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MASTER THESIS

Specialty: Economics/Policies/Infrastructures and Green Hydrogen Technology

Topic:

Comparative analysis of the cost of Green hydrogen and White hydrogen in Africa: "Case of Bourakébougou, Mali"

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DEDICATION

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Acronyms and Abbreviations

AfDB	:	African Development Bank
AKE	:	Alkaline electrolyzer
CAPEX	:	Capital Expenditure
CCUS	:	Carbon Capture Utilization Storage
CO_2	:	Carbon dioxide
DCF	:	Discount Cash Flow
ECOWAS	:	Economic Community of West African States
EU	:	European Union
EC	:	European commission
GHG	:	Greenhouse gas
H_2	:	Hydrogen
IEA	:	International Energy Agency
IRENA	:	International Renewable Energy Agency
kg	:	Kilogram
kW	:	Kilowatt
kWh	:	Kilowatt-hour
kWp	:	Kilowatt-peak
L	:	Liter
LCOH	:	Levelized Cost of Hydrogen
m^2	:	Square meter
MW	:	Megawatt
NASA	:	National Aeronautics and Space Administration
NREL	:	National Renewable Energy Laboratory
NPV	:	Net Present Value
OPEX	:	Operational Expenditure
PPP	:	Public Private Partnerships
PEM	:	Proton exchange membrane electrolysed
PSA	:	Pressure Swing Adsorption
PtL	:	Power to Liquid
PV	:	Photovoltaic
SADC	:	Southern African Development Community
SOE	:	Solid oxide electrolyzer
SMR	:	Steam Methane Reforming
USD	:	United States Dollar

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Résumé

Les émissions de gaz à effet de serre (GES) contribuent au changement climatique en raison de la production et de l'utilisation conventionnelles de l'énergie dans le monde. Dans ce contexte, les économies mondiales évoluent vers des systèmes énergétiques plus propres afin d'atteindre la neutralité carbone. Ainsi, l'hydrogène devient de plus en plus un élément clé de ce développement grâce à ses voies de production flexibles, ses usages polyvalents et sa capacité à faciliter l'électrification décarbonée, la sécurité énergétique et les applications industrielles. Alors que l'attention mondiale se concentre davantage sur l'hydrogène vert issu de l'électrolyse alimentée par les énergies renouvelables, son utilisation en Afrique reste limitée en raison de coûts d'investissement élevés, de lacunes en matière d'infrastructures et d'un accès restreint aux financements. En revanche, l'hydrogène blanc, naturellement présent et découvert à Bourakébougou, au Mali, représente une alternative potentiellement moins coûteuse, mais sa compétitivité par rapport à l'hydrogène vert en Afrique n'est pas encore établie. Cette recherche comble cette lacune en réalisant une évaluation économique comparative de la production d'hydrogène vert et blanc à Bourakébougou, Mali. En adoptant une approche de modélisation économique fondée sur le coût actualisé de l'hydrogène (LCOH) et la valeur actuelle nette (VAN), l'étude prend en compte les dépenses d'investissement (CAPEX), les dépenses d'exploitation (OPEX) et une analyse de flux de trésorerie actualisés sur une durée de 25 ans. Les résultats montrent que l'hydrogène vert, produit par électrolyse alimentée par l'énergie solaire hors réseau, présente un CAPEX élevé et un OPEX faible, avec un LCOH de 4,78 USD/kg et une VAN relativement faible de 9,54 millions USD. À l'inverse, l'hydrogène blanc, extrait naturellement des couches géologiques souterraines, affiche un LCOH de 1,79 USD/kg et une VAN élevée de 44,39 millions USD, constituant ainsi une option économiquement plus viable dans les conditions actuelles. L'analyse de sensibilité révèle que le facteur le plus déterminant de l'économie de l'hydrogène vert est le CAPEX, tandis que l'OPEX exerce un impact plus fort sur l'économie de l'hydrogène blanc. L'hydrogène vert se distingue par ses avantages environnementaux et socio-économiques à long terme, tandis que l'hydrogène blanc présente une perspective économique à court terme pour Bourakébougou, particulièrement dans une région disposant de ressources géologiques favorables.

Mots-clés: Hydrogène, Analyse économique, Hydrogène vert, Hydrogène blanc, Coût Actualisé de l'Hydrogène (LCOH)

Abstract

Greenhouse gas (GHGs) emissions contribute to climate change due to conventional energy production and use across the globe. In this sense, economies worldwide are now transitioning to cleaner energy systems with the purpose of providing net-zero carbon. Therefore, hydrogen is increasingly becoming a key part of this development due to its flexible production pathways, versatile uses, and ability to facilitate decarbonized electrification, energy security, and industrial applications. While more global attention focuses on green hydrogen from renewable electrolysis, its use in Africa remains limited by high capital costs, infrastructures gaps, and accessible funds. On the other hand, naturally occurring white hydrogen discovered in Bourakébougou, Mali offers a potential low-cost alternative, but it cost competitiveness compared to green hydrogen in Africa is not known. This research addresses this knowledge gap by conducting a comparative economic assessment of green and white hydrogen production in Bourakébougou, Mali. Utilizing economic modelling approach, Levelized Cost of Hydrogen (LCOH) and Net Present Value (NPV), the research takes into account capital expenditure (CAPEX), operating expenditure (OPEX) and a discounted cash flow analysis for a 25-year project duration. The result indicates that green hydrogen, produced by off-grid solar-powered electrolysis, is of high CAPEX and a low OPEX with a LCOH of 4.78 USD/kg and a relatively low NPV of 9.54 million USD. On the other hand, white hydrogen, naturally extracted from subsurface geological layers, has a LCOH of 1.79 USD/kg and a high NPV of 44.39 million USD and represents more economically feasible option under prevailing conditions. Sensitivity analysis determines that the most significant driver of green hydrogen economics is CAPEX and OPEX has a stronger impact on white hydrogen economics. Green hydrogen is determined to have significant long-term environmental and socio-economic benefits, whereas white hydrogen has a short-term economic prospect for Bourakébougou, particularly in a region with favorable geological resources.

Key words: Hydrogen, Economic analysis, Green hydrogen, White hydrogen, Levelized Cost of Hydrogen (LCOH)

INTRODUCTION

Motivation

As climate change creates a pressing issue for international cooperation, and nations are moving towards decarbonization policies that seek to reduce the use of fossil fuels and greenhouse gas (GHG) emissions (Muñoz Díaz et al., 2023). Hydrogen as a clean energy career is fast becoming viewed as a critical enabling of hard-to-decarbonize industries like chemical manufacturing, steel manufacturing, shipping, and long-distance aviation (Agarwal, 2022). Though hydrogen production is picking up speed globally, Africa with its rich renewable energy potential comes up against specific challenges such as insufficient investment funds, poor infrastructure, and technological capacity(IRENA, 2023).

Green hydrogen, produced by water electrolysis with renewable energy, has attracted global attention as a zero-carbon source of energy (Franco et al., 2025). However, its production requires significant capital investment in electrolyzers, renewable energy sources, storage units, and related infrastructure for African countries that have limited financial and technical capability (Ballo et al., 2022).

On the other hand, white hydrogen naturally produced by geological processes such as serpentinization and radiolysis offers a cheap alternative possibly (Musa et al., 2024). It does not require energy-intensive, electrolysis or large-scale of renewable infrastructure and can be extracted directly from underlying rock formation. The Bourakébougou field in Mali is an example of commercially extracted white hydrogen with little processing and offers a specific opportunity in the energy transition of Mali (Maiga et al., 2023).

Despite the growing interest towards clean hydrogen, there have been no research that provide a comprehensive economic assessment of the cost of green versus white hydrogen in Africa. Prior research has mostly highlighted global economic feasibility without paying attention to location-specific factors such as regional resources availability, energy prices, infrastructure, and access to markets. This hamper planning for informed investment and policymaking for hydrogen projects in the continent.

Problem Statement

While the building of global trend towards hydrogen as a clean energy carrier is driven by clean production from renewable energy sources, there is a vast knowledge gap on its cost-effectiveness in Africa. Green hydrogen, produced from the electrolysis of water using renewable energy sources is widely regarded as a key element for net-zero emissions, its application in Africa is often constrained by high capital expenditures, poor infrastructure, and reduced access to technologies capacity. On the other hand, the presence of naturally occurring white hydrogen in Mali at Bourakébougou has the possible cost competitiveness. However, the absence of a difficult, site-specific economic comparison of green and white hydrogen production constrains policymakers, investors, and researchers ability to evaluate their relative cost feasibility. Without such comparative analysis, stakeholders are unable to appropriately assess costs, risks, and opportunities of embracing hydrogen technologies in Africa, particularly regions with unique geological and socio-economic features such as Bourakébougou. This lack of information limits prudent decision-making and undermines efforts towards devising effective plans for energy transition, industrialization, and climate change mitigation on the continent.

Research Questions

1. What are the differences between production costs of green and white hydrogen in Bourakébougou, Mali?

2. How do LCOH, NPV and other economic performance drive such cost difference

By responding to these questions, this research fills a research gap of Bourakébougou hydrogen economics, and provides evidence-based policymaking recommendation, investment recommendations, and future research directions to enable clean energy transition in the region.

Goal and scope

The research is interested in conducting the comparative economic analysis of green and white hydrogen production in Bourakébougou, Mali. The analysis is done entirely on production cost assessment using economic modelling approach to calculate LCOH and NPV; examine key cost components; capital expenditures (CAPEX), and operating expenditures (OPEX). And conduct a sensitivity analysis to estimate the impacts of variation in capital and operational inputs on the competitiveness of each hydrogen production. As hydrogen is a clean energy carrier of hope for international energy transition, the cost dynamics of its various forms of production become the subject matter of particular interest for Africa, as renewable equipment is limited, high upfront cost, and technological capacity are the issues of major concern.

The research evaluates two distinct production pathways:

i. Green hydrogen, which is produced through electrolysis using renewable energy resources, in this instance solar photovoltaic technologies (Niamey, 2024). Green hydrogen has a significant environmental benefits, although its economic feasibility is generally compromised by high initial capital expenditure as well as energy input costs (IRENA, 2018).

ii. Natural occurring underground rock structures white hydrogen is an economically feasible choice (Blay-Roger et al., 2024). Direct extraction from the ground, following purification and minimal processing, could be less expensive in suitable geological location like Bourakebougou, Mali.

This assessment only takes into account the production process and temporary onsite storage, not transportation, distribution, or utilization applications.

By focusing on production cost modeling, this research aims to provide clear, evidence-based information that can be used to guide policy development, investment decision-making, and strategic planning in relation to hydrogen in Africa's emerging clean energy environment.

Chapter 1. Literature Review

1.1 The role of hydrogen in global energy transition

The function of hydrogen is to serve as an energy carrier, and not as primary energy source, and therefore it needs to be produced in an energy consuming process. It can be produced from diverse energy carriers, such as coal, natural gas, nuclear power and renewable resources (IRENA, 2018). Hydrogen is increasingly in focus as the world energy landscape is changing, proving to be versatile, a clean-burning fuel, and an enabler for decarbonizing multiple sectors of the economy (International Energy Agency, 2021).

Significant shifts spreading the energy transition are amongst others faster implementation of emission-free technologies, digitalization and breaking-up of power generation that is achievable here due to renewable energy (Adolph, 2016). Hydrogen is emerging as one of the key components of this shift. It’s often mentioned as a fuel molecule that, when burned, could fuel a clean, global economy. It has the potential to replace fossil fuels in heavy transport, steel making and many other industrial processes, and emits no pollution at its point of use (Adolph, 2016). Hydrogen is a clean, sustainable, and flexible energy carrier, free of carbon when processed from renewable source (IRENA, 2018). It is capable of being transported long distances, has high energy content when compressed or liquefied, and generates no direct emissions when consumed (Reminder, 2024). Its safety record is in line with natural gas or petrol (International Energy Agency, 2021). As (Adolph, (2016), argued; hydrogen has the potential to serve as much as 24% of the world's energy demand by 2050 and generate USD 700 billion hydrogen per year hydrogen market value with many revenues coming from system and equipment of hydrogen.

Today, hydrogen serves as an industrial commodity. Worldwide demand for hydrogen amounted to around 94Mt in 2021 and has grown by 62% in the past 20 years (Agarwal, 2022). Two industries; oil refining and chemical, dominate this demand (IRENA, 2018). The oil refineries consume around 40 million tons of hydrogen annually as an intermediate, reactant and a source of power (CIF, 2022). The chemical industry uses about 45 million tons of which the majority is used in ammonia and methanol production (CIF, 2022). Ammonia is reactive for fertilizer, whereas methanol is a precursor to a range of products such as plastics, gums, and resins (CIF, 2022).

This is in contrast to its potential, which goes far beyond the industrial energy use of today. It is estimated that global demand for clean hydrogen could increase more than two-fold to above 180 million tons per annum by 2030 (Agarwal, 2022). According to the International Renewable Energy Agency (IRENA, 2024), implementation of all planned projects that achieve final investment decisions could expand low-emission hydrogen production by a factor of five by 2030, to more than 4 million tons per year. Moreover, global capacity of electrolyzers has grown remarkably from barely 1 GW in 2023 to 20 GW in projects with financial investment decisions (International Energy Agency, 2021).

Hydrogen is a potentially feasible strategy to decarbonize sectors that are difficult to electrify, such as heavy industry, long-haul transport, and power. It is also an essential enabler for the bridging of the intermittency of power from renewable sources such as solar and wind (IRENA, 2021). In that sense, hydrogen acts as an enabler for net-zero emissions as well as for sustainable low-carbon energy systems.

On a global scale there is growing recognition of hydrogen as a key enabler of deep decarbonization. Some countries, like Germany, France, Japan, South Korea, and the European Union, have already included hydrogen in their national energy strategies (International Energy Agency, 2021). Hydrogen consumption is expected to increase six-fold compared to the current levels by 2030 under the Net Zero Emissions by 2050 (NZE) Scenario developed by the (International Energy Agency(2021), where clean hydrogen is expected to cover 40% of the global hydrogen demand. National hydrogen strategies are being published in a number of countries that are setting policy for early-stage projects and market-building (IRENA, 2021).These developments are suggestive of the increasing recognition around the world of hydrogen's potential to make a material contribution to climate action, energy security, and the development of clean energy technologies.

1.2 Hydrogen in Africa

In total, the Economic Community of West African States includes 15 member countries with a total area of 5.12 million km² and a population of approximately 397.21 million people (ECREEE ECOWAS, 2023), but its total annual economic output reaches just past 683.71 billion

USD. At only 3.4% of the world's habitable land and 5.1% of its population, the region of the whole ECOWAS is 0.81% small on global GDP terms (ECREEE ECOWAS, 2023). In the year of 2020, the gross domestic product per capita of ECOWAS member countries was still markedly lower than the world average 10,916.10 USD. But their economic trend shows strength, with GDP up by as much as 3.9% in 2020 and further 4.4% 2021, similar to world GDP growth rate over the same period itself over 3.4% (ECREEE ECOWAS, 2023).

As the pursuit for global decarbonization gathers momentum, hydrogen has grown potential as a renewable alternative energy carrier. Bringing a huge volume of renewable resources into the equation and experiencing a rapid growth in energy demand, Africa has exceptionally good conditions for participation in the global hydrogen economy (IRENA, 2021). The continent has a large potential for solar energy almost everywhere, with particularly rich and low-cost solar resources concentrated in North Africa (IRENA, 2023). Along the coasts, the strongest wind potential is found, while hydropower is more pronounced in the southern regions (ECREEE ECOWAS, 2023).

Notwithstanding its abundant resources, however, Africa continues to face frightening energy access problems. It has been indicated that approximately 48 percent of the population, or roughly 600 million people, did not have access to reliable electricity. This situation was created due to a financial constraint (Gueye, 2025). Not only does this dependence on fossil fuels hinder economic development, but it also contributes to environmental degradation and global warming. This underscores the urgent need for clean and sustainable energy substitutes (ECREEE ECOWAS, 2023).

Green hydrogen, produced by electrolyzing water using renewable electricity (either from solar, hydro, or wind resource), offers a feasible model for Africa's future energy (S N & Sarathy, 2024). Africa has a renewable energy potential and Europe, as a major possible purchaser of green hydrogen is strategically located to make good use of this natural advantage. These efforts are active ones, since they will reduce the difference in production costs between green and traditionally made hydrogen bringing Africa into the global hydrogen economy more quickly (Adolph, 2016). The advantages are not exclusive to exporting goods; hydrogen can also meet the growing domestic energy needs and help industrial decarbonization.

Africa's closeness to international markets also enhances its status as a significant hydrogen exporter. According to (IRENA, 2023),sub-Saharan Africa provides the best opportunity for competitive green hydrogen production worldwide. The region could supply as much as 35% of the world's hydrogen with a production cost under 1.5 USD/kg in a best-case scenario ,therefore playing a key role in global clean energy transition (ECREEE ECOWAS, 2023). This point is reinforced by the H_2 Atlas, which estimates that the ECOWAS region alone has a production potential of 120,000 TWh (432 EJ) hydrogen under this cost threshold, and which accounts for almost 25% of the entire sub-Saharan Africa total hydrogen potential (Ballo et al., 2022).
Besides green hydrogen, the discovery of naturally occurring native hydrogen in geological formations as in Bourakébougou, Mali could bring new strength to, and expand, Africa's hydrogen range (Federation & June, 2023). When thorough, foot-traveled, and economical, this could offer complementary production based on green hydrogen and broaden the African range in the hydrogen sector. Clean energy seems to play a crucial role in Africa's economic transition (Gueye, 2025) through a change in both the way energy is produced and consumed. Ultimately, hydrogen is a more resilient, inclusive and sustainable energy future that the continent looks forward to ushering in with its own participation (Ballo et al., 2022).

1.3 Hydrogen in global market

As countries continue to improve and implement their national hydrogen strategies, so to it is not simply an assessment of where the energy landscape lies but also countering oneself decision-making within this future international hydrogen market that will find importers, exporters or regional hub cities whereas on the other hand we hope our future economic development moves towards more self-sustaining units such as Chile which has established an entire hydrogen energy system (International Energy Agency, 2021).The transition marks a significant exit from the current global energy system dominated by fossil fuels. Hydrogen is emerging as an important part of this desired cleaner, more secure and sustainable future power stand (IRENA, 2024).To date, over 37 billion USD in government funds has been committed to hydropower development financing around the world. The private sector is now planning to invest more than 300 billion USD (International Energy Agency, 2021). However, the amount for reaching carbon neutrality by 2050 is an overall 1,200 billion USD spent on low-carbon hydrogen production and use by 2030 (International Energy Agency, 2021).One of the main problems to widespread use is the cost differential between renewable low-carbon hydrogen and hydrogen made from non-renewable fossil fuels. Today, fossil-fuel-based hydrogen remains the most affordable option in many places. The International Energy Agency (2021) that the levelized cost of hydrogen production from natural gas varies from 0.5 USD to 1.7 USD/kg of hydrogen, depending on regional gas prices. When carbon capture, utilization, and storage (CCUS) technologies are introduced to deal with the emissions, the cost rises to 1USD to 2USD per kg. Furthermore, since green hydrogen through electrolysis using renewable energy which is surely the ideal means of doing things for a renewable future costs between 3 USD and 8USD/kg, without supportive policies or subsidy frameworks (International Energy Agency, 2021), it lacks competitiveness.

There are several pathways to hydrogen production, however this research concerns itself with only two: green hydrogen and white hydrogen. Green hydrogen, produced through the electrolysis of water by renewable energy, is gaining prominence around the world not only due to its economies of scale but also it is entirely non-polluting and has the potential to clean up difficult-to-decarbonize industries (Abdelsalam et al., 2024). White hydrogen, on the other hand, is a naturally occurring form which can be obtained from geological and geochemical sources. This "fuel" may not only work out more economically than other hydrogens but could also take less energy to use than them (Peninsula et al., 2023). Production of white hydrogen is still under study to ensure its global commercial feasibility. Timely investments by sovereign states advance the global hydrogen economy. Public private partnerships (PPP) and international cooperation aiming at ambitious climate-tourist targets to make it a reality ("Futur. Hydrog.," 2019). More than 50 countries such as Germany, Japan, South Korea, Australia, Chile, Canada, Morocco, Namibia, India, and the United States have made or plan to adopt a national hydro strategy to nurture hydrogen infrastructure and support market development, records ("Futur. Hydrog.," 2019). Alongside this, hydrogen is becoming more economically feasible as the cost of renewable energy technologies fall. In the past decade, the price of solar photovoltaic systems has come down almost 80%; wind power investment by over 40% (IRENA, 2021). This tends to reduce green hydrogen production costs globally indeed.

Hydrogen generation and storage are leaning points, which supply model for global energy management (S N & Sarathy, 2024). It is now leading to shifting power dynamics within regions where natural gas production becomes more widespread and also attracting increased investment from outside for infrastructure related to production, storage, or export needs as well as potential downstream processing facilities. Therefore, many countries who possess a wealth of renewable energy resources and are able to produce hydrogen in a low-cost manner have the chance of turning into global energy exporters (Vechkinzova et al., 2022).

1.4 Hydrogen opportunities and challenges in Africa

Africa's massive renewable energy resources mean that it has the potential to become a big player in hydrogen economics. The continent boasts abundant sunlight and sunshine, which could create a natural region for producing clean power in the form of hydrogen. This is called 'green' hydrogen because it is made using renewable resources and produces no carbon emissions (IRENA, 2024). In both the Northern and Sahel regions, solar irradiation is among the highest in the world. Coastal areas are perfect for wind generation, and countries in central and southern Africa have great hydroelectric resources (ECREEE ECOWAS, 2023).With clean energy solutions becoming increasingly in demand from around the world, Africa finds itself in a favorable position to send hydrogen to international markets. For instance, Europe, where countries have their own climate targets (as also emphasized by the European Green Deal) and are eager for some saviors (IRENA, 2024). Several African countries including Namibia, Morocco, Egypt, South Africa have already started to develop national strategies for hydrogen or release research, financed typically with money from international financial institutions and governments abroad help to cover the costs (International Energy Agency, 2021).

Nevertheless, hydrogen development is poised to solve the dual energy generation problem of Africa, supplying export markets as well as providing domestic access to electricity. As a partner to local energy systems, hydrogen infrastructure can power unserved peoples, revive industry, and terminate reliance on oil imports. In addition, it brings opportunities for economic growth and job creation as well as skills in clean energy fields(Obanor et al., 2024). But all this is far from easy. One problem, for instance, is that owing to the creation of infrastructure is very costly; hydrogen generation requires incredible expenditures in cables and pipes for water, electrical lines, and storage terminals which in the impoverished stages of nearly all African economies would remain first to be completed. The efforts to overcome these technical and logistical hurdles are backed up by huge amounts of capital investment in building hydrogen factories. Most countries will have to rely on concessional finance, hybrids, or marginal partnerships abroad because there is so little economic space left for big initiatives of such kind. Besides, investment still faces difficulties because regulatory policy in Africa is unclear; undefined hydrogen strategies lead the way to investment incentives. Uncertain frameworks for incentives can be used to fund discouragement and delay project implementation (IRENA, 2023). In the same vein, technical capabilities in the region are also thin, which leaves many innovative projects shackled by foreign technology-provider dependence. Last but not the least, water shortage proves to be another problem; electrolysis in hydrogen generation requires fresh water, which is not available in nearly all areas. So sustainable water management policy or in partnership with desalination facilities is a must.

It remains no less crucial to ensure a fair and inclusive transition. Hydrogen investment must be good for locals and the country, while avoiding repetition of deep export-oriented dependency on extraction processes. The substantive access, environmentally friendly practices and community engagement will determine whether hydrogen truly comes into its own in Africa (Fashina et al., 2018). Nonetheless, Such challenges are not impossible. Resources strategic partnerships with institutional backers such as the European Union (EU), Germany's H2Global initiative or the African Development Bank (AfDB), can use funds to bring necessary technical skills and develop policy environments supporting themselves as well as investors. Both ECOWAS the Economic Community of West African States (ECOWAS) and Southern African Development Community (SADC), among others are promoting regional cooperation in various ways (ECREEE ECOWAS, 2023).With the right investment, sound policy making, and participatory planning, hydrogen can be a cornerstone of Africa 's sustainable development, one which helps the continent leapfrog fossil technologies and contributes meaningful to global carbon reduction.

1.5 Hydrogen technologies overview

While hydrogen is a versatile energy carrier, as well as being able to be produced from renewable and non-renewable sources, it is also the pivot for sustainable and low-carbon energy systems in the future (Nnabuife et al., 2023). In subsequent developments bring down the environmental footprint while increasing capacity (Nnabuife et al., 2023). By far, the most commonly used method is steam methane reforming (SMR) which produces both lots of greenhouse gases and has significant environmental consequences. This situation reflects a lack of attention by the production side to its impact on environment (Agarwal, 2022).

As the global energy transition accelerates, building cleaner and more sustainable hydrogen technologies has become a major priority for researchers, industry, and policymaking. Green hydrogen, for instance, refers to hydrogen produced from renewable energy sources by electrolysis or even hydrogen, with no relationship with oil or coal. It is these technologies which offer hope in decarbonizing our pattern of energy consumption for the future. However, they need to arrive at both technical efficiency as well as having competitive production costs before they can ever replace fossil materials on anything other than a minor scale (Agarwal, 2022).

There are advantages to going with any of the hydrogen production methods. Cleaner methods can result in less emissions, or jobs not greenhouse gases. Fully capable of storing energy on site, they offer the potential for decentralized production, but they also pose difficulties. Major energy losses, significant capital costs and infrastructure needs as well as environmental constraints are all challenges they must overcome (Nnabuife et al., 2023). These problems underscore a critical need for more and better investment in research and innovation, in order to raise the bar on performance while cutting costs in production.

To provide a comprehensive overview, the main hydrogen production pathways and the corresponding sources of energy are covered in table 1. This study focuses on green hydrogen produced from renewable energy of electrolysis and white hydrogen produced from natural geologic formations.

Table 1. Overview of hydrogen production pathways

Production pathway	Energy source (s)
Electrolysis	
Electrolysis of water	Solar, wind, nuclear, microbial
Photolytic splitting of water	Solar
Biological	
Fermentation	Biomass
Thermochemical	
Thermal splitting of water	Solar
Gasification	Biomass, oil, coal
Pyrolysis	Biomass, natural gas
Steam reforming	Natural gas
Plasma reforming	Natural gas
Partial oxidation	Natural gas, oil, coal

(Adapted from Niamey, 2024)

1.5.1 Green hydrogen

Hydrogen is the first chemical element in the periodic table and takes up only small mass of the Earth's atmosphere (Anouti et al., 2020). As a carbon-free energy carrier, it has great potential to transform our world into one where clean, green, and sustainable fuels hold power. There are many ways of making hydrogen. National renewable energy laboratory's (NREL) energy netting server shows that it can be produced by the electrolysis of water and by fossil-based processes such as steam methane reforming or coal gasification or biomass conversion (Nnabuife et al., 2023).

However, fossil fuels still account for about 96% of global hydrogen production-absolutely hydrogenated fat (Anouti et al., 2020). To differentiate between production routes a color coding was introduced. Green hydrogen, is a hydrogen which has been made by electrolysis under the power of renewable energy sources such as sunlight, wind or hydropower(IRENA, 2018). The method offers zero direct CO_2 emissions, clean and renewable alternatives for traditional hydrogen production. Green hydrogen is not only clean, but also storable and transportable, which means it serves as a flexible energy vector too. World demand is projected to be approximately 530m tons by 2050, with the potential to replace some 10.4bn barrels of oil equivalent (Anouti et al., 2020).

This demand growth is expected in many sectors, such as transportation, heating, power production and chemical manufacturing and steel production. Although green hydrogen brings many benefits, the production process is extremely energy intensive. According to Muñoz Díaz et al., (2023) study, methanol electrolysis method, could reduce energy consumption by up to 60%, therefore underlining potential for further improvements in efficiency. Their research compared efficiencies between water electrolysis, methanol electrolysis and hybrid sulfur electrolysis, indicating possible technological innovation routes.

Markedly these regions are all major net importers of energy, with high consumption levels in the transport, industrial and residential- heating sectors (Anouti et al., 2020).But the current cost of green hydrogen, still nearly twice that of gray hydrogen (from natural gas without carbon capture), is a major economic difficulty (ECREEE ECOWAS, 2023). Fortunately, costs are expected to fall thanks largely to technological advances in electrolyzers, declining renewable power prices and economies of scale. According to the (IRENA, (2018) it might be achievable by 2030 that green hydrogen which at this point will be a real alternative as source for low-carbon energy replaces so expensive to produce its carbon-based counterpart (“Futur. Hydrog.,” 2019).

In addition to serving as a direct fuel, green hydrogen can be converted into secondary products such as green ammonia, green methanol, and power-to-liquid (PtL) fuels. On the other hand 55 Mt of hydrogen fuel equivalent could be reached by 2050 (Anouti et al., 2020; CIF, 2022). Since the 2020s green hydrogen has also been seen increasingly as an enabling carrier for sectoral decarbonization, especially in hard-to-abate industries like steel and chemicals, which have few alternatives to burning fossil fuels (CIF, 2022). In electricity systems powered mainly by renewables, green hydrogen is also expected to contribute significantly to long-term energy storage, smoothing out the peaks and channels of power generation from solar or wind (CIF, 2022). There are three main electrolysis technologies used in green hydrogen production:

- Proton Exchange Membrane (PEM) Electrolysis
- Alkaline Water Electrolysis (AWE)
- Solid Oxide Electrolysis (SOE)

Each of these operates at different temperature ranges, employs different electrolyte materials, and has different efficiency profiles details will be provided below in our upcoming section on Green Hydrogen Production Techniques (Nnabuife et al., 2023).

1.5.2 White hydrogen

White hydrogen, also known as native, natural or geological hydrogen, is a hydrogen that is naturally formed within the earth's subsurface by geochemical processes (Blay-Roger et al., 2024).

There is no doubt that unlike industrial hydrogen, white hydrogen is of geologic source and therefore it can become a low-cost zero-carbon resource to supplement green hydrogen in energy uprising; its development in the right direction (Prinzhofer et al., 2018).

It comes from natural geological processes such as Serpentinization (in which chemical reactions occurring between ultramafic rocks and water form hydrogen), radiolysis (ionizing radiation from radioactive elements such as uranium, thorium, and potassium breaks down water molecules during their electron spin), and mantle degassing reactions (the hydrogen produced can move through porous rock and be stored in the same way as natural gas) (Blay-Roger et al., 2024; Frost & Beard, 2007; Musa et al., 2024).

With improved models, development techniques and more successes from field studies, white hydrogen drills have in recent years found themselves becoming more of a hot topic (Prinzhofer et al., 2018). Its potential rich rewards mean that forgotten history must inevitably be uncovered and examined systematically.

The most well-documented discovery is the Bourakebougou hydrogen field in Mali, where natural hydrogen has been extracted since the 1980s (Maiga et al., 2023). The field has been exploited to supply electricity for a local village, and more than 20 boreholes of exploration wells in this area have shown that native hydrogen does exist and can persist (Maiga et al., 2023).

The Bourakebougou scheme represents a very small beginning, showing that white hydrogen can be put to practical use with today's human technology.

There is ongoing exploration work in countries including France, the United States, Russia, Brazil and, particularly Australia where promising geological compositions for natural occurring hydrogen can be discovered with ease (Musa et al., 2024).

If such findings prove that these reserves are being used sustainably at geologic timescales, white hydrogen could soon become a major source of power for future generations to enjoy (Kelemen et al., 2011).

White hydrogen has some advantages:

- Low energy requirement: Especially when compared with green hydrogen, which needs to be split from water simply because it lacks any naturally radiating geological deposit, much less gray hydrogen from fossil fuels, white hydrogen is an energy-saving form that occurs without any demand for high-powered equipment (Blay-Roger et al., 2024).
- Small carbon footprint: Production has few emissions, making it a clean energy source (Blay-Roger et al., 2024).
- Potential for continuous renewal: Some geological may consist of formations suitable to continuous hydrogen production, with a semi-renewable supply (Musa et al., 2024).
- Decentralized production: This can mean locally self-sufficient energy to help off-grid preparation and even small-scale industries of some kind, as in developing countries with poor infrastructure (Blay-Roger et al., 2024; Kelemen et al., 2011; Musa et al., 2024).

But despite such obvious advantages, white hydrogen industry is still in its early stages.

There are a number of issues to be resolved now:

- ✓ Barriers For Data Attainment in Exploration: Despite the rising number of exploratory wells being drilled every day, most figures regarding costs, volumes of hydrogen and where to find it are treated as trade secrets or are otherwise confidential (Maiga et al., 2023).
- ✓ There is a gap in regulation: some country national energy politics and mining laws cannot give status to white hydrogen as single resource; this leads inevitably to legal and investment uncertainties, which inhibit progress (Patonia et al., 2024).
- ✓ Technical Barriers: To date, the technology for exploration, extraction and storage has yet to be fully developed and standardized (Peninsula et al., 2023).
- ✓ Environmental Risks: Hydrogen itself is clean, but the extraction techniques do not seem environmentally good depending on geological conditions (Blay-Roger et al., 2024; Musa et al., 2024; Peninsula et al., 2023) As it has been said, the latest science of white hydrogen gives short term opportunities to areas like geological highlands in Africa which have little infrastructure but a high imperative for clean power paced.

With more research, politicizing and international coordination, white hydrogen could become a necessary part of the world's hydrogen economy; it may be transition disruptor to Net Zero Emissions.

1.6 Comparative of green and white hydrogen

Green and white hydrogen represents two of the most promising hydrogen production paths that is low in emissions, each contribute to a new idea of hydrogen business which is flourishing now. Both strategies have garnered increasing global attention for achieving a sustainable atmosphere free from carbon pollution but, in different perspective to production methods, energy input requirements, cost structure, technological maturity, and environmental protections. In this section, comparison with a focus on largely on production methods and market conditions for wither or not, they gain wide acceptance as well as how much can be produced from what level of input are examined.

1.6.1 Production methods

1.6.1 Green Hydrogen

Green hydrogen is produced by water electrolysis. This is a process in which an electric current breaks the water molecules in hydrogen gas (H_2) and oxygen gas (O_2) (Kotowicz et al., 2024). If the electricity used to make it is from renewable sources like solar, wind or hydro, that makes it "green". Henceforth the whole operation can be truly carbon-free (IRENA, 2018); Electrolyzers are the heart of this process, a device that electrochemically converts electric energy into chemical energy stored in hydrogen (Abdelsalam et al., 2024). The efficiency of an electrolyzer system is vital, since it determines how many units of electrical energy are needed to produced one unit of hydrogen (Abdelsalam et al., 2024).

Three principal electrolyzer technologies are widely studied and deployed in table 2

Table 2. Comparison table of different electrolyzer technologies

Technology	Market maturity	Advantages	Limitations	References
Alkaline Electrolyzer (AKE)	Most mature, 70% of global capacity	Low CAPEX (USD 500-1000/kW)	Slower dynamic response (less suitable for intermittent renewables)	(Anouti et al., 2020; International Energy Agency, 2021; Kotowicz et al., 2024)
		Long operational life (up to 60,000 hrs)	Lower efficiency (60-70%)	
		Low degradation (0.1%/1,000 hrs)		
Proton Exchange Membrane (PEM)	Commercial, 30% of market	Fast respone (5 second startup, 100%/s load change)	High CAPEX (USD 700-1,400/kW)	(International Energy Agency, 2021; Kotowicz et al., 2024)
		compact design	Reliance on scarce nobles metals (platinumand Iridium)	
		High purity hydrogen output	Environmental impacts from material extraction	
			Not commercialize	

Solid Oxide Electrolyzer (SOE)	Emerging, still under development	High efficiency (80% with thermal intergration)	Long startup times, higher CAPEX 2000 USD/kW	(Abdelsalam et al., 2024; Anouti et al., 2020)
		Suitable for industrial waste heat recovery	Shorter system lifetimes	
			Limited manufacturer availability	

Each of these technologies has different strengths depending on the application. Alkaline electrolyzers are still the most common and lowest-cost option, with PEM electrolyzers offering flexibility in integrating with renewables at material cost barriers. Solid oxide electrolyzers, as yet still being developed, show improved efficiencies for sector coupling in industry.

Given that this research focuses on green hydrogen production through alkaline electrolysis, only this technology is considered in the analysis.

Figure 1 illustrates the schematic diagram of an alkaline electrolyzer used for green hydrogen production using an electrolysis due to alkaline being used for the green hydrogen production in this research.

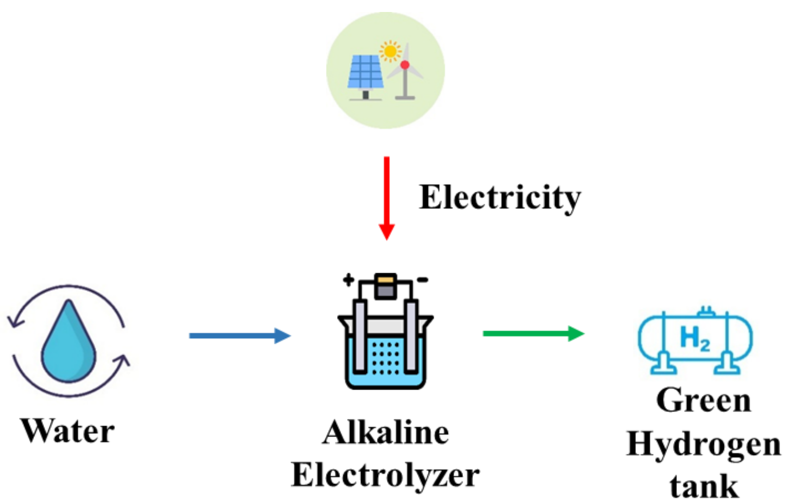

Figure 1. Illustration of green hydrogen production (Adapted from Abdelsalam et al., 2024; Muñoz Díaz et al., 2023)

1.6.2 White Hydrogen

White hydrogen, also known as natural or geogenic hydrogen, is a hydrogen gas that forms within the earth (Blay-Roger et al., 2024). It is naturally formed, unlike green hydrogen, which requires extensive inputs of energy, infrastructure, and technology.

White hydrogen is a naturally occurring hydrogen found in geological formation, offering a potential low-emission and low-cost energy sources. In geological reservoir, similar to those used for natural gas, It may be economical feasible to extract white hydrogen, the available methods are still at an early stage of development and under exploration (Blay-Roger et al., 2024; Peninsula et al., 2023.).

White hydrogen production, as illustrated in Fig. 2, is a results from the combination of biological and abiotic processes (Blay-Roger et al., 2024; Musa et al., 2024). Organic matter decomposition and fermentation are some of the biological processes involved, while abiotic processes are involved by the radiolysis of uranium- and thorium-enriched subsurface rocks, serpentinization of Fe- and Mg-enriched mantle rocks (olivine and pyroxene) and direct reduction of water (Blay-Roger et al., 2024). Among these, serpentinization is the most promising abiotic process in which chemical reaction between ultramafic rocks and water generates hydrogen as a byproduct (Blay-Roger et al., 2024; Frost & Beard, 2007).

These reactions mostly take place in tectonically active areas such as mid-ocean ridges, transform faults, and ophiolite complexes where fractures allow water to seep into the lithospheric mantle. Research have shown that Serpentinization accounts for 80% of the natural hydrogen produced on Earth, while the remaining portion is dominated by radiolysis (Kawagucci et al., 2018).

Radiolysis refers to the splitting of water molecules by ionizing radiation resulting from the radioactive disintegration of isotopes like uranium (U), thorium (Th), or potassium (K) that are found in crustal rocks (Klein et al., 2020). The intensity and effectiveness of serpentinization depends on many geological and chemical factors. Reaction speed increases at 200-300°C, however as the pressure mounts things become quite tasted and the hydrogen flows freely. The water-to-rock mass ratio is crucial; It defines the availability of reactants. Rock structures or water impurities that are either not present or added impact on how this flow happens and ultimately leads to hydrogen production (Berndt et al., 1996; Blay-Roger et al., 2024; Frost & Beard, 2007).

White hydrogen deposits have been found in various geological settings. These include groundwater aquifers, hydrocarbon wells, mine tunnels, and hydrogen seeps above or below the sea (Musa et al., 2024).

However, in such conditions the purity and concentration of hydrogen can differ considerably with source and immediate surroundings. The presence of other gases such as methane, carbon dioxide, or nitrogen can also have an impact on production needs as well as costs (Maiga et al., 2023).

1.6.2.2 Exploitation of white hydrogen

The white hydrogen scientific exploration, although still begun, now has been documented in an increasing number of literatures. These have covered its occurrence, formation processes and potential for use by people Frost & Beard, (2007) presented a general understanding of serpentinization reactions in ultramafic rocks and the importance of natural hydrogen production in that process. Kawagucci et al., (2018) found that serpentinization may generate up to 80% of the Earth's hydrogen, and Klein et al., (2020) described how radiolysis from radioactive decay within crustal rocks makes a significant contribution too. Recent research claim, (Blay-Roger et al., 2024; Musa et al., 2024), maps hydrogen occurrences like the groundwater system, hydrocarbon wells and diamond mine. These show not only geological differentiation but also the potential for low-cost extraction.

The possibility of corresponding geothermal occurrence has also supported this viewpoint: for instance, Bourakebougou in Mali is mentioned by many observers (Maiga et al., 2023) as the first major discovery of natural hydrogen. In a joint effort between Peninsula Research Group (Peninsula et al., 2023) and the International Renewable Energy Agency (IRENA, 2023), it evaluates how economic feasibility itself for natural hydrogen includes adapting technology in order to obtain it and how to combine it with future energy systems. In sum, it formations in many literatures are still small, but increasing gradually that sees white hydrogen as one possible alternative carrier to low-carbon energy transition, yet also has doubt about its purity in reservoir.

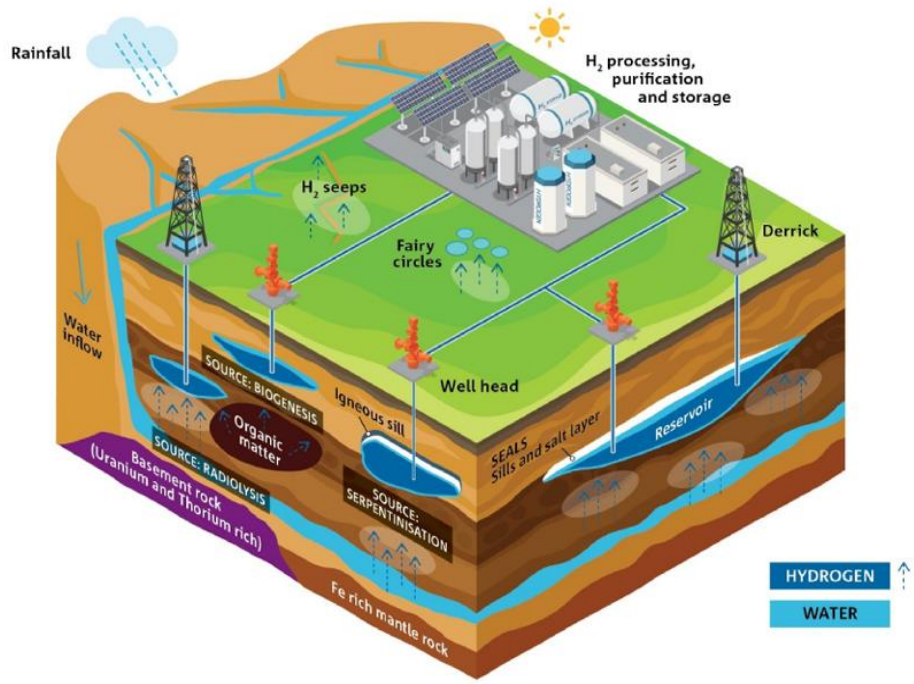

Figure 2. Schematic diagram of white hydrogen formation (Musa et al., 2024).

1.6.2 Production costs

The cost of hydrogen production varies significantly depending on the source and method of generation. While both green and white hydrogen are considered low-carbon alternatives, their cost structures differ markedly due to differing technological requirement, resource availability and extraction processes.

1.6.2.1 Green hydrogen

The cost of production of green hydrogen is reflected in table 3; cost of renewable electricity, which accounts for 60–70% of the cost (International Energy Agency, 2021). The steep fall in the cost of solar PV and wind technologies has already improved the economics of green hydrogen. Hydrogen from onshore wind, for instance, was estimated at USD 2.35/kg in 2020, significantly lower than from solar PV (Kotowicz et al., 2024). The cost of hydrogen (LCOH) in 2021 was USD 4–6/kg, around twice the cost of grey hydrogen without carbon capture (International Energy Agency, 2021).

Future cost savings are expected through declining renewable electricity costs and falling electrolyzer prices. Prices for electrolyzers have dropped by 60% since 2010, with further drops of 40–80% expected through design innovation, standardization, economies of scale, and increased manufacturing (IRENA, 2021). Similarly, renewable electricity has also come down considerably; solar PV by 80% and onshore wind by 40% over the past decade (Anouti et al., 2020). Therefore, green hydrogen can achieve cost parity with fossil fuel-based hydrogen in 2030 in the resource availability regions of Africa at the price range of 1–2USD/kg (IRENA, 2018, 2021). Nevertheless, there are also setbacks in the form of high up-front capital expenditure, underdeveloped infrastructure, and worse financing conditions in developing economies.

Table 3. Production cost

Key Drivers	Cost Estimate USD/kg H_2	References
LCOH in 2021; two time higher than grey hydrogen. Electricity = 60–70% of total cost.	4-6	(International Energy Agency, 2021)
From wind power (onshore turbines, 2020). Lower than solar PV.	2.35	(Kotowicz et al., 2024)
Possible in regions with rich solar or wind resources (North & Sub-Saharan Africa). Driven by declining renewable electricity prices.	1-2 (projected by 2030)	(IRENA, 2018, 2021)
Electrolyzer costs dropped 60% since 2010; expected to fall an additional 40% in short-term and up to 80% long-term.		(IRENA, 2021)

1.6.2.2 White hydrogen

White hydrogen remains in its early stage, with the only operational project to date being Bourakébougou in Mali. The well has been continuously producing hydrogen of up to 98% purity since its discovery in 1987, helpful for the surrounding village by providing electricity for over a decade (Maiga et al., 2023). Exploration activity, however, is increasing rapidly, with more than 40 companies already exploring in regions such as Australia, Canada, USA, Brazil, Turkey and France(Hydrogen, 2025), while recently a 46-million-ton reserve was discovered in Lorraine, France(Paul Messad, 2023) . Therefore certain production costs are still unclear awaiting field-scale information, initial projections suggest that white hydrogen can be manufactured at below 1 USD/kg in favorable geological region and the 6 USD/kg of green hydrogen (Paul Messad, 2023). Yet, some of the important challenges include unknown reservoir sizes, uncertain lifetimes and flow rates, geologic hazards, and the lack of developed extraction technologies (Peninsula et al., 2023). These risks underline both the disruptive potential and the current limitations of white hydrogen as a competitive choice in Africa's energy transition.

1.7 Knowledge gap

In spite of the growing international momentum toward clean hydrogen particularly green hydrogen as a sustainable energy carrier, a critical knowledge gap persists regarding the comparative economics of green and white hydrogen in Africa. Most existing economic and techno-economic analyses, including Levelized Cost of Hydrogen (LCOH) models have been designed for industrialized areas such as Europe, North America, and East Asia, which benefit from mature infrastructure, well-established renewable energy markets, and reliable datasets that support detailed modelling and projections (International Energy Agency, 2021; Kotowicz et al., 2024). Africa, however, is underrepresented in these analyses even though it has abundant renewable resources (solar, wind, and hydropower) and is increasingly valued for having rich geological reservoirs of naturally occurring hydrogen (Musa et al., 2024; Obanor et al., 2024).

While green hydrogen has been the focus of extensive economic and techno-economic studies, white hydrogen has relatively little attention, even as its scientific and commercial significance increases. The Bourakébougou structure of Mali, one of the highly notable production site reported in the world, has established the technical feasibility of exploiting naturally occurring hydrogen (Prinzhofer et al., 2018). Nevertheless, no detailed of economic model studies have been performed comparing white hydrogen with green hydrogen or fossil fuel-based alternatives in Bourakébougou.

This research addresses these gaps by conducting a comparative economic analysis of green and white hydrogen production in Africa, using Bourakébougou, Mali as a test case. Focusing on LCOH, NPV and financial indicators such as CAPEX and OPEX, this research tries to provide the first evidence-based assessment of white hydrogen's economic potential over green hydrogen in the study area.

1.8 Research justification

There is an urgent need for evidence-based data regarding the cost-effectiveness and economic feasibility of hydrogen production in Africa. As global demand for low-carbon hydrogen continue to increase, driven by decarbonization drivers, industrial transformation, and energy security requirements, Africa holds immense opportunities with its huge renewable resources and emerging deposits of naturally occurring white hydrogen (CIF, 2022; International Energy Agency, 2021; Maiga et al., 2023).

Embracing this potential requires regionally suitable economic modeling and not industrial market-based assumptions. Africa's diverse infrastructure, regulatory systems, and market conditions require local analysis in order to ensure realistic investment planning and policy formulation. Local employment generation, industrialization, and energy access can be facilitated by hydrogen production as well, all of which are central to sustainable development in the entire continent.

This research contributes to filling that gap by:

- ❖ Conducting a Levelized Cost of Hydrogen (LCOH) analysis of green and white hydrogen production, with Bourakébougou, Mali, as the case study to illustrate the potential of naturally occurring hydrogen.

- ❖ Putting costs into Bourakébougou resource and infrastructure realities.
- ❖ Identifying the particular opportunities and challenges of each hydrogen pathway

The outcomes are to inform hydrogen development in Africa to enable energy transition, industrialization, climate change mitigation, energy access, and sustainable economic development.

Chapter 2. RESEARCH METHODOLOGY

2.1 Economic Model Overview

This research developed an economic model to evaluate cost feasibility of hydrogen production in Bourakébougou, Mali, from two distinct paths: green hydrogen, produced through an off-grid solar-powered electrolysis plant, and white hydrogen, sourced from naturally occurring subsurface sandstone reservoirs. The production capacity of 2,740 kilograms per day (or approximately 1,000,100 kilograms per year) is applied on both pathways to enable a similar comparison. For white hydrogen, such production is equivalent to a concrete wellfield of ten vertical wells, of which one is an exploratory well and nine production wells. The figure is consistent with reported flow rates of 1,500 cubic meters of hydrogen daily per well in Mali, equivalent to about 135 kilograms daily that was not designed for gas extraction reported a natural hydrogen flow rate, and is consistent with scaling assumptions used in recent literature (Maiga et al., 2023; Patonia et al., 2024; Prinzhofer et al., 2018). Purpose-built production wells are expected to achieve higher sustainable flow rates than exploratory boreholes. For green hydrogen, photovoltaic and electrolyzer capacity are sized to generate the same daily output. Production level is therefore not set up as a fixed operating value but as an assumption under base-case scenario to facilitate comparative modelling.

The model applies a Discounted Cash Flow (DCF) basis for a 25-year project duration. Within this basis, annual costs and hydrogen production are projected to estimate cost components such as capital expenditure (CAPEX) and operating expenditure (OPEX), and to calculate two opposite economic metrics; the Levelized Cost of Hydrogen (LCOH) is the discounted lifetime cost per kilogram of hydrogen produced and the Net Present Value (NPV) represents the discounted net cash flow throughout the project duration and reflect the overall financial feasibility of each path. Meanwhile hydrogen infrastructure in the area is not so far extensive, the model relies predominantly on secondary data sources, including peer-reviewed articles, industry reports, and publicly available techno-economic data sets. All economic factors are expressed in constant 2025 United States dollars to enable comparison, and the main assumptions regarding production, technology performance, and cost factors are in Table 3. This standardized methodology offers a consistent platform for comparing white and green hydrogen under the specific conditions of Bourakébougou, as well as generating insights regarding the broader feasibility of hydrogen development in sub-Saharan Africa.

Table 4. Parameters associated with hydrogen production

Variable	Description
CAPEX	Capital expenditure (USD)
OPEX (**Variable**)	Operational expenditure (USD/year)
$\mathbf{H_t}$	Hydrogen production=2,740kg/day or 1,000,100 kg/year
n	Total project time =25 year
r	Discount rate =7%

(Adapted from Muñoz Díaz et al., 2023)

2.1.1 Green Hydrogen Model

The green hydrogen economic model is based on a stand-alone solar photovoltaic (PV) system integrated with alkaline electrolysis and battery. The electrolyzer capacity expected to produce 2,740 kilograms of hydrogen per day in Bourakébougou, Mali. This production level was used as a base-case scenario to enable a good comparison with the white hydrogen pathway. Although the main focus of this research is on the economic feasibility, a concise description of the system design must be given in order to gain an understanding of how the technical and cost parameters were utilized.

The system is designed to operate for approximately eight hours a day when solar irradiance is high, supported by a lithium-ion battery storage system to manage supply fluctuation. This configuration was optimized based on local solar resources, with the average irradiance being 6 $kWh/m^2/day$, and to minimize costs while providing hydrogen production throughout the year. Water is supplied by a solar-powered borehole, and the diameter (6 inches) and depth (50 m) define the pumping energy requirement, which is accounted for as capital costs. Hydrogen is compressed to 350 bar and kept in high-pressure containers, with storage volume determined from daily production and hydrogen density (30 kg/m^3). The space needed for the PV array and structural items is 23,966 m^2, and land cost is utilized as a component of capital investment. Technical parameters are given in Table 5, while other performance factors such as battery efficiency and depth of discharge use were adjusted to meet regional installation conditions.

Capital expenditures (CAPEX), as shown in Table 6, include the expense of PV modules, electrolyzers, battery storage, hydrogen storage tanks, and water infrastructure. CAPEX of 700 USD/kWp for PV covers module costs only, in constant 2025 USD. Electrolyzer CAPEX of 500 USD/kW includes 270 USD/kW for stack replacement at mid-life. Battery CAPEX and replacement were reduced from literature estimates to account for local logistics and deployment conditions. Hydrogen tank cost is provided per kilogram of capacity. These modifications make the CAPEX reflect actual costs of installing the system in the study area.

Operating expenditures (OPEX) in Table 7 include annual maintenance of the PV array, batteries, electrolyzers, hydrogen tanks for storage, water treatment, and insurance and administration. Electrolyzer O&M of 10 USD/kW/year is roughly equivalent to 2% of the assumed electrolyzer CAPEX, by industry practice. Water treatment, insurance, and administration costs were made regional to cover a reasonable estimate of recurring operating expenses through the duration of the project.

All of the CAPEX, OPEX, and technical requirements were incorporated into a 25-year Discounted Cash Flow (DCF) model in accordance with international standards of hydrogen assessment. It provides estimates of two supporting economic performance metrics: the Levelized Cost of Hydrogen (LCOH) is the cost per kilogram of hydrogen, and the Net Present Value (NPV) give the financial feasibility of the project. These metrics provide an in-depth analysis of the cost competitiveness and investment feasibility of the system under the specific technological and regional conditions of Bourakébougou.

Schematic diagram of the green hydrogen production system is presented in Figure 3, illustrating interrelationship among the dominant subsystems like solar PV generation, electrolyzer, energy storage, water supply, and hydrogen storage, all of which are under the cost modeling framework.

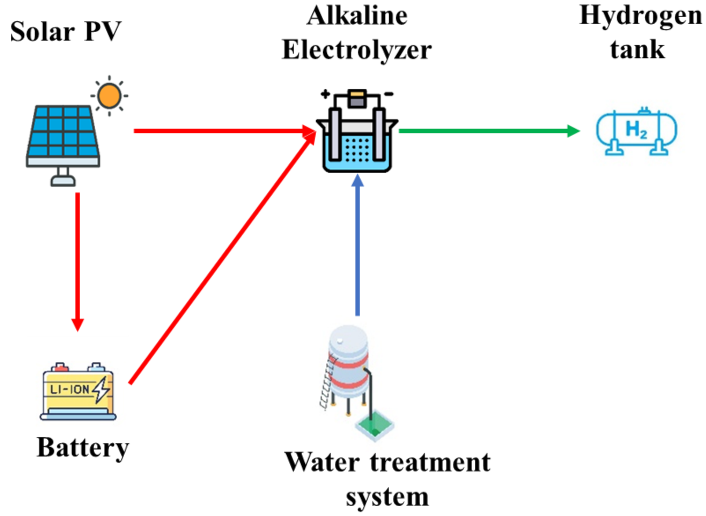

Figure 3. Schematic diagram of green hydrogen production system (Adapted from Kotowicz et al., 2024; Muñoz Díaz et al., 2023)

Table 5. General data assumptions for green hydrogen production

Item	Value	Unit	Reference
Assumed quantity	2,740	kg/day	Assumption
Electrolyzer (AKE) consumption	50	kWh/kgH_2	(International Energy Agency, 2021)
Water consumption	22.25	L/kg H_2	(Bhandari & Shah, 2021)
Standard Test Condition	1	kW/m^2	(Firman et al., 2022)
Bourakebougou solar radiation	6	kWh/m2/day	(NASA, 2024)
Performance ratio	0.7		(IRENA, 2024)
Depth of Discharge	0.8		(IRENA, 2017)
Battery efficiency	0.9		(IRENA, 2017)
Storage pressure	350	bar	(Muñoz Díaz et al., 2023)
H_2 density	30	kg/m^3	(Muñoz Díaz et al., 2023)
Borehole depth	50	m	(Martínez-Santos et al., 2017)
Diameter	6	inch	(Martínez-Santos et al., 2017)
Land	23,966	m^2	(Mrs. Diarra, 2019)

Table 6. Green hydrogen Capital Expenditure

Component	Cost	Unit	Reference
Solar PV	700	USD/kWp	(Bhandari & Shah, 2021)
Electrolyzer (Alkaline)	500	USD/kW	(Kotowicz et al., 2024)
Stack replacement	270	USD/kW	(International Energy Agency, 2021)
Battery (Lithium-iron battery)	300	USD/kWh	(Bhandari & Shah, 2021)
Battery replacement	150	USD/kWh	(Bhandari & Shah, 2021)
Hydrogen tank	300	USD/kg	(Muñoz Díaz et al., 2023)
Land	0.3	USD/m^2	(Mrs. Diarra, 2019)
Borehole drilling	1,600	USD (Total)	(Martínez-Santos et al., 2017)
Solar pumping	1,300	USD (Total)	(Martínez-Santos et al., 2017)
water tank	5,000	USD(Total)	(Muñoz Díaz et al., 2023)
water treatment system	1,500	USD (Total)	(Muñoz Díaz et al., 2023)
Installation & miscellaneous (5%)	0.05	of total capex	(Madheswaran et al., 2022)

Table 7. Operational Expenditure (OPEX)

Component	Annual Cost	Unit	Reference
Solar PV	7.4	USD/kWp/year	(Bhandari & Shah, 2021)
Battery	0.3375	USD/kWh/year	(Bhandari & Shah, 2021)
Electrolyzer	10	USD/kW/year	(Bhandari & Shah, 2021)
Maintenance of H_2 tank	6	USD/kg/year	(Muñoz Díaz et al., 2023)
Water treatment	3,000	USD/year	(Mohamed et al., 2022)
Insurance& Admin (0.5%)	0.005	Of total capex	

2.1.2 White Hydrogen Model

White hydrogen economic model assesses the economic feasibility of extracting naturally occurring hydrogen from the Bourakébougou underground sandstone reservoir in Mali. In direct comparison with the green hydrogen pathway, the model assumes a production capacity of 2,740 kilograms per day of hydrogen. Even though economic feasibility is the drive of this study, a brief description of the technical chain is provided in table 8 to put cost assumptions into perspective.

The hydrogen is produced from geological reservoirs in a direct method without any non-natural production cycle, but using technologies adapted from natural gas drilling and production. One exploration well and nine vertical production wells have been included in the modeled system, with the produced hydrogen at a reservoir depth of about 500 meters and an initial reservoir pressure of 5 bar. The composition of gas at Bourakébougou is roughly 98% hydrogen (Prinzhofer et al., 2018), but the requirement exists for a polishing step to meet 100% purity for storage. Trace amounts of contaminants such as nitrogen (1%), and methane (1%) must be removed to avoid corrosion, ensure safety, and meet end-use purity requirements (Maiga et al., 2023). For this reason, the model includes a Pressure Swing Adsorption (PSA) unit for conditioning. The process of purification and handling is estimated to consume around 4.5 kWh per kilogram of hydrogen, which is the sum of energy used in gas drying, impurity removal, and support operations (DOE, 2013). After purification, the hydrogen is compressed with grid power and stored in 350-bar high-pressure storage tanks. Figure 4 illustrates a simplified flow diagram of the white hydrogen production system, employing established processes in natural gas production, and relying on reports of Bourakébougou fields (Maiga et al., 2023; Prinzhofer et al., 2018). The system boundaries are production well, rotary drilling ring, purification system, and storage. A land space of approximately 20,000 m² was presumed for surface facilities and well pads, consistent with typical spacing requirements for small-scale cluster production.

The CAPEX items (Table 9) include drilling a nine production well and a one exploration wells, installation of compression facilities, PSA purification unit, hydrogen storage tanks, and site preparation. The OPEX items (Table 10) include hydrogen tank maintenance at 2% CAPEX, PSA system maintenance, grid electricity costs for purification and compression, labor, insurance and administrative charges.

All parameters were combined into a 25-year Discounted Cash Flow (DCF) model using the 7% discount rate, in relation to the green hydrogen scenario. According to this model, the

Levelized Cost of Hydrogen (LCOH) and Net Present Value (NPV) were determined to assess the long-term economic attractiveness of white hydrogen production in the research area.

This model then comes into relevance with respect to the early development stage of white hydrogen production. Although technical data remains incomplete for Bourakébougou, the intersection of high natural hydrogen concentration with continuous extraction tests positions it as one of the globe's most promising sites for assessing the cost-competitiveness for this low-carbon production path.

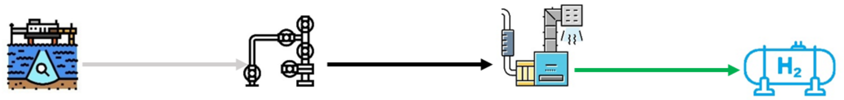

Figure 4. Schematic diagram of white hydrogen production system (Adapted from Musa et al., 2024; Peninsula et al., 2023)

Table 8. General data assumptions for white hydrogen production

Component	Value	Unit	Reference
Production capacity	2,740	kg/day	Assumption
Reservoir depth	500	m	(Maiga et al., 2023)
Reservoir area	9,885	km^2	(Patonia et al., 2024)
Reservoir type	sandstone		(Maiga et al., 2023)
Reservoir pressure	5	bar	(Maiga et al., 2023)
Number of wells	10		Assumption
Exploration well	1		Assumption
Production well	9		Assumption
storage pressure	90	bar	(Patonia et al., 2024)
Hydrogen density	6.1	kg/m^3	(Patonia et al., 2024)
Land	20,000	m^2	
Energy require	4.5	kWh/kg	(DOE, 2013)
Hydrogen purity	98	%	(Maiga et al., 2023)

Table 9. White hydrogen Capital Expenditure (CAPEX)

Component	Cost	Unit	Reference
Land	0.3	USD/m^2	(Mrs. Diarra, 2019)
Planning and approvals	223,134	USD (total)	(Patonia et al., 2024)
Site preparation	1,000,000	USD (total)	(Maiga et al., 2023)
Exploration wells	837500	USD/m	(Musa et al., 2024)
Production wells	125000	USD/m	(Musa et al., 2024)
Processing facility	1,000,000	USD (total)	(Musa et al., 2024)
Hydrogen tank	300	USD/kg	(Musa et al., 2024)
Installation & Misc (5%)	0.05		(Madheswaran et al., 2022)

Table 10. Operational Expenditure (OPEX)

Component	Cost	Unit	Reference
Hydrogen tank(O&M)	4	USD/kg/year	(Musa et al., 2024)
Membrane (PSA)	20000	USD/year	(Musa et al., 2024)
Electricity	0.28	USD/kWh	(Drave et al., 2025)
Labor	40,000	USD/year	(adjusted for study area Martínez-Santos et al., 2017)
Admin (1%)	0.01		
Insurance (0.5%)	0.005		

2.2 Levelized Cost of Hydrogen (LCOH)

The Levelized Cost of Hydrogen (LCOH) in this study is calculated using the following general equation:

$$\mathrm{LCOH} = \frac{\mathrm{CAPEX} + \sum_{t=1}^{n} \frac{\mathrm{OPEX}}{(1+r)^{t}}}{\sum_{t=1}^{n} \frac{H_t}{(1+1)^{t}}} \quad (1)$$

Where:

CAPEX= Total capital expenditure (USD)

OPEX= Operational expenditure (USD/year)

H_t= Hydrogen production (kg/year)

n= Project lifetime (years)

r= Discount rate

This formula calculates the total discounted operation costs over the system life and then divides by the total discounted hydrogen produce, deriving a per-unit cost of production (USD/kg H_2). Using this analysis evenly on both green and white hydrogen production scenarios makes it easy and comparable to assess their economic feasibility under site conditions in Bourakébougou, Mali.

The LCOH is the main economic metric utilized in this study to determine the cost-effectiveness of hydrogen production over the whole project duration. It incorporates operating costs and capital expenditures, hydrogen production, together with financial parameters like the discount factor and project life. LCOH has broad industry and academic acceptance as a normalized metric to contrast the long-term economic feasibility of different hydrogen production technologies across locations and scenarios (Franco et al., 2025; IRENA, 2021).

2.2.1 Discounted cash flow and net present value analysis

The Net Present Value (NPV), derived from the Discounted Cash Flow (DCF) method, is calculated in this study using the following general formula:

$$NPV=\sum_{t=1}^{n} \frac{NCF_t}{(1+r)^t} \quad (2)$$

Where:

- NCF_t = Net cash flow in year *t* (USD)
- r = Discount rate
- n = Project lifetime (years)

This equation discounts all net cash flows of annual scale (revenues less expenses) back to their current value and adds them over the life of the project. A positive NPV means the project creates more value than it costs, which is an indicator of financial feasibility.

Here, DCF calculation was carried out in order to evaluate the financial feasibility of both white and green hydrogen manufacturing plants in Bourakébougou, Mali. DCF considers the time value of money, and comparison between future cash flows and initial investments can be done realistically (Musa et al., 2024).

The study assumes a 25-year project life, with the base case being a 7% discount rate reflecting a moderate risk profile that most accurately describes private sector energy investments. Sensitivity analysis at discount rates of 5%, 6%, 8%, and 9% was also conducted to reflect different investor expectations based on global benchmarks. As approximated by the International Renewable Energy Agency (IRENA, 2024) and the International Energy Agency (International Energy Agency, 2021), discount rates for the interval of between 3% (for low-risk public projects) and 10% (for high-risk private investments).

By applying this DCF-NPV method in the same way to both hydrogen scenarios, the analysis gives a clear and strong estimate of long-term financial performance.

2.2.2 Sensitivity analysis

Sensitivity analysis in financial modeling is used to examine how various changes in the principal input parameters affect a specific output variable, the Levelized Cost of Hydrogen (LCOH) (Musa et al., 2024). The analysis can determine what the most influential factors are on the economic feasibility of the system for hydrogen production.

Sensitivity analysis was carried out for the current study to measure the impact of the independent variables namely, Capital Expenditure (CAPEX), Operational Expenditure (OPEX) and Discount Rate. One by one, all these parameters were independently changed within the range ±10% to ±20% of the base-case values while keeping all other variables fixed.

The purpose was to observe how the changes would affect the resulting LCOH and therefore stress most economically sensitive aspects of the system. The study was conducted with simplified models based on the base-case outcome of the discounted cash flow (DCF) model. Rather than updating the full year-by-year cash flow for each case, percentage changes were added directly to CAPEX, OPEX, and the discount rate.

The related effects on LCOH were then estimated using the same process outlined in Section 3.2. This process provided a realistic and transparent method for figure out cost drivers and risk across both the green and white hydrogen paths under consideration.

2.3 Data sources and assumptions

Economic analysis in this study relies on a wide range of input parameters that include operational expenses, capital expenses, technical specifications, hydrogen production rate, and financial assumptions. These data were sourced from a mix of peer-reviewed papers, industry reports, and technology datasheets particularly those by NASA POWER and International Renewable Energy Agency (IRENA).

For the green hydrogen path, recent cost reports for major components such as solar photovoltaic (PV) systems, alkaline electrolyzers, lithium-ion batteries, hydrogen storage tanks, and water infrastructure were collected for off-grid renewable hydrogen production systems (Bhandari & Shah, 2021; International Energy Agency, 2021; Martínez-Santos et al., 2017).
These were adjusted to estimate the study site, Bourakébougou, Mali, in light of logistical restraints, transport charges, and regional price variations.

In the white hydrogen case, significant assumptions such as reservoir depth (500 m), purity of hydrogen (98%), number of wells, and area of production were derived from geological surveys and field reports pertaining to the natural hydrogen discovery in Bourakébougou (Maiga et al., 2023).

CAPEX and OPEX projections for the exploration and production well drilling, compression infrastructure, pressure swing adsorption (PSA) equipment, and hydrogen storage facilities were adopted from technical reports on subsurface hydrogen systems and analogous oil and gas developments (Blay-Roger et al., 2024; Musa et al., 2024).

Where cost data were not found directly available, estimated values were made through comparative benchmarks of international hydrogen pilot projects and scaled as necessary.
Financial parameters used in the two models like discount rate (7%), and project duration (25 years) adhere to international best practice recommended by International Renewable Energy Agency (IRENA, 2024) and International Energy Agency (International Energy Agency, 2021).

Chapter 3. Results and discussion

3.1 Economic Comparison of green and white hydrogen in Bourakebougou

This chapter presents the comparative economic study of white and green hydrogen production system in Bourakébougou, Mali.

This research applied important financial metrics and cost drivers: Levelized Cost of Hydrogen (LCOH), Net Present Value (NPV), annual revenue, and detailed breakdowns of Capital Expenditure (CAPEX) and Operational Expenditures (OPEX).

3.1.1 Green hydrogen analysis

Table 11 shows the overall capital expenditure (CAPEX) of 49.94 million USD for the green hydrogen production system, with the solar PV system (22.83 million USD) and electrolyzer units (8.56 million USD) being the largest contributors, followed by battery storage (7.14 million USD), electrolyzer stack replacement (4.62 million USD) and a onetime battery replacement (3.57 million USD). Together, these three technologies (PV, electrolyzers, and batteries) account for more than 80% of the total CAPEX, and this points to the capital-intensive nature of renewable hydrogen systems. Other components such as hydrogen storage tanks, land acquisition, borehole drilling, water treatment facilities, and a 5% installation margin contribute very little to the cost. A graphical summary of the CAPEX breakdown is in Figure 5.

Annual operating expenses (OPEX) are estimated at 497,014 USD (Table 12) and include PV panel and electrolyzer maintenance, battery and hydrogen tank maintenance, water treatment operations, labor, insurance, and administrative fees. Each OPEX component's contribution is illustrated in Figure 6.

With the discounted cash flow (DCF) model for a 25-year life, under a PV capacity factor of 17.5% and a battery buffer of 23.8 MWh (1.4 hours of electrolyzer load, not an entire-day backup), the economic outcomes are the following: the Levelized Cost of Hydrogen (LCOH) is 4.78 USD/kg, the Net Present Value (NPV) is 9.54 million USD, and the annual revenue from hydrogen sales is 5.6 million USD.

Although the positive NPV indicates long-term financial feasibility of Bourakébougou at favorable market prices, the relatively high LCOH indicates that green hydrogen production in Bourakébougou is no way cost competitive. The costs are predominantly of solar PV, electrolyzers, and battery storage, as reported in existing literature singling out electricity and electrolyzer prices as primary determinants of green hydrogen economics (International Energy Agency, 2021).

Table 11. Green hydrogen CAPEX cost breakdown

Parameter	Size/Qty	Unit	Total cost	Unit
Solar PV	32,619.05	kWp	22,833,333.33	USD
Electrolyzer (Alkaline)	17,125.00	kW	8,562,500.00	USD
Stack replacement			4,623,750.00	USD
Battery (Lithium battery)	23,784.72	kWh	7,135,416.67	USD
Battery replacement			3,567,708.33	USD
Hydrogen tank	4,110.00	kg	822,000.00	USD
Land	23,965.75	m^2	7,189.73	USD
Borehole drilling	1.00		1,600.00	USD
Solar pumping	1.00		1,300.00	USD
water tank	1.00		5,000.00	USD
water treatment system	1.00		1,500.00	USD
Installation & Misc. (5%)			2,211,571.85	
Total CAPEX			49,939,362.96	USD

Table 12.OPEX cost breakdown

Parameter	Size/Qty	Unit	Annual cost	Unit
Solar PV (O&M)	32619.04762	kWp	228,333.33	USD
Battery (O&M)	23784.72222	kWh	8,027.34	USD
Electrolyzer (O&M)	17125	kW	171,250.00	USD
Maintenance of H_2 tank	4110	kg	16,440.00	USD
Water treatment	1		3,000.00	USD
Labour			40,000.00	USD
Administration (1%)	0.01		19,975.75	USD
Insurance (0.5%)			9,987.87	USD
Total OPEX			497,014.29	USD/year

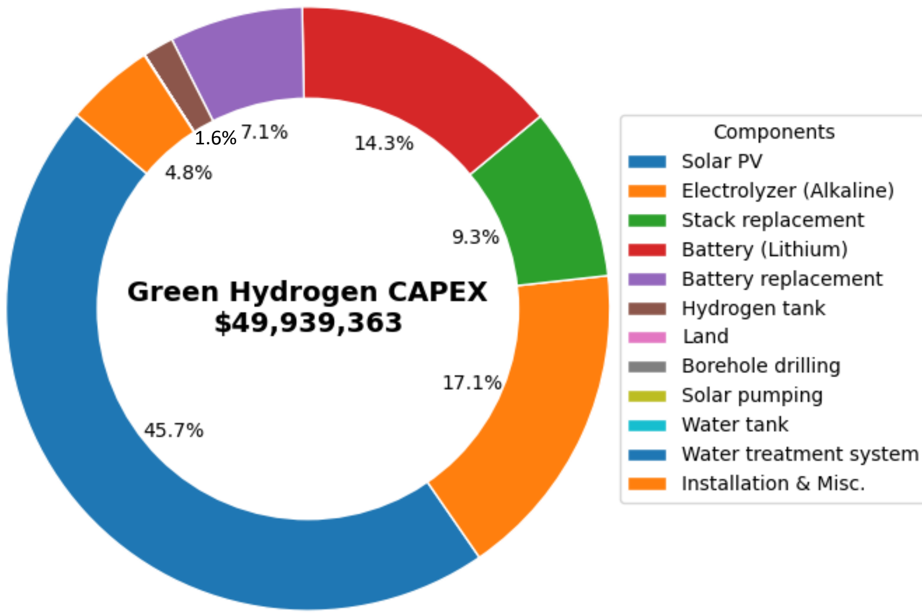

Figure 5. CAPEX costs breakdown

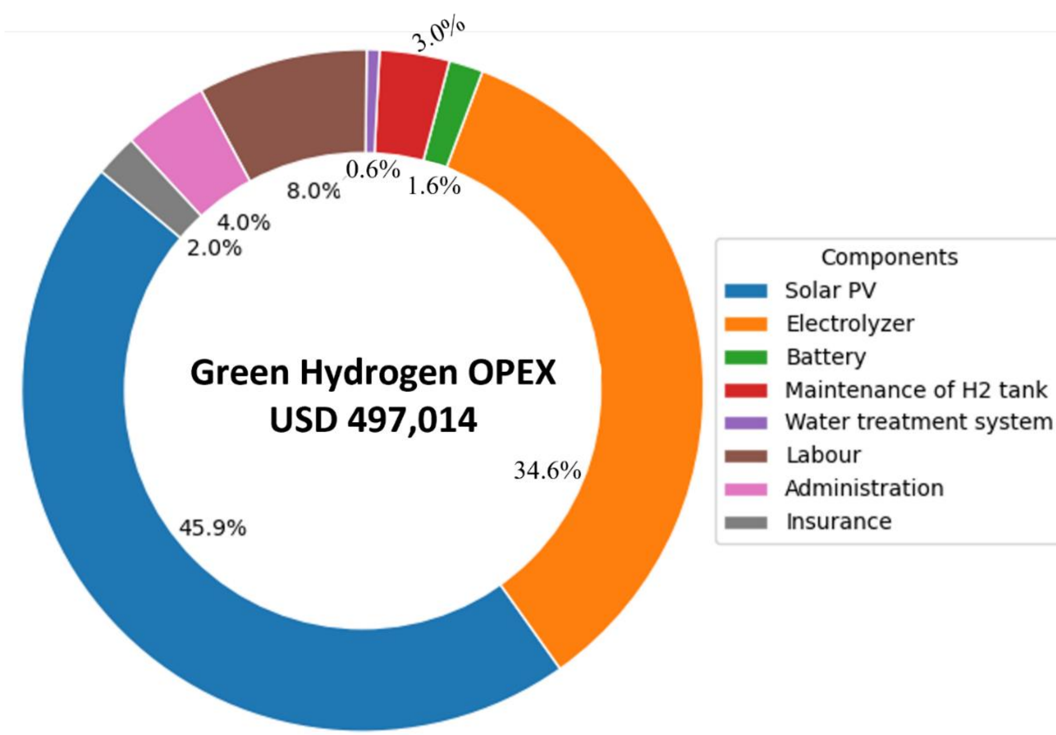

Figure 6. OPEX costs breakdown

3.1.2 White hydrogen analysis

As opposed to the green hydrogen approach, the white hydrogen production model is considerably more cost competitive. Total CAPEX is estimated at 5.26 million USD, as detailed in Table 13. Major cost items are the production wells and hydrogen processing facility (totaling 2 million USD), site preparation and infrastructure development (1 million USD), hydrogen storage tanks (822,000 USD), and planning, permit, and installation costs, at 5% of total CAPEX. A breakdown of the percentage of CAPEX is presented in Figure 7, where the contribution of each investment item relative to total capital cost is illustrated.

The total yearly operating expenses (OPEX) was calculated at USD 1.34 million (Table 14). This is contributed mainly by electricity consumption for purification (USD 1.26 million), then maintenance of hydrogen storage tanks (2% of CAPEX), replacement of Pressure Swing Adsorption (PSA) membranes from time to time, and administration (1%) and insurance (0.5%) costs of the total capex divided by the lifetime of the project and multiple by each percentage. A graphical distribution of the OPEX is shown in Figure 8, indicating the contribution of each part.

Although the white hydrogen model maintains a higher OPEX annually, it is preferred with substantially lower initial capital expense, which gives much better finances. On a project life of 25 years, the white hydrogen model maintains a Levelized Cost of Hydrogen (LCOH) of 1.79 USD/kg, Net Present Value (NPV) of 44.39 million USD, and yearly revenue from the sale of hydrogen at 5.6 million USD. These results indicate the economic benefit of white hydrogen in the current conditions of Bourakébougou. The combination of naturally occurring hydrogen, minimal infrastructure requirements, and lower CAPEX allows for much lower cost per unit of hydrogen.

As a result, white hydrogen is a highly competitive and scalable alternative to green hydrogen in regions with access to natural hydrogen reservoirs and geologically feasible locations (Maiga et al., 2023; Musa et al., 2024).

Table 13. White hydrogen CAPEX cost breakdown

Component	Cost	Unit	Qty	Unit	Total cost	Unit
Land	0.3	USD/m^2	20,000	m^2	6,000.00	USD
Planning and approvals	223,134	USD (total)	1		223,134.33	USD
Site preparation	1,000,000	USD (total)	1		1,000,000.00	USD
Exploration wells	837500	USD/m	1		837,500.00	USD
Production wells	125000	USD/m	9		1,125,000.00	USD
Processing facility	1,000,000	USD (total)	1		1,000,000.00	USD
Hydrogen tank	200	USD/kg	4110	kg	822,000.00	USD
Installation & Misc (5%)	0.05				250,681.72	USD
Subtotal			5,013,634.33			
Total CAPEX					5,264,316.05	USD

Table 14. OPEX cost breakdown

Components	Cost	Unit	Qty	Unit	Annual cost	Unit
Hydrogen tank(O&M)	4	USD/kg/year	4110	kg	16,440.00	USD
Membrane (PSA)	20,000.00	USD/year	1		20,000.00	USD
Electricity	0.28	USD/kWh	4500450	kWh/year	1,260,126.00	USD
Labour	40,000	USD/year	1		40,000	USD
Administration (1%)	0.01				2,105.73	USD
Insurance (0.5%)	0.005				1,052.86	USD
Subtotal Opex					1,298,954.00	
Total Opex					1,339,724.59	USD

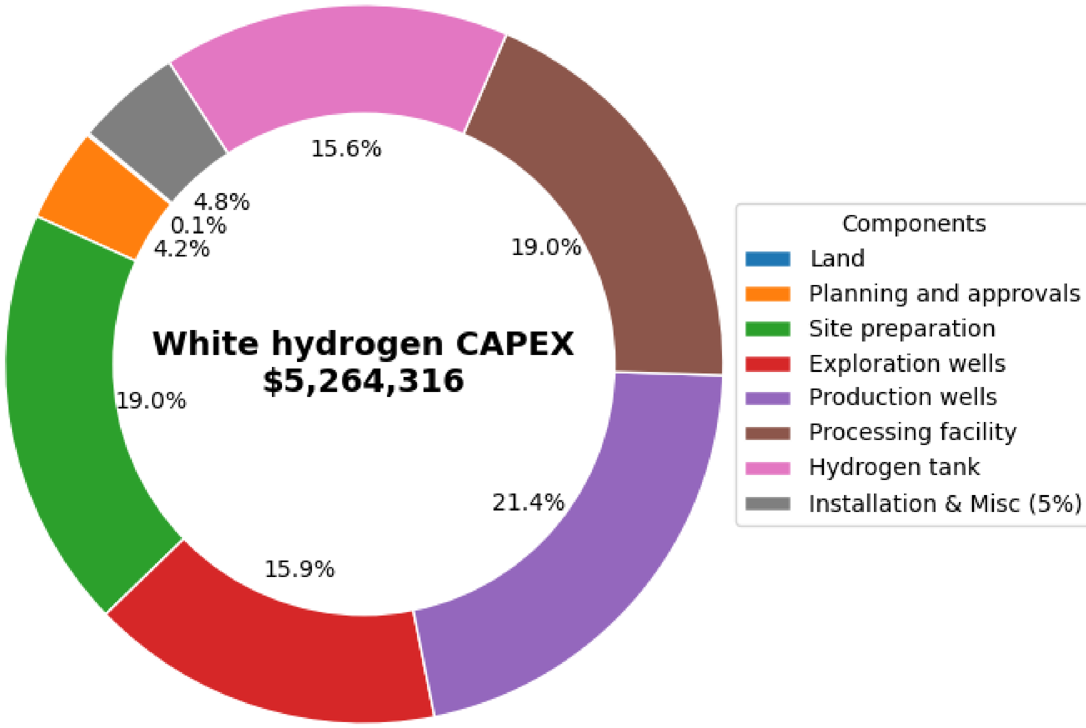

Figure 7. CAPEX costs breakdown

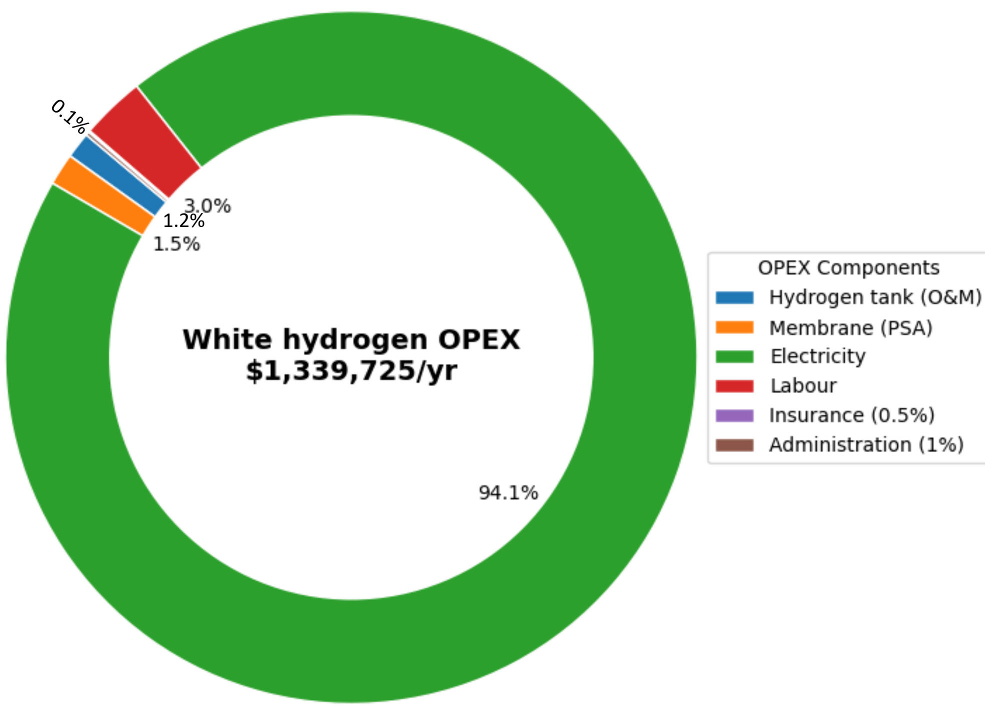

Figure 8. OPEX Costs breakdown

3.1.3 comparative discussion

The comparison puts in perspective the fact that, the circumstances of Bourakébougou, white hydrogen is cheaper and economically feasible pathway for the production of hydrogen. Having naturally occurring hydrogen at subsurface levels reduces capital and operating costs by an extremely great margin, giving a plain economic advantage compared to green hydrogen.
This beneficial cost outline is largely attributed to the minimal infrastructure requirement for extraction and processing in comparison to the capital-heavy renewable equipment needed for green hydrogen production.

While green hydrogen would be ideally suited to long-term sustainability needs and decarbonization strategies, it remains economically constrained by the high costs of solar PV installations, electrolyzers, and battery storage.

These findings are in line with recent studies emphasizing economic feasibility of hydrogen generation highly based on resource availability, technological readiness, and infrastructure spending (IRENA, 2021; Maiga et al., 2023; Musa et al., 2024).

White hydrogen can serve as a scalable and cost-effective complement to renewable-based hydrogen production in regions that possess white hydrogen reservoirs, encouraging diversified supply of hydrogen.
Table 15 summarized the comparative assessment of the two sets of hydrogen results.

Table 15. Comparison table results

Parameter	Green hydrogen	White hydrogen
CAPEX	49.94 Million USD	5.26 Million USD
OPEX	497,014 USD	1.34 Million USD
LCOH	4.78 USD/kg	1.79 USD/kg
Revenue	5.6 Million USD	5.6 Million USD
NPV	9.54 Million USD	44.39 Million USD

3.2 Sensitivity analysis

As discussed previously, sensitivity analysis was performed to examine the effects of the variations in capital expenditure (CAPEX), operational expenditure (OPEX), and discount rate on the Levelized Cost of Hydrogen (LCOH). The analysis included variations of ±10% and ±20% relative to base-case assumptions. For each of the scenario, LCOH was re-calculated to observe how sensitive hydrogen production costs are with respect to variations in the key parameters. For the base case, LCOH has been estimated at 4.78 USD/kg for green hydrogen and 1.79 USD/kg for white hydrogen, which is considered as the reference point for comparison for all the sensitivity cases.

3.2.1 Green hydrogen

Sensitivity analysis indicates that green hydrogen LCOH is most sensitive to CAPEX. Increasing the CAPEX by 20% moves LCOH to 5.64 USD/kg and lowering CAPEX by 20% takes it below around 3.92 USD/kg. This reflects the capital-intensive nature of battery storage, solar PV, and electrolyzers, whose combined share contributes to the majority of the total investment.

OPEX variations are smaller, however a substantial impact. A 20% rise in OPEX raises the LCOH to approximately 4.88 USD/kg, while a 20% reduces it to approximately 4.68 USD/kg. The impact of a discount rate change is relatively small, with changes of 5% to 9% shifting the LCOH by only a few cents per kilogram.

On the overall, these observations reveal that economic competitiveness of green hydrogen in Bourakébougou is more reliant on minimizing capital expenses, especially on renewable energy and electrolyzer plants. Minimizations in efficiency or cost within these aspects would have the most significant contribution in making green hydrogen competitive under local conditions.

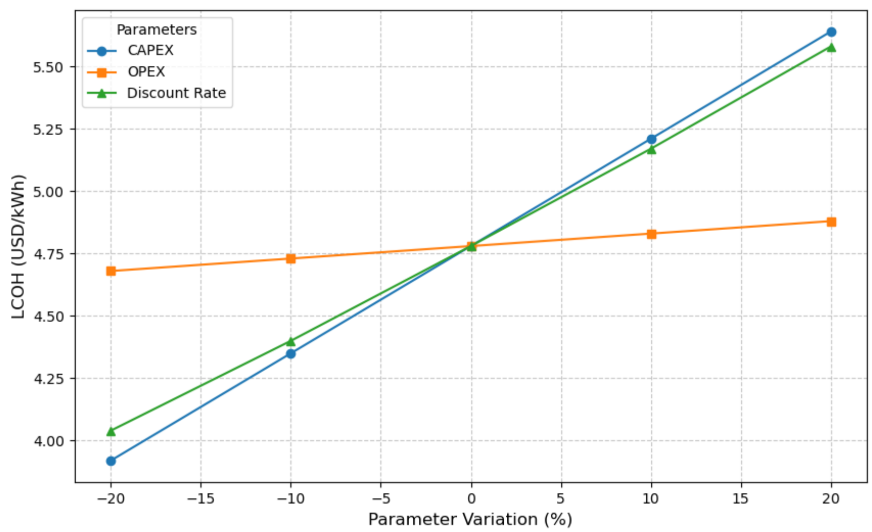

Figure 9.Green hydrogen sensitivity analysis

3.2.2 White hydrogen

For white hydrogen, sensitivity analysis indicates that LCOH is less sensitive to CAPEX but more sensitive to OPEX variation. When CAPEX is reduced by 20%, the LCOH falls to about 1.70 USD/kg, and when CAPEX goes up by 20%, it rises to 1.84 USD/kg. OPEX variation, however, affects more reducing it by 20% lowers LCOH to 1.52 USD/kg, and increasing it by 20% raises it to 1.93 USD/kg.

The discount rate only has a partial impact, and LCOH varies between 1.71 USD/kg at a 5% rate to 1.75 USD/kg at 9%. This means that financial conditions, even though relevant, are not the fundamental driver of cost competitiveness for white hydrogen.

Overall, the study indicates that the economic feasibility of white hydrogen in Bourakébougou is most sensitive to the efficiency of operations rather than initial capital expenditures. Having a low-cost of electricity supply available for purification and curtailing recurring system maintenance will therefore be critical in order to maintain its economic advantage over green hydrogen.

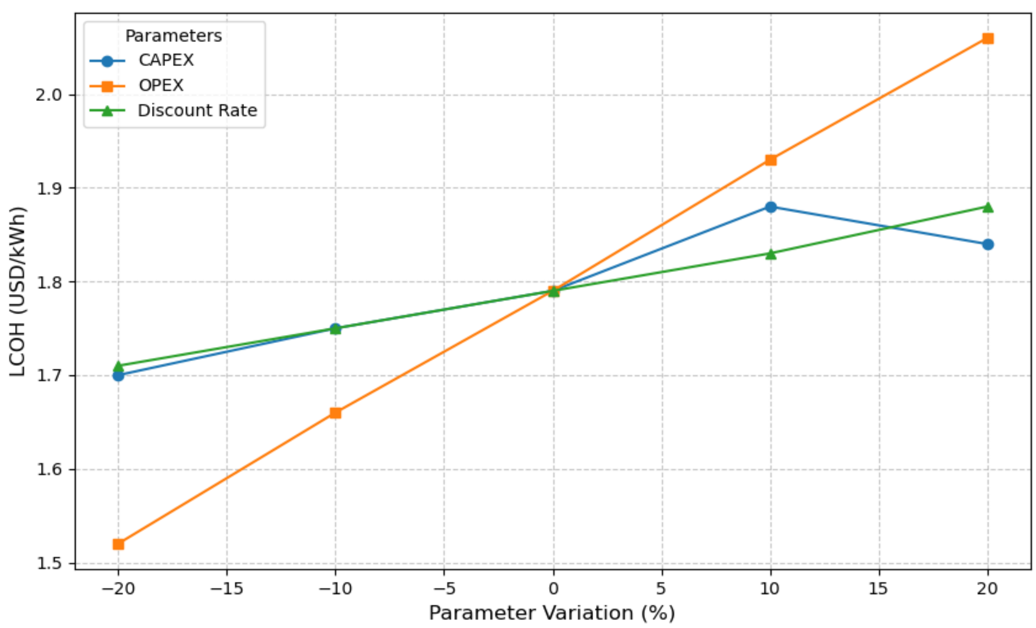

Figure 10. White hydrogen sensitivity analysis

3.2.3 Comparative discussion

The comparative sensitivity analysis shows several important differences between the two hydrogen paths. Green hydrogen is more sensitive to capital cost variation, in the likeness of a high upfront capital investment required to set up renewable energy infrastructure, electrolyzer innovation and storage plants. White hydrogen, on the other hand, has a lower base-case LCOH and lower sensitivity to capital costs, due to a more stable cost through its relatively low infrastructure requirements.

Operational expenses are significant in both streams of production, with white hydrogen being slightly more exposed due to the need for continuous purification and maintenance practices. The discount factor affects both forms of hydrogen the same way, highlighting the significance of funding conditions in determining project economics.

Generally, the analysis confirms that reducing capital expenditure is critical to improving the feasibility of green hydrogen, nevertheless increasing operational efficiency is the most feasible way of saving costs and improving white hydrogen's competitiveness in Bourakébougou.

Conclusion

The study investigates a comparative economic analysis of green and white hydrogen production in Bourakébougou, Mali, on the basis of similar financial metrics and cost drivers namely, Levelized Cost of Hydrogen (LCOH), Net Present Value (NPV), capital expense (CAPEX), and operating expense (OPEX). The analysis provided different economic outlines for both production paths based on the cost of technology, resource availability, and financial parameters.

The green hydrogen system, although possessing a positive NPV of 9.54 million USD, encounters a huge economic run due to its huge initial capital expenditures, mainly by the cost of solar photovoltaic systems, electrolyzers, and battery storage. At an estimated LCOH of 4.78 USD/kg, green hydrogen is at the moment of noncompetitive in terms of cost, especially under present market circumstances.

Sensitivity analysis confirmed that CAPEX plays a major role in its economic feasibility, stressing the extreme significance of cost savings on technology and good finance to make it more competitive.

On the other hand, the white hydrogen system displayed clear economic advantages, mostly due to its lower CAPEX requirements and harnessing of naturally present hydrogen.

With an LCOH of 1.79 USD/kg and a much higher NPV of 44.39 million USD, white hydrogen provides a cheaper production scenario for Bourakébougou. While OPEX expose to purification costs are significant cost driver, sensitivity analysis revealed that the production of white hydrogen is generally more cost-sensitive than that of green hydrogen.

In general, the findings confirm that capital efficiency, cost structures of technology, location and resource availability are key for hydrogen production economics.

Green hydrogen remains a long-term strategic priority for future sustainable energy transitions, white hydrogen presents a near-term and economically attractive alternative in areas of favorable geological conditions.

These results provide significant lessons for policymakers, investors, and researchers in evaluating and undertaking hydrogen production strategies in Bourakébougou and other similar situations across Africa.

Recommendations

The following recommendations are made to enable the development of hydrogen production in Bourakébougou, Mali, from the outcome of this research:

1. Give Priority to White Hydrogen Exploration and Development

Due to the superior economic performance, immediate priority should be given to the development of white hydrogen extraction at scale where natural reservoirs exist. This entails investment in geological surveys, pilot production plants, technologies for extraction and purification to optimize operational efficiency and reduce OPEX.

2. Encourage Research on Green Hydrogen Cost Reduction

To make green hydrogen more competitive, there must be research and development (R&D) of low-cost renewable energy systems, electrolyzer efficiency, and battery storage systems. Cooperation with research institutions and technology suppliers can accelerate innovation and cost reduction.

3. Establish Clear Regulatory Frameworks

Policymakers should establish regulatory and permitting frameworks for hydrogen production, especially white hydrogen extraction, to move environmental protection, resource management, and investment certainty forward.

4. Enable Infrastructure Development

Investment in enabling infrastructure such as purification units, storage, and transportation networks will be instrumental in giving a free rein to a full economic value of both green and white hydrogen projects in the region.

5. Encourage Local Capacity Building and Knowledge Transfer

Initiatives that build local technical capacity and involve local communities in hydrogen projects can enhance project sustainability, drive job creation, and ensure long-term socio-economic benefits.

6. Monitor Global Market Trends

As the global hydrogen market further emerges, ongoing tracking of market prices, technology costs, and policy evolution will be essential in ensuring the feasibility and competitiveness of hydrogen projects in Bourakebougou, Mali.

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