEX. In the long term, by 2050, the ROE reaches 122.55%, demonstrating that the project becomes highly profitable once the investment is fully amortised and stable revenues are achieved. When hydrogen export prices decline sharply over time, the strongly negative ROE of -270.83% indicates that the project would be financially unviable in the event of a price decline. The simultaneous elimination of revenues from oxygen sales and carbon credits results in a dramatic drop in ROE to -206.93%, confirming their essential contribution to overall profitability. The elimination of carbon credits alone or the absence of O_2 sales results in ROEs of -144.18% and -175.25%, respectively, demonstrating that these additional revenue sources are essential to ensure financial competitiveness. Finally, variations of ±1% in the discount rate do not affect the base case ROE, which remains at -110.25%, indicating that the project is relatively resilient to moderate variations in financing costs. These results clearly demonstrate that co-product monetisation is essential to the viability of the business model. Without these revenues, the project loses its financial attractiveness, and investor confidence could decline. Overall, these results demonstrate that, even if the project faces significant initial losses, long-term profitability is achievable, provided that hydrogen export prices remain stable and co-product revenues are optimised.

- **Sensitivity Analysis Results (ROI)**

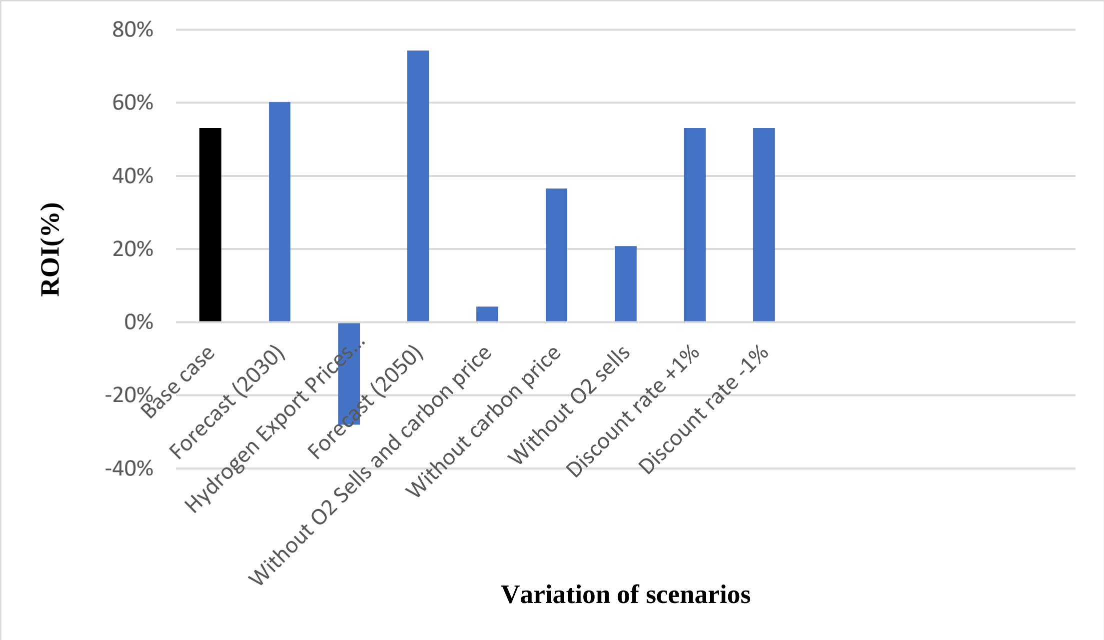

Figure 12:Variations of ROI

Source: Own figure

The sensitivity analysis shows that the project delivers a return on investment (ROI) of 53.12% in the base case, indicating solid profitability with more than half of the invested capital recovered through net profits over its lifetime. Projections suggest an increase in ROI to 60.25% by 2030, driven by higher demand and efficiency improvements. In 2050, ROI reaches 74,30%, showing that over the long term, the project becomes more profitable due to higher net returns. When hydrogen export prices decline sharply over time, ROI decreases by 28.03%, highlighting the business model's high sensitivity to international market price fluctuations. The simultaneous elimination of revenues from oxygen sales and carbon credits causes a dramatic decrease in ROI to 4.26%, confirming their critical contribution to overall profitability. Eliminating only carbon credits reduces ROI to 36.6%, while excluding oxygen sales lowers it to 20.78%, demonstrating that these supplementary revenue streams are vital for maintaining the project's financial appeal. Lastly, a ±1% change in the discount rate does not affect ROI, which stays steady at 53.12%, indicating a degree of resilience against moderate shifts in financing costs. Overall, these findings emphasise that the project's financial feasibility relies as much on favourable market conditions as on co-product optimisation and cost management.

- **Sensitivity Analysis Results (Payback Period in Years)**

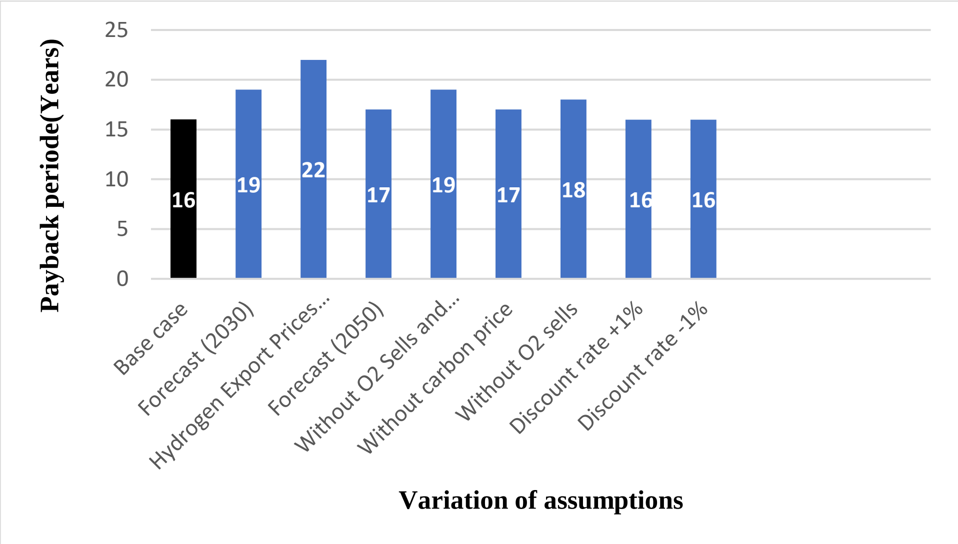

Figure 13:Variations of Payback period

Source: Own figure

The payback analysis offers insight into the project's liquidity and capital repayment profile. This graph indicates a payback period of 16 years and 1 month in the 2025 baseline scenario, which is lengthy but still aligns with a 25-year asset life. Under market and technological conditions, projections for 2030 and 2050 show an increase in the capital payback period to 19 years and 17 years, respectively, despite cost reductions. This could affect investor patience and willingness to finance similar projects. If hydrogen export prices decrease substantially, the investment would be recovered in 22 years, making it very long for investors. The most complex scenario is the "No CO_2 and O_2 Revenue" scenario, with a payback period extending to 19 years. This confirms that losing key revenue streams has a significant impact on liquidity and risk, highlighting their importance for the business case. Other scenarios, such as removing the carbon price alone (17 years and 7 months) or the O_2 price alone (18 years and 4 months), still surpass the baseline scenario with partial revenue reductions and are more manageable. This suggests a lower dependency on carbon value compared to O_2 sales and underlines oxygen valorisation as a priority lever for local industrial applications. Overall, the project is sensitive to price fluctuations, as declining H_2 prices could undermine the investment case. The co-product strategy is crucial, as monetising O_2 and, to a lesser extent, carbon value significantly shortens the payback period. Sensitivity tests on the discount rate also demonstrate the influence of financing terms on cash recovery. A 1% variation in the discount factor does not affect the payback period; it remains unchanged.

Interpretation of financial indicators

Sensitivity analysis revealed that the financial viability of the green hydrogen export project strongly depends on considering all revenues, including the sale of oxygen and carbon credit pricing. Scenarios excluding oxygen, carbon price, or both showed a substantial decrease in NPV, IRR, ROI, and ROE, often rendering the project unprofitable. These results also showed that even if the costs of hydrogen components decrease in 2030 and 2050, leading to improvements in the efficiency of capital expenditures, the decrease in hydrogen prices does not affect the project's profitability. Adjustments to the discount rate also impact the project's value.

3. Discussion

This thesis aimed to design and evaluate a sustainable business model for producing and exporting green hydrogen from Senegal to Germany, using the Business Model Canvas (BMC) framework. This section presents an integrated analysis of the study's results, as presented earlier, considering all blocks of the BMC, as well as the feasibility of certain parameters. The discussion is organised around thematic pillars that encompass the commercial, technical, financial, and strategic aspects of the project, while critically analysing the creation, distribution, and capture of value within the proposed business model.

3.1 Market alignment and value creation

The proposed model aligns closely with Germany's demand strategy for importing green hydrogen at a competitive price from countries rich in renewable resources, to decarbonise their sectors. It also resonates with Senegal’s Vision 2050, which emphasises a structural transformation of the economy, the creation of skilled jobs and the promotion of renewable energies (Ministère de l’Économie, 2024b, 2024a). The green hydrogen project contributes to these objectives while consolidating Senegal's geostrategic position in the global energy transition.

Additionally, the model takes into account both domestic and international markets. For the Senegalese industry, particularly ICS, it offers hydrogen at 5 USD/kg and oxygen as a complementary product. At the same time, it targets German industrial buyers such as ArcelorMittal and Hydrogen Hamburg Port at a hydrogen price of 8 USD/kg. By supplying

7791.531594 tonnes of H_2 per year and 62332.2527 tonnes of O_2 annually, the project addresses both current and projected demand, generating economic and strategic value. It is supporting both Germany's and Senegal's energy security and decarbonisation objectives.

The BMC framework allows for systematically mapping customer segments, value propositions, revenue streams, and customer relationships, which are clearly defined, and helps design a profitable and resilient business model. The project meets both local and international demand, which helps define its value proposition and guides pricing for revenue generation, while maintaining strong customer relationships, which build trust and credibility.

However, the sensitivity analysis highlights a vulnerability to falling hydrogen prices, which could reduce revenue forecasts by 48.33 million USD based on the 2030 forecast and by 38.82 million USD in the 2050 forecast, potentially affecting project profitability. This highlights the importance of early contracts, long-term purchase agreements, and market support mechanisms such as carbon pricing or contracts for difference (CFDs). By integrating these risk mitigation measures into the BMC, the business model not only ensures profitability but also enhances Senegal's competitiveness in the European hydrogen market by securing stable demand and reducing market uncertainty.

3.2 Operational Feasibility and Infrastructure Requirements

The operational success of the project depends on the integration of renewable electricity generation, electrolysers, water supply from SONES, storage, and export logistics via the Port of Dakar. Efficient logistics across the entire value chain is crucial and requires the involvement of all stakeholders. While Senegal benefits from abundant solar and wind resources, the country still lacks hydrogen-specific infrastructure, such as terminals for hydrogen transport.

Some critical operational risks, including water shortages and supply chain delays, could affect timelines and financial performance. The project also entails significant investment costs. Sensitivity analysis reveals that reducing operating expenses can significantly enhance profitability, highlighting the importance of operational efficiency. Within the BMC, these aspects correspond to key resources and key activities, which are essential for operational success.

By guaranteeing a reliable production and export of high-quality hydrogen at a competitive price, the model strengthens Senegal's competitive advantage in the hydrogen export market. It also positions the country as a credible and attractive supplier to Germany. Moreover, the findings show that operational efficiency has a direct impact on cost structure and overall profitability, demonstrating how the BMC framework can translate technical feasibility into a commercially viable and competitive business model.

3.3 Financial viability and risk outlook

The revenue stream of the business model comes from selling hydrogen, oxygen, and carbon credits. The model indicates positive financial performance, demonstrating the project's overall viability. Key financial indicators include an NPV of 69.24 million USD, an IRR of 12%, an ROI of 53.12%, an ROE of -110.25%, and a payback period of 16 years and 1 month, highlighting strong long-term value creation despite initial negative returns for equity holders.

This significant decrease highlights the project's high sensitivity to variations in investment costs, indicating limited financial resilience to these fluctuations. The analysis also reveals risks related to revenue decline or the absence of O_2 sales and carbon pricing mechanisms, which could render the project unprofitable. Revenue variation has a more substantial impact, with NPV decreasing notably as hydrogen prices fall in both the 2030 and 2050 scenarios. These results suggest that cost reductions, while helpful, are not sufficient alone to ensure the project's long-term viability.

Therefore, implementing robust risk mitigation strategies such as fixed-price supply contracts, diversification of revenue streams, sovereign guarantees, concessional loans, and securing low-interest green financing will be essential. Green bonds offer a promising option for providing long-term, low-cost financing for climate-friendly infrastructure, such as renewable energy and hydrogen. The company, with support from the Senegalese government, can issue sovereign or project-linked green bonds in collaboration with multilateral development banks. These elements correspond to cost structure, revenue streams, and key partnerships in the BMC, ensuring that the model remains profitable under varying market conditions.

By linking financial metrics to strategic decisions, the model identifies key factors for competitiveness, including diversified revenue streams, cost efficiency, and financial robustness, which are essential for attracting investors and sustaining long-term export operations.

3.4 Strategy partnership and policy synergy

Partnerships are central to competitiveness. The project's success largely depends on bilateral and multilateral partnerships. Key stakeholders include the Senegalese government, which plays a central role in accessing land, securing water rights, and establishing incentives to attract investment in renewable hydrogen production. Support from SENELEC, the Ministry of Environment, and the Ministry of Petroleum and Energy will be crucial for obtaining regulatory approval and coordinating the network. Partnerships with German customers and all institutions involved in a green hydrogen project are essential. The German auction platform H2Global, along with the KfW investment pipeline, presents promising opportunities for export guarantees and long-term purchases. In addition to these partnerships, Senegal's geographic proximity to Europe provides a logistical advantage that reduces transport costs and enhances competitiveness compared to exporters located further away, such as in the Middle East or Latin America. This proximity, combined with diplomatic cooperation, reinforces Senegal's credibility as a reliable long-term supplier of green hydrogen to Germany. The EU Green Deal, through the Africa-EU Energy Partnership, maintains a partnership with Senegal that closely aligns in promoting renewable energy, energy access, and sustainable development, reinforced by Senegal's Just Energy Transition Partnership.

Development banks and climate finance institutions play a crucial role in mitigating investment risks and providing concessional capital. Harmonising regulatory processes and customs mechanisms is necessary for smooth trade flows. Analyses confirm that political incentives (e.g., carbon pricing) significantly influence financial outcomes. Without carbon pricing, IRR and return on investment decline sharply, which could discourage investors. Nonetheless, this alignment must move from theory to practice. Institutional coordination, streamlining permitting procedures, and diplomatic engagement are required to turn political goodwill into profitable partnerships. The project must also consider the local community, employee working conditions, and other related factors. These considerations align with the key partners block of the BMC, illustrating how strategic collaboration and policy synergy strengthen competitiveness, reduce operational and financial risks, and enhance Senegal's credibility as a green hydrogen exporter to Germany

3.5 Contribution to development and energy justice

In addition to the company's production and marketing objectives, the hydrogen business model not only meets German demand but also supports Senegal's long-term development vision. It aligns with the Senegalese government's ambitions in Vision Senegal 2050 to build "a resilient, inclusive, and low-carbon economy." Through this vision, the government seeks to harness renewable energy's potential to drive industrialisation, create jobs, and improve social well-being(Ministère de l'Économie, 2024b, 2024a). By fostering local value creation, such as employment opportunities, skills development, and increased access to clean energy, the model directly underpins these national objectives. Furthermore, it aims to ensure a fair distribution of benefits among project stakeholders and local communities, echoing the principles of energy justice promoted by Vision Senegal 2050, where sustainable growth and social equity remain central pillars. The hydrogen supplied to local companies helps enhance energy security and decarbonise the industrial sector.

Beyond domestic benefits, the model also strengthens collaboration between Senegal and Germany through shared commitments to climate action and sustainable development. For the project to succeed, revenues from hydrogen exports must benefit local communities. This should be complemented by promoting technology transfer and expanding access to electricity. Involving local actors in decision-making, reinvesting revenues in social programmes, and implementing capacity-building initiatives can further enhance the project's legitimacy and ensure alignment with the principles of energy justice.

Within the BMC framework, these elements correspond to the value proposition, customer relationships, and social impact dimensions**,** illustrating that competitiveness is not limited to economic returns but also depends on legitimacy, social acceptance, and equitable development. By combining profitability with operational reliability and socio-economic benefits, Senegal can position itself not only as a credible green hydrogen exporter but also as a champion of just and inclusive energy transitions.

Conclusion and recommendations

1. Conclusion

Climate change is the most urgent global challenge of our time. The transition to a low-carbon energy system is both essential and urgent. Green hydrogen offers a promising way to decarbonise difficult sectors such as heavy industry, transportation, and energy storage. Although economic and infrastructure challenges still hinder its transition. Nevertheless, findings confirm that Senegal possesses significant renewable resources suitable for green hydrogen production, making it a promising candidate. Moreover, Germany's ambition to import green hydrogen from countries rich in renewable energy presents a substantial market opportunity.

This thesis aimed to design and evaluate a business model that facilitates the production and export of green hydrogen from Senegal to Hamburg, Germany. This study adopted a mixed-method approach combining qualitative and quantitative techniques through the Business Model Canvas (BMC) framework with literature review, financial modelling, and business model analysis. This approach enabled an integrated understanding of both the business strategy and financial viability of the project. The study applied the "Investment for Emission Reduction" model to design the project along the value chain.

The Business Model Canvas emphasises a value proposition centred on environmentally friendly energy trade and economic opportunities for the company, Senegal, and Germany. Key partnerships support this and identify renewable energy infrastructure, electrolysis systems, and export logistics as crucial activities and resources. Financially, the project demonstrates positive indicators in the baseline scenario, including a favourable internal rate of return (IRR), return on investment (ROI) and net present value (NPV) over 25 years. Although ROE is initially negative due to high investment and debt servicing, it improves significantly in 2030 and 2050 scenarios, reflecting increasing shareholder value.

Sensitivity analysis indicates that although initial investment costs (CAPEX) remain high, expected cost reductions by 2030 and 2050 could enhance feasibility. Nonetheless, even with cost decreases, the project remains less viable than the baseline due to low prices anticipated in those years. The study also emphasised the importance of co-product oxygen and the carbon price at the model level. It highlighted the necessity for a regulatory framework to encourage investment, infrastructure development, access to skilled labour, and technological progress. The analysis underlined the importance of risk mitigation strategies to ensure long-term viability. From a strategic perspective, this economic model not only aims to generate revenue but also to create local jobs and foster industrial development. To this end, it should incorporate principles of energy justice, benefit local communities, and facilitate technology transfer to train specialists. Finally, this thesis lays the groundwork for further research into the economic models of green hydrogen derivatives, in response to the growing international demand for green fuels.

2. Recommendations

To enhance the competitiveness and sustainability of Senegal's green hydrogen production and exports to Germany, the following recommendations are proposed:

A. Strategic and Regulatory Framework

• Develop a national green hydrogen roadmap with clear targets and incentives

• Ensure export certification and standards align with EU regulations

B. Financial and Investment Strategy

• Secure long-term purchase agreements with German industrial partners

• Mobilise blended finance (grants, concessional loans, equity) through instruments such as H2Global, the African Development Bank, or EU Green Deal funds

• Foster joint ventures with local energy actors, public institutions, and European developers

C. Human Capital and Local Value Creation

• Implement training programmes for green hydrogen technicians and engineers

• Promote community integration through Environmental & Social Impact Assessments

D. **Infrastructure and Operational Efficiency**

• Streamline land access and permitting for solar/wind infrastructure and electrolysers

• Upgrade Dakar port with hydrogen export terminals

These recommendations can be implemented through coordinated government leadership, blended finance mechanisms, and public-private partnerships. A national roadmap and a simplified permitting system would establish the regulatory framework. In addition, purchasing agreements and platforms such as H2Global could secure investment and market access. Training programs and community integration would ensure local value creation, and the gradual modernisation of the Port of Dakar would establish export infrastructure.

3. Limitations and assumptions

This study offers valuable insights into the feasibility and design of a business model for exporting green hydrogen from Senegal to Germany. However, it has several limitations that should be considered to contextualise the results and guide future research:

• Due to limited access to primary data, this thesis relies on secondary sources, including theories that may not accurately reflect the local context or anticipate future developments, which can introduce uncertainty.

• The Excel financial model used to forecast capital expenditure and production costs for 2030 and 2050 is based on scenarios that may lack precision in predicting future cost reduction trajectories, potentially affecting dynamic market behaviour.

• The research was conducted within a tight academic schedule, limiting the depth of analysis in integrating the environmental and social layers of the Business Model Canvas (BMC).

• The scope of the value chain focuses on the production, storage, and transportation of the product to Germany. Aspects such as the readiness of the Port of Hamburg's infrastructure, distribution, and storage facilities in Germany were not evaluated and could influence the long-term economic viability and sustainability of the business model.

• The model does not account for broader geopolitical uncertainties that might impact cross-border energy trade.

- Although the study considers the policy initiatives and strategies of Germany and Senegal, it does not address the customs implications of hydrogen imports, as bilateral financing instruments could affect competitiveness and profitability.

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Appendix

Table 9:Literature Review on Hydrogen Business Models: Key Findings and Gaps

Author	Focus	Key Points	Limitations
Roland Berger (2023)	Market outlook for hydrogen by 2030	Green H_2 market led by large-scale export projects (e.g., to Germany, Japan). - Export seen as main driver of growth.	- Limited attention to local/regional African markets. - Focus mainly on the demand side (import countries).
Zhao et al. (2023)	Economic models for hydrogen refuelling stations	-Multi-level approach for profitability & infrastructure acceleration. - Focus on station operators and consumers.	- Still theoretical, limited empirical validation. - Demand uncertainty & tech immaturity not fully addressed.
Frontier Economics (BEIS, 2020)	Business models for large-scale low-carbon H_2 in the UK	- Categorises models into four types: (1) contractual payments, (2) regulatory models, (3) end-user subsidies, (4) supply obligations. - Aims to reduce costs and risks.	-UK-specific regulatory context. -Limited adaptability to African policy/market environments.

H. Zhang et al. (2023)	Unified framework integrating clean energy, H_2 systems, and networks (Sweden case)	- H_2 from renewables as long-term storage. - Analyses transport market actors (producers, station operators, heavy-duty vehicles).	- Fragile due to immature technology & uncertain demand. - Heavy reliance on subsidies. - Focused on Sweden, not emerging economies.
Yang et al. (2024)	Hydrogen credit-subsidised business models	- Proposes 3 approaches: (1) Emission Reduction Investment, (2) H_2 Credit Investment, (3) Profit Sharing. -Promotes collaboration across the value chain.	- Still conceptual, with a few pilot applications. - Strong dependence on effective carbon markets.
Deloitte (2023)	Addressing "first-mover dilemma" in H_2 markets	-Identifies uncertainties: demand, regulation, technology, infrastructure, and collaboration. - Business models: take-or-pay contracts, risk insurance, book-and-claim systems.	- More focused on advanced economies. - Limited guidance on financing in high-risk regions (Africa).

Table 10:Table of assumptions

Cost	Unit	Value	Reference
Project lifetime years	**years**	25	*Author*
Discount rate	**%**	5	(Kotowicz et al., 2024b)
PV plant	MW	100	*Author*
Wind plant	MW	100	*Author*
H_2 is liquefied destinated to Gemany customers	% of H_2 produced	80	*Author*
H_2 is compresses to Senegalese customers	% of H_2 produced	20	*Author*

Table 11: Data from local

Cost	Unit	Value	Reference
Solar irradiance	kWh/m2/day	5.8	*(Ministere energy, 2025)*
Wind speed m/s	m/s	6	*(IRENA, 2012)*
Project lifetime years	years	25	*Author*
Land required for electrolyser Siemens	300 MW	15 000 m^2	*(Madheswaran et al., 2022)*
Co2 emission of hydrogen from renewable electricity2 generation	kg CO2-eq/kg	0	*(IEA, 2025)*
Working Capital Rate	15% of the annual change in the total operating costs		*(Energy, 2025)*

Table 12: Learning rate

Type	Unit	Value	Reference
Learning rate Depending on the technologies	%	8-15	*(Lu et al., 2025)*
Carbon price		€70/tCO2 by 2030, €130/tCO2 by 2040, €500/tCO2 in 2044	*(Enerdata, 2023)*

Learning rate Truck transport	%	20	*(Reuß et al., 2021)* *(Hydrogen Council, 2021)*
Learning rate solar Pv	%	14–20	*(Joseph Nyangona, 2024)*
Learning rate Wind	%	8–12	*(Joseph Nyangona, 2024)*
PEM electrolysers	%	10-15	*(Joseph Nyangona, 2024)*
Learning rate hydrogen liquified plant	%	17.13	*(Panji B. Tamarona, Rene Pecnik, 2024)*
Learning rate hydrogen storage	%	10-13	*(Hydrogen Council, 2020)*
Africa price in 2030	€3.2 kgH2 $3.7 kgH2	Exchange rate 1 euro=1.17 dollar 28/06/2025	(Egli et al., 2025b)
Price of H2 in 2050 Africa	1.6 EUR/kg	1.87 USD/kg Exchange rate 1 euro=1.17 dollar 28/06/2025	*(Winkler et al., 2025)*
H2 price cost Germany	3.5 and 6.5 EUR/kg in 2030 and between 2.5 and 4.5 EUR/kg in 2050.	4.09 and 7,60 USD/kg 2.92 and 5.26 USD/kg Exchange rate 1 euro=1.17 dollars 28/06/2025	*(Fraunhofer Institute for Systems and Innovation Research ISI, 2024)*
H2 price cost Germany in 2030	$3-8/kg	Average=5.5 USD/kg	*(Eckert, 2024)*

Table 13: German Demand by Sectors

German demand by sector	Amount in TWh	Source
Steel industry	28–29	*(Nationaler wasserstoffrat, 2024)*
Chemical industry	21–45	*(Nationaler wasserstoffrat, 2024)*
Other process industries	7–8	*(Nationaler wasserstoffrat, 2024)*
Transport sector	33	*(Nationaler wasserstoffrat, 2024)*
Heating market	5–10	*(Nationaler wasserstoffrat, 2024)*
Total	94–125	*(Nationaler wasserstoffrat, 2024)*

Table 14: Potential for future local consumption in Senegal

Presence of fertiliser production	Presence of Chemical Industry	Presence of the Iron and steel industry	Presence of the Petrochemical/ Natural Gas industry	Reference
Phosphate production	Industries Chimiques du Senegal (ICS)	Future projects Iron ore and steel production units	Tortue Ahmeyim liquefied natural gas (LNG) and Yakaar Teranga, projects led by BP in Senegal	(ECREEE ECOWAS, 2023)

Table 15: German needs

German Customers	Unit	Amount	Reference
ArcelorMittal((Steel)	tons of hydrogen per year.	34,360	*(Schutte et al., 2022)*
Hamburg Port		Not mention	

Table 16: Demand estimate for Oxygen for the Hospital

Demand Hospital	Unit	Amount	Source
Peak weekly oxygen need	liters	34,372,800	*(PATH, 2021)*
Maximum weekly supply	liters	51,984,680	*(PATH, 2021)*

Table 17: Average consumption per month in cubic meters, Dakar

Hospital	Unit	Amount	source
Bouffler	m3	600	*(PATH, 2021)*
Hôpital d'Enfant Diamniadio	m3	577	*(PATH, 2021)*
Centre Hospitalier de l'Ordre de Malte	m3	150	*(PATH, 2021)*
Mathlaboul Fawzeini	m3	1,200	*(PATH, 2021)*

Table 18: Assumption demand for hydrogen in the Senegal industry

Industry	**Production**	**Annual production**	**Sources annual production**	**Kg of h2 needed per tonne**	**Sources kg of tonnes needed**	**Demand assumption of hydrogen**
Industries Chimiques du Sénégal (ICS)	H2SO4	1,8 millions de tonnes par an	(Price Waterhouse Coopers Advisory Sénégal SAS (PwC)221, 2025)	50 kg H_2 per tonne H2SO4	Calculated	90 millions kg H_2
Sococim production	Cement	3.5 millions de tonne par an	(Senegal, 2023)	24 kg H_2 per tonne of clinker	(S, 2023)	143,5 millions kg H_2
Dangote	Cement	1.5 million par an 1.6 million	(Senegal, 2023)	24 kg H_2 per tonne of clinker	(S, 2023)	61.5 millions kg H_2
Ciment du sahel	Cement	600,000 tonnes par an	(Senegal, 2023)	24 kg H_2 per tonne of clinker	(S, 2023)	24.6 millions kg H_2
Industries chimiques du Sénégal (Ics)	H2SO4	20000 tonnes par an		50 kg H_2 per tonne H2SO4	Calculated	1 millions kg H_2

Arcelor mittal(Iron)	Iron	15 millions et 25 millions de tonnes Average 20 million	(L Usine nouvelle, 2007)	54 kg per tonne of reduced Iron	.(Series, 2025)	1,080 millions kg H_2
Grande Côte Opérations (GCO)	Zircon	85 000 tonnes de zircon	(Ite, 2024)	33 kg H_2 per tonne of zircon	Calculated	2.8 millions kg H_2
Grande Côte Opérations (GCO)	Zircon	570 000 tonnes d'ilménite	(Ite, 2024)	33 kg H_2 per tonne of zircon	Calculated	18.81 millions kg H_2
Fabrimetal	Iron	350,000 tons	(Seiter, 2023)	54 kg per tonne of reduced Iron	.(Series, 2025)	18.9 millions kg H_2
SAR	Crude oil	1 200 000 tonnes/an 1 500 000 tonnes/an	(SAR, 2025)	26.7 kg per tonne of crude oil	(Minister de l energie, 2025)	32 millions kg H_2
Total demand of hydrogen						1473.11 million kg H_2 =1.473 million tonnes of H_2

Table 19: Keys resources, Keys activities and Keys Partners

Phase of H2 value chain		**Key Resources**	**Key Activities**	**Key Partners**
Project planning & construction permits	**Project planning & construction permits**	Software like (Homer), human capital, permits and licenses	Technical feasibility assessment, economic feasibility assessment, environmental study, infrastructure construction and coordination with the relevant authorities for obtaining permits and licenses, transport logistic	E&P companies (), Bureau d etude Ministry of the Environment, Ministry of Energy/Ministry of Petroleum and Energy, (Eiffage, 2025) Cofisec and Eiffage Senegal
RE production	**PV plant**	PV panel, Inverters, , Wise, land, Labor, Cabling and Connectors, SUPPORT pv panel	Installation of solar plant, Operation and Maintenance, the production of electricity, land acquisition, monitoring and control system	SolaireDirect TSE (Touba Solar Energy) and Senstock Kama Solaire and Solektra International
	Wind plant	Wind Turbines, Land, Labor, Cabling and Connectors, transformers	Installation of wind power plant, Operation and Maintenance, the production of electricity, land acquisition,	**Vesta** (RE)

			monitoring and control system	
Green Hydrogen production	**Electrolyser**	Electricity from RE, water purified, Electrolyser PEM, land, labour, control units, security and monitoring systems, and cooling systems.	Hydrogen production, installation and management of cooling systems, storage of hydrogen, and land acquisition	Siemens Energy (Germany)
	Ultrapure water	Water from SONES, Electricity from RE	The supply of ultrapure water, Water Supply and Purification	EnviroFALK
	Compresseur	Hydrogen compression, Electricity from RE	treatment of hydrogen by compressing it	Linde Engineering (Germany)
	Liquified hydrogen	Hydrogen liquified system, Electricity from RE	treatment of hydrogen by liquefying it	Linde Engineering (Germany)
Storage		Hydrogen storage	Storage of hydrogen	Linde Engineering (Germany)
Transport	**Road transport**	hydrogen transport trucks,	Truck Transport (Road Transport) of Hydrogen,	Total Energies Marketing Sénégal
	Maritime transport	ship liquid hydrogen	Ship Transport (Maritime Transport) of Hydrogen	Kawasaki Heavy Industries, Port autonom of Dakar, Hamburg Port

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