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ECONOMIC EVALUATION OF GREEN HYGROGEN PRODUCTION, STORAGE, AND EXPORT FROM NIGER TO EUROPE

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DEDICATION

This work is dedicated to my wonderful parents: my uncle Bassirou Manzo, my mother, Mariama Namousalé, whose unwavering love and steadfast support continually inspire me; and my father, ROUFAÏ ELHADJI MAMANE, whose memory remains deeply rooted in my heart every day.

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DECLARATION

I, Nana Tamamatou ROUFAI ELHADJI MAMANE, hereby declare that this thesis titled "Economic Evaluation of Green Hydrogen Production, Storage, and Export from Niger to Europe" is the result of my independent work and research, unless otherwise stated and properly acknowledged. I affirm that this work has not been previously submitted for any other academic degree, diploma, or certificate. I have properly cited all sources of information, ideas, and data used in this thesis. The content of this thesis reflects my research and analysis, and any assistance received has been appropriately acknowledged. I understand that any violation of academic integrity and plagiarism guidelines could lead to serious consequences, including rejection of this thesis and potential disciplinary actions according to the regulations of the Université de Lomé, Togo.

I take full responsibility for any errors or omissions in this work.

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Date: 17th September 2025 Signature: 

ABSTRACT

This thesis investigates the economic viability of producing, storing, and exporting green hydrogen from Niger to Europe, addressing a notable gap in existing research. Niger has abundant solar energy potential, substantial agricultural waste, and proximity to Europe; however, it is not currently involved in any global hydrogen projects. The study uses a techno-economic evaluation approach, combining resource assessment, cost modeling, and logistics analysis. It explores three hydrogen production methods: biomass gasification, dark fermentation, and solar steam methane reforming (SSMR), which uses methane derived from slaughterhouse blood. Techno-economic modeling shows that the levelized cost of hydrogen (LCOH) from biomass pathways is between 2.5 and 5.1 USD/kg. However, solar-assisted SSMR can get lower values when the irradiation conditions are good and exceed 2,000 kWh/m^2/year. Levelized cost of storage (LCOS) analysis compares various storage options, such as compressed gaseous hydrogen and liquefied hydrogen. Compressed hydrogen is a suitable choice for storage in small to medium-sized applications, while liquefied hydrogen is better suited for long-distance exports at $5.98/kg. The export route is evaluated through retrofitted oil pipelines to Europe at $ 0.85/ton/km. Findings show that Niger's solar and agricultural waste resources make hydrogen production competitive. Dark fermentation offers a decentralized option, gasification provides scalability, and SSMR proves efficient when paired with solar power. Retrofitted pipelines emerge as the most cost-effective long-term export solution. Overall, results indicate Niger could become a new hydrogen supplier, aiding Europe in achieving renewable energy goals, boosting local industry growth, increasing energy access, and strengthening the economy.

Keywords: Biomass gasification, dark fermentation, solar steam methane reforming, hydrogen

RESUME

Ce mémoire étudie la faisabilité économique de la production, du stockage et de l'exportation d'hydrogène vert du Niger vers l'Europe, comblant ainsi un vide dans la littérature. Le Niger possède du soleil, des déchets agricoles, est proche de l'Europe, mais n'est pas inclus dans un projet mondial d'hydrogène. L'étude utilise une approche d'évaluation technico-économique (analyse des ressources, modélisation des coûts et évaluation logistique). Trois voies de production sont étudiées : la gazéification de biomasse, la fermentation sombre et la réforme du méthane assistée par énergie solaire (SSMR), à partir de méthane issu des sous-produits d'abattoirs. La modélisation technico-économique révèle que le coût nivelé de l'hydrogène (LCOH) des voies de biomasse se situe entre 2,5 et 5,1 USD/kg. Cependant, la SSMR combinée au solaire peut atteindre des coûts plus faibles lorsque l'irradiation dépasse 2000 kWh/m²/an. L'analyse des coûts de stockage nivelés (LCOS) compare l'hydrogène comprimé et liquéfié : l'hydrogène comprimé convient aux applications de petite et moyenne taille, tandis que l'hydrogène liquéfié est plus adapté aux exportations à longue distance, avec un coût de 5,98 USD/kg. L'exportation par oléoduc réaménagé Niger-Bénin est estimée à 0,85 USD/tonne/km, ce qui constitue la solution la plus économique à long terme. Les résultats montrent que les ressources solaires et agricoles du Niger rendent la production d'hydrogène compétitive. La fermentation sombre représente une option décentralisée, la gazéification est évolutive, et la SSMR est efficace en combinaison avec le solaire. En somme, cette étude révèle que le Niger pourrait devenir un nouveau fournisseur d'hydrogène, soutenant les ambitions européennes de transition énergétique, tout en favorisant l'industrialisation, l'accès à l'énergie et le développement socio-économique du pays.

Mots-clés : Gazéification de la biomasse, fermentation sombre, réforme solaire du méthane, hydrogène vert.

LIST OF ACRONYMS AND ABBREVIATIONS

AD: Anaerobic digestion

ASME: American Society of Mechanical Engineers

ATM: atmosphere

API: American Petroleum Institute

BMBF: Bundesministerium für Bildung und Forschung

BMP: Biochemical methane potential

C: Canal

C/N: Carbon-to-nitrogen ratio

CAGR: Compound Annual Growth Rate

CAPP: Central African Power Pool

C_CE: Carbon Conversion Efficiency

Crew: Annual crew cost

CCS: Carbon Capture & Storage

CETM: Annual maintenance cost of onshore storage tanks

CEPCI: Chemical Engineering Plant Cost Index

CPort**:** Port cost per ship

CPL**:** Ship leasing

CGH_2: Compressed Gaseous Hydrogen

CH_4: Methane

CO: Carbon monoxide

CO_2-eq: Carbon dioxide equivalent

°C: degree Celsius

COMELEC: Maghreb Electricity Committee

CO_2: Carbon dioxide

COGAS: Combined Gas and Steam turbine

COP26: 26th Conference of the Parties

COL: Cooling Operating Labor

CRF: Capital Recovery Factor

CSM: Annual ship maintenance costs

CUT: Cooling Utility

$: Dollar

$/kWh: Dollars per kilowatt-hour

$/ton: Dollars par ton

$/L: Dollars par litre

DIF: Diffuse Horizontal Irradiation

DRP-CCDRM

DMC: Direct Manufacturing Costs

DNI: Direct Normal Irradiation

DOE: Department of Energy

E: Equation

EAPP: East African Power Pool

EJ/yr: Exajoules per year

EN: European Norms (European Standards)

ENP: European Neighborhood Policy Agreement

EU: European Union

FAOSTAT: Food and Agriculture Organization Corporate Statistical Database

FMC: Fixed Manufacturing Costs

FW: Food Waste

GE: General Expenses

GHG: Greenhouse gases

GHI: Global Horizontal Irradiation

GJ: Gigajoule

GSP: Global Strategic Partnership

GTI: Global Tilted Irradiation at Optimum Angle

GW: Gigawatt

H: Hour

H_2: Hydrogen

H_2O: Water

H2STAR:

HDPE: High-Density Polyethylene

HR: Pyrolysis heating rate

IMP-EGH: International Master Programme – Energy & Green Hydrogen

IPCC: Intergovernmental Panel on Climate Change

IRENA: International Renewable Energy Agency

IRR: Internal Rate of Return

ISO: International Organization for Standardization

J: joules

K: kelvin

Kg : Kilograms

Km: kilometer

kWh: kWp: Kilowatt

kWh/kWp: Kilowatt-hour per kilowatt peak

kWh/m^2: Kilowatt-hours per square meter

KPIs: Key Performance Indicators

L: Litter

L/h: Liters per hour

LCOH: Levelized Cost of Hydrogen

LCOS: Levelized Cost of Storage

LCOT: Levelized Cost of Transport

LH_2: liquid hydrogen

LNG: Liquefied Natural Gas

LOX: Liquid Oxygen

M: Millions

m^2: square meters

m^3: Cubic meters

MJ: Mega Joules

MDEA: Methyldiethanolamine

MPa : Mega pascal

MSW: Municipal Solid Waste

Mt: Million tonnes

MW: Megawatt

NA: North Africa

NDCs: Nationally Determined Contributions

NGOs: Non-Governmental Organisations

NH_3 : Ammonia

NPV: Net Present Value

OHC: Oil Hydrogen Concentration

OFMSW: Organic Fraction of Municipal Solid Waste

O&M: Operation and Maintenance

OPEX: Operating Expenses

ISO: International Organization for Standardization

pH: potential of hydrogen

PQH: Practical Quantity of Hydrogen

PSA: Pressure Swing Adsorption

PSA-A: Pressure Swing Adsorption – Type A

PSA-B: Pressure Swing Adsorption – Type B

PV: Photovoltaic

PWh LHV: Petawatt-hour based on Lower Heating Value

QH: Quantity of Hydrogen

QGIS: Quantum Geographic Information System

RCP: Representative Concentration Pathway

RE: Renewable Energy

RES: Renewable Energy Sources

RPR: Residues-to-product ratios

S: sulfur

SAE: Standard of the Society of Automotive Engineers

SAPP: Southern African Power Pool

SAWH: Submerged Arc Welded Tubular Hydrogen

SCP: Specific Power Consumption

SI Units: International System of Units

SDGs: Sustainable Development Goals

SMR: Steam Methane Reforming

SSMR: Solar Steam Methane Reforming

SSF: Simultaneous Saccharification and Fermentation

SSA: Sub-Saharan Africa

Syngas: Synthesis Gas

TIC: Total Installed Cost

TDC: Total direct cost

STP: standard temperature and pressure

ton/h: Tons per hour

TQH: the theoretical hydrogen

TS: Total Solids

TWh: Terawatt-hour

UK: United Kingdom

UN: United Nations

USD: United States Dollars

VS : Volatile Solids

VFAs: Volatile fatty acids

W/m^2: Watt per meter square

WAPP: West African Power Pool

WASCAL: West African Science Service Center on Climate Change and Adapted Land Use

W_{empty} cargo: Weight of empty cargo system

W_{equip}: Weight of ship equipment

W_{hull}: Weight of the ship's hull

W^{LH_2}): Weight of liquid hydrogen cargo

W^{LH_2} : Weight of the liquid hydrogen fuel tank

$W_{machine}$: Weight of ship machinery

W_{sss}: Weight of ship's superstructure

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INTRODUCTION

1. Background

International climate agreements, such as the Paris Agreement and the UN Sustainable Development Goals (SDGs), are accelerating the global energy transition, which is transforming energy systems worldwide. In this context, green hydrogen has emerged as a promising energy carrier that could help decarbonize hard-to-abate sectors such as heavy industry, aviation, maritime transport, and seasonal energy storage. Green hydrogen can be produced from renewable sources, such as solar energy or biomass. It can significantly complement electrification by enabling large-scale energy storage, stabilizing power grids, and reducing reliance on fossil fuels. The International Renewable Energy Agency (IRENA) states that renewable hydrogen could play a significant role in achieving net-zero emissions by 2050, benefiting both the economy and the environment.

Africa, rich in renewable resources and experiencing growing energy demands, has recently attracted global interest in green hydrogen. Countries such as Morocco, Egypt, Namibia, and South Africa have launched large-scale hydrogen projects aimed at becoming exporters to Europe and other markets. Niger, despite abundant sunlight (5–6 kWh/m²/day), ample agricultural biomass, and geographic proximity to Europe, is not yet involved in many hydrogen initiatives. Structural challenges, including weak infrastructure, limited industrial capacity, and political instability, hinder its participation in this emerging market. However, these challenges also present opportunities to develop tailored strategies that leverage Niger’s local resources to foster a competitive green hydrogen sector.

As part of its plan to attain climate neutrality, the European Union's Hydrogen Strategy seeks to import up to 10 million tons of renewable hydrogen by 2030. This presents African countries with the chance to become significant suppliers, fostering industry growth and international partnerships to combat climate change. Niger’s proximity to Europe, coupled with its crude oil pipeline connecting it to Benin's Sèmè-Kpodji port, positions it well for exporting green hydrogen to European markets. Nonetheless, the absence of comprehensive economic studies on hydrogen production, storage, and export from Niger hampers investment, planning, and infrastructure development.

This thesis addresses this critical gap by conducting a complete techno-economic analysis of producing green hydrogen using local resources (such as agricultural waste and slaughterhouse blood), storing it as compressed or liquefied hydrogen, and transporting it to Europe via modified oil pipelines or railways. The study aims to evaluate the technical and financial feasibility of establishing a green hydrogen value chain in Niger through integrated cost modeling, resource assessment, and logistics analysis. The findings aim to inform policymakers, investors, and researchers about Niger’s potential as a future hydrogen supplier and to guide them in identifying strategic pathways to achieve this goal. They also aim to contribute to the sustainable development of the region’s energy and economy.

2. Problem Statement

The absence of a comprehensive economic assessment of hydrogen production in Niger for the European markets presents a significant barrier to realizing the potential of green hydrogen as a sustainable energy source. Despite Niger’s considerable resource base, including abundant renewable energy options, research on the economic feasibility of producing and exporting hydrogen to Europe remains scarce [1]. This gap constrains efforts to attract investment, develop robust infrastructure, and establish viable business models. Furthermore, Niger’s infrastructural limitations and political risks introduce additional uncertainty, underscoring the urgency of assessing the economic viability of hydrogen projects within this context. A thorough economic evaluation is therefore essential to determine the costs, benefits, and market conditions required for successful hydrogen production and export. Addressing this gap will generate critical insights to support informed decision-making, guide policy development, and foster the emergence of a hydrogen economy that aligns environmental sustainability with economic growth opportunities for Niger [2].

3. Research Questions

1) What is the green hydrogen production potential in Niger, considering resource availability, infrastructure, and national policy frameworks?
2) What are the cost implications of various storage and transportation methods for exporting green hydrogen to Europe?
3) What are the infrastructure and logistical needs for green hydrogen production and export systems to be optimized to comply with European regulatory standards?

4. Research Hypotheses

a. Niger possesses biomass and solar energy potential for green hydrogen production.
b. Green Hydrogen can be produced, stored, and exported with minimum costs.
c. There are infrastructure and logistical solutions to export green hydrogen to Europe while complying with the European regulations.

5. Research Objectives

The research objectives outline the key goals and directions guiding this study.

5.1 Main Objective

The main objective of this thesis is to analyze the economic feasibility of green hydrogen production and export from Niger to Europe.

5.2 Specific Objectives

a) Assess green hydrogen production potential in Niger using biomass and solar resources;
b) Evaluate the cost associated with hydrogen production, storage, and export logistics;
c) Identify the logistical and infrastructure needs for transporting green hydrogen from Niger to Europe, while proposing viable strategies to enable efficient export routes.

6. Significance of the Study

This study is relevant to the global energy transition, as countries seek sustainable alternatives to fossil fuels to meet climate goals. The growing demand for green hydrogen in Europe offers a strategic opportunity to explore Niger's potential as a green hydrogen producer and exporter. The research promotes renewable energy sources, such as biomass and solar power, examining how green hydrogen can become a new export, boost industry, create jobs, and attract foreign revenue while supporting decarbonization. It also addresses infrastructure and policy issues, such as repurposing oil pipelines, developing storage solutions, and export strategies. Through techno-economic analysis, the study guides policymakers and investors on Niger's potential in the green hydrogen market, laying a foundation for future investments, research, and policies.

7. Thesis Structure

Chapter 1 provides an extensive review of the existing literature on the global green hydrogen market, with a particular focus on Africa, specifically Niger. Chapter 2 explains the research methodology, detailing data collection methods, tools, and techniques used to assess the economic viability of green hydrogen activities. Chapter 3 presents findings and discussion, showing the economic evaluation of green hydrogen in Niger. The thesis concludes in Chapter 4 with a summary of key findings and policy suggestions for Niger to develop a sustainable hydrogen sector.

CHAPTER 1: LITERATURE REVIEW

I.1 Global Energy Transition and Green Hydrogen Development

To achieve the goals of the Paris Agreement [3], the global system must transform within 25 years. IRENA's 1.5°C pathway shows that over two-thirds of the necessary CO_2 reductions depend on expanding electrification, which currently relies on renewable energy. In this decarbonized future, electricity will become the primary energy carrier, increasing from over half to more than one-fifth of total final energy used [4].

Renewable green hydrogen bridges the gap between renewable electricity and sectors, such as heavy industry, aviation, shipping, and seasonal storage. Using electrolysis, renewable power can provide a decarbonization solution for areas limited by cost or technology [4]. The chart in (Appendix A) shows a sharp rise in global clean energy investments, increasing from $33 billion in 2004 to $2,083 billion in 2024. The most significant investments have been made in renewable energy, power grids, electrified transport, and a growing interest in hydrogen since 2020 [5]. While global decarbonization efforts create new opportunities for green hydrogen countries like Niger, they remain underexplored, highlighting the need for targeted economic and technical assessments to enable participation in the global hydrogen market (See Appendix K).

I.2 Market and Competitive Landscape

As the global green technology market rapidly develops, several African countries, including Morocco, Egypt, and South Africa, have emerged as leaders due to their advanced infrastructure, strategic coastal locations, and strong international partnerships (Appendix B) [6]. Figure in the (Appendix K) shows that in 2023, the hydrogen market was valued at $172.42 billion, led by North America. It is expected to grow to $309.17 billion by 2030 with an 8.7% CAGR. Green hydrogen dominates production, while transportation and power generation are the top application sectors.

I.2.1 Overview of Niger's Renewable Potential

Niger possesses significant renewable energy resources, especially in solar, wind, and biomass, which remain mostly untapped. Niger's high solar irradiance levels [7], make it an ideal location for solar energy projects, with some northern areas also benefiting from favorable wind conditions for hybrid systems. Renewable energy in Niger is in its early stages, with strategies highlighting solar power for rural and industrial use. However, underdeveloped infrastructure, financing gaps, and governance issues hinder resource exploitation, making large-scale hydrogen projects uncertain without external support.

I.3 Green Hydrogen Potential in Africa

The potential for green hydrogen in Africa stems from its abundant renewable resources and growing opportunities for sustainable energy exports (see Appendix B).

I.3.1 Solar Energy Potential in Africa

Africa, with its abundant solar resources, holds great potential to tackle energy and climate challenges while driving economic growth [8]. Africa owns 40% of the globe's potential for solar power, yet it only accounts for 1.48% of the total global capacity for electricity generation from solar energy [24]. While Africa faces major electricity issues, Sub-Saharan Africa suffers most, with over two-thirds of the world's population lacking access to electricity [9]. Over half of Sub-Saharan Africa lacks electricity and relies on traditional biomass [8].

The potential of solar energy is enormous throughout Africa, due to a variety of factors, including proximity to the equator and the frequent occurrence of dry, bright days. For instance, South Africa has the potential for concentrating solar power of 43,274/GW/year and a potential for solar photovoltaic of 42,243 TWh/year [8]. Northern Africa has vast solar potential, with minimal land able to power the entire EU. This is witnessed in the high annual solar irradiation; for example, Algeria, Morocco, Egypt, and Tunisia have the total annual irradiation of 2700kWh/m^2, 2600 kWh/m^2, 2800 kWh/m^2, respectively. (See Appendix J), which shows PV solar power potential across Africa [7].

I.3.2 Biomass Energy Potential in Africa

Renewable energy, especially biomass, offers a sustainable alternative to fossil fuels, helping cut CO_2, meet rising energy demand, and boost economic development [10]. Vast, unused lands in Africa and Latin America could produce significant amounts of renewable energy through biomass, meeting future energy demands. This would cut CO_2 emissions, replace fossil fuels, and create millions of jobs [11].

The multiplication of food supply required by countries in Africa in 2025 to meet the minimum per-capita nutritional requirements (on average), assuming the United Nations' median population projection, and caloric requirements as reported by the World Resources Institute [10]. The table in Appendix A not only reflects increased strain on agricultural production but also implies a substantial rise in agricultural residue generation. Agricultural residues can fuel decentralized green hydrogen production, boosting rural electrification, economic growth, and sustainability. Estimated increase in food supply requirements based on population growth and calorific needs (1990-2025) [26], as shown in (Appendix C).

I.3.3 Hydro Potential Energy in Africa

Hydropotential will play a crucial role in meeting Africa's growing energy needs, but its development will be impacted by climate change. We assess the future annual usable capacity and variability of supply for 87 existing hydropower plants in Africa based on a multimodel of 21 global climate models and two emissions scenarios (representative concentration pathways, RCP 4.5 and 8.5).

The report by the International Renewable Energy Agency (IRENA), Africa's installed hydropower capacity is expected to reach 100 GWh by 2030, with a potential hydropower capacity is expected to reach 100 GW by 2030, with a potential hydropower capacity of up to 1,750 GW. However, increased reliance on hydropower in Africa could increase climate-induced vulnerability. Furthermore, concentrating hydropower resources in a small number of basins (for example, the Nile in East Africa and the Zambezi in Southern Africa) increases vulnerability to changes in hydrological regimes. The lack of extraordinary diversity in hydropower plant siting could exacerbate the risks of climate-induced disruptions in electricity systems.

Table 1: Electrification rate, total hydropower installed capacity, and analysis of hydropower capacity in African pools [12]

Power Pool	Electrification Rate (%)	Existing Installed Capacity (GW)	Existing Hydropower Installed Capacity (GW) (% of Total)	Analysis Hydropower Capacity (GW)
COMELEC	97%	99.9	5.0 (5%)	3.7
WAPP	52%	24.3	5.9 (24%)	4.7
CAPP	25%	6.9	4.3 (62%)	3.9
EAPP	54%	11.5	15.1 (75%)	13.7
SAPP	86%	66.4	14.0 (21%)	7.7
All power pools	47% (SSA) / 97%(NA)	209	44.3 (21%)	33.7

The electrification rate indicated the percentage of the population (urban and rural) with access to electricity. The existing installed capacity includes all sources of electricity generation. The total hydropower installed capacity is the sum of each country's capacity with access to electricity generation. The total hydropower installed capacity analysis includes the Grand Ethiopian Renaissance Dam and excludes pumped hydro and power plants with a capacity of less than 40 MW. The difference between the SAPP's existing and analyzed capacities is due to a lack of data in Angola. SSA, Sub-Saharan Africa, NA, North Africa.

I.4 Strategic Hydrogen Initiatives in Leading African Countries

In recent years, green hydrogen has emerged as a cornerstone of Africa's clean energy transition, with several countries taking bold steps to position themselves as global leaders in hydrogen production and export. Among these, Morocco, Egypt, South Africa, and Namibia have launched strategic hydrogen initiatives that are drawing international investment and establishing frameworks for large-scale deployment (see Appendix K).

Morocco is covered by the European Neighborhood Policy Agreement (ENP) of 2004 and is a member of the Union for the Mediterranean. The country is harnessing its exceptional solar and wind potential to become a hub for green hydrogen and green ammonia with a significant project in partnership with European and Gulf investors. Its National Hydrogen Roadmap outlines a vision to supply both domestic industries and export markets [13][13].

Egypt, through its Suez Canal Economic Zone, has signed multiple agreements to develop gigawatt-scale hydrogen and ammonia plants. These projects aim to decarbonize heavy industries, support the maritime sector, and capitalize on Egypt's strategic geographic location [14].

South Africa is advancing its hydrogen society roadmap, focusing on green hydrogen for transportation, industry, and synthetic fuels. Pilot projects in the Northern Cape and collaborations with Germany and Japan show the country's goal to become a leading hydrogen player on the continent [15].

Namibia has positioned itself as a global pioneer by launching Africa's first large-scale green hydrogen strategy, supported by international funding. Its flashing project in the Tsau/khaeb National Park aims to produce green hydrogen and derivatives for export by 2030 [16].

Together, these countries exemplify Africa's growing leadership in green hydrogen, driven by its abundant renewable resources, strategic location, and strong political commitment. Their initiatives are not only critical for the global decarbonization effort but also for creating jobs, building resilient energy systems, and unlocking new economic opportunities on the continent.

I.5 Opportunities and Challenges for Hydrogen Development in Africa

Africa has vast renewable resources and a growing global interest, positioning it well for green hydrogen production. Countries such as Niger, Morocco, and South Africa have significant potential for-scale solar, biomass, wind, and hydroelectric projects. With strategic partnerships, green hydrogen could drive Africa's industrialization and sustainable growth, despite existing challenges. Africa's hydrogen potential is hindered by weak infrastructure, limited transport, and financing challenges (see Appendix L)[17]. Africa's hydrogen potential is hindered by weak infrastructure, limited transport, and financing challenges. Countries rely on foreign aid and lack local capital, technical skills, and research capacity for hydrogen projects. Stronger policies, regional cooperation, and targeted investments are key for Africa to lead in sustainable energy [6].

Table 2: Comparative Overview of Green Hydrogen Strategies in Africa

Country	Renewable Potential	Key Projects/Strategies	Export Potential	References
Namibia	High solar & wind	National Hydrogen Strategy (2021); EU & Germany partnerships	Export hub for Europe	[18]
Morocco	Solar (Noor Ouarzazate), wind	Green Hydrogen Roadmap; German & Spanish cooperation	High export potential to Europe	[19]
South Africa	Solar & wind	Hydrogen Society Roadmap (2020); heavy industry projects	Regional use + EU/Asia export	[20]
Niger	Solar (5–6 kWh/m²/day), biomass	No national strategy; potential oil pipeline retrofit to Europe	Emerging, underexplored	[21],[22]

Several African countries, such as Namibia, Morocco, and South Africa, have already positioned themselves as leaders in the hydrogen economy through national strategies and international partnerships. In contrast, Niger, despite its abundant solar and biomass resources and its strategic proximity to Europe, remains underexplored and lacks the infrastructure and policy frameworks required for competitiveness. This highlights the importance of conducting economic assessments, such as the present study, to evaluate Niger’s potential role in the African and global hydrogen landscape.

I.6 Biohydrogen from Biomass (Five Selected Feedstocks in Niger)

Biomass is a promising feedstock for green hydrogen production, especially in agricultural regions where plant-based residues are abundant and often underused [18]. Niger has abundant biomass from crops like sugarcane, rice, cassava, sweet potatoes, and groundnuts. These residues offer high energy potential for green hydrogen production [19]. Sugarcane tops and leaves, typically discarded after harvest, contain significant lignocellulosic content, making them suitable for thermochemical conversion [20]. Rice husks, produced during the rice-milling process, are rich in carbon and silica and have been extensively studied as a feedstock for bioenergy applications. Rice offers a sustainable source of dry biomass with favorable properties for combustion and gasification. Sweet potato residues, including vines and peels, are often left unused but can be effectively transformed through dark fermentation [21]. Lastly, groundnut shells and straw, generated during processing and post-harvest stages, represent a significant untapped resource that can support decentralized hydrogen production, especially in rural areas [22]. These local feedstocks can drive clean energy, boost jobs, and support a circular bioeconomy in Niger.

I.7 Conversion Methods

Conversion methods describe the technological pathways used to transform resources into green hydrogen.

I.7.1 Pyrolysis

Biomass pyrolysis is gaining interest as an advanced and cost-effective method for producing hydrogen and other valuable products [23]. Conventional pyrolysis can be classified into three main types based on the operational parameters used: (i) slow pyrolysis, (ii) fast pyrolysis, and (iii) flash pyrolysis. Recently, a new form called intermediate pyrolysis, which lies between slow and fast pyrolysis, has also been developed [24]. Recently, a new form called intermediate, which lies between slow and fast pyrolysis, has also been developed. Pyrolysis type and product yields depend mainly on heating rate, temperature, time, and feedstock size [25]. Refer to the supplementary material for operational parameters and yields across various conventional pyrolysis processes.

I.7.2 Gasification

Gasification is a thermochemical process that converts solid biomass into a hydrogen-rich syngas by exposing it to a limited amount of oxygen or steam at high temperatures (typically 800-900°C) [26]. Unlike direct combustion, gasification does not produce a flame; instead, it creates a mixture of gases, mainly composed of hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2) [27]. This syngas can be purified to obtain hydrogen for clean energy applications. It is especially suitable for dry agricultural residues, offering a scalable method for producing green hydrogen in biomass-rich areas, such as Niger.

I.7.3 Dark Fermentation

Biohydrogen can be produced via anaerobic (dark fermentation) and photoheterotrophic (light fermentation) microorganisms that utilize carbohydrate-rich biomass as a renewable source. The process begins with acid or enzymatic hydrolysis of biomass, producing a concentrated sugar solution. This solution is then fermented by anaerobic microbes, resulting in the production of hydrogen and CO_2. Subsequently, photoheterotrophic bacteria, such as Rhodobacter sp, ferment these organic acids to generate CO_2 and H_2, a process known as light fermentation. Combining dark and light fermentation methods has been to increase hydrogen yield from carbohydrates [26].

I.7.4 Hydrogen from Solar Energy via Steam Methane Reforming (SMR)

SMR involves separating hydrogen from the syngas that exists the WGS reactor, which contains H_2, CO_2, CH_4, and CO [28]. This separation can be achieved through various techniques. The most common method is pressure swing adsorption (PSA), which can produce high-purity hydrogen and CO_2 (up to 99.9% or higher purity). CO2 is captured after compression. Therefore, the product must be cooled before entering the PSA. H_2 is separated into PSA-A, and CO_2 is separated into PSA-B. Unreacted CH_4 and CO are burned to provide heat for the reformer [29].

In Niger, biogas produced from slaughterhouse blood can power SMR to generate hydrogen, especially when combined with solar energy, thereby reducing emissions. Pilot projects in similar regions show this hybrid bio-solar approach can reliably supply clean hydrogen locally. In the context of Niger, this pathway is especially relevant. Urban centers like Niamey, Maradi, and Zinder host managed and environmentally harmful [30]. Niger's strong solar potential and low-cost waste methane enable viable, decentralized hydrogen production within a circular economy.

Table 3:Table 3: Comparison of Biomass-to-Hydrogen Conversion Technologies for Niger

Conversion Technology	H_2 Yield (%)	Estimated Cost (\$/kg H_2)	Local Applicability (Niger)	Advantages	Limitations	References
Pyrolysis	57	0.9	Medium – requires trained personnel and specialized equipment	Produces both biochar and H_2; flexible feedstock	Variable yield; high initial cost; requires optimization	[31],[32]
Gasification	75	3.0	Good, suitable for dry agricultural residues	High yield; scalable; mature technology	Requires biomass drying; syngas purification needed	[33],[34]
Dark Fermentation	83	2.29	Very suitable for rural areas and wet biomass	Low cost; simple technology; decentralized production	Low yield; slow production; requires sugar-rich substrates	[35],[36]
SSMR	86.3	4.5	Promising due to high solar potential and methane recovery from slaughterhouse blood	High efficiency with solar input; scalable for export	Dependent on methane availability & solar irradiation; infrastructure-intensive	[37],[38]

Gasification gives a 75% hydrogen yield and costs about 3.0 \$/kg H_2 but needs biomass drying and syngas purification. Dark fermentation offers 83% yield at 2.29 \$/kg H_2, is low-cost and straightforward, but slow, and needs sugar-rich feedstock. Pyrolysis yields 57% hydrogen at 0.9 \$/kg H_2, using solar energy and methane from slaughterhouse blood. However, SSMR is infrastructure-intensive and relies on steady solar and methane availability.

I.8 Hydrogen methods of storage

Hydrogen methods of storage refer to the different technologies used to contain and preserve hydrogen for later use safely.

I.8.1 Compressed Gas

Compressed gaseous hydrogen (CG H_2) is the most mature and widely used hydrogen storage technology. It is simple, cost-effective, and allows rapid filling and releasing hydrogen. However, it has low volumetric density (39.1 kg/m3 at 70 MPa) and raises safety concerns at high pressures. Operating at 50-55 MPa offers a balance between performance, cost, and safety. New cryo-compressed hydrogen (CcH_2) combines temperatures of 20 K and pressures of 35 MPa to achieve a density comparable to that of liquid hydrogen (LH_2) with reduced energy consumption [39].

I.8.2 Liquefied Hydrogen

Considering a vast hydrogen infrastructure, large quantities of hydrogen could be transported and stored as a cryogenic liquid. Hydrogen is being looked at as a transportation fuel because it can be used easily in conventional internal combustion engines or, more efficiently, in fuel cells. The world's hydrogen liquefaction capacity was estimated to be about 290 tons per day in 2003 and 355 tons per day in 2009. A single liquefier requires (1500 MW), indicating that a hydrogen transportation system would need an infrastructure at least 100 times larger than current levels. Presently, large-scale hydrogen liquefiers are built on modifications of the original precooled Claude cycle [40].

I.8.3 Chemical Storage (Ammonia, LOHC)

Hydrogen storage remains a key challenge, whether for stationary applications or long-distance transportation. Ammonia is proposed as a promising solution because it can store hydrogen as a liquid chemical under mild conditions. However, using ammonia instead of pure hydrogen presents challenges, including health and environmental concerns related to handling ammonia, as well as competition from other markets like fertilizers. Moreover, the technical and economic efficiency of various steps, such as ammonia production via the Haber-Bosch process, distribution, storage, and possibly cracking back into hydrogen, significantly influences the overall supply chain [41].

I.9 Infrastructures Evaluation of Green Hydrogen Transport (rail vs pipeline)

These comparative studies highlight the advantages of pipelines for long-term cost efficiency and the flexibility of rail transport; however, there is limited analysis on how these options apply to Niger's infrastructural and political context. This gap will be addressed in the methodological section of this thesis.

Table 4:Comparison of Hydrogen Transport Options

Transport Option	**Cost ($/kg H_2)**	**Feasibility in Niger**	**Advantages**	**Limitations**	**Reference**
Pipeline (repurposed oil pipeline)	0.0503	Medium (requires retrofit & political stability)	Continuous flow is efficient for long distances	High CAPEX, political risks	[42]
Rail transport (compressed or liquefied H_2)	0.89	High (existing rail link Niger–Benin corridor)	Flexible, uses existing infrastructure	Higher OPEX, losses in liquefaction	[43]

I.10 Gaps in the Literature and Research Justification

Despite increasing global interest in green hydrogen as a crucial component of sustainable energy systems, the current literature reveals a significant gap that hinders a detailed understanding of its development in emerging regions, particularly West Africa. Four significant research gaps have been identified that hinder strategic planning, investment, and policymaking for green hydrogen deployment in Niger. While many studies have shown the potential of biomass and solar-based hydrogen production elsewhere, they often overlook the specific conditions in Niger. In particular, localized assessments of biomass availability, conversion costs, and integration with solar-powered processes remain limited. Additionally, comparative analyses of hydrogen export logistics, including pipelines and rail transport, are largely missing for West Africa. Closing these gaps is essential to provide a thorough techno-economic evaluation and to guide strategic decisions for sustainable hydrogen production and export from Niger.

CHAPTER 2: MATERIALS AND METHODS

This chapter describes the materials, data sources, and methodological approaches used in this study to evaluate the production, storage, and export potential of green hydrogen in Niger.

II.1 Study Area

Niger, officially the Republic of Niger, is a landlocked country in West Africa characterized by a semi-arid to arid climate, vast open landscapes, and abundant renewable resources, especially solar energy and biomass. It shares borders with Algeria and Libya to the north, Mali and Burkina Faso to the west, Chad to the east, and Nigeria and Benin to the south. Niger spans three zones: the Sahara, the Sahel, and Sudan. It is divided into eight administrative regions: Niamey (the largest city and the capital), Zinder, Maradi, Dosso, Agadez, Tillabéry, Diffa, and Tahoua [44]. Many of which are strategically considered for renewable energy development and emerging hydrogen initiatives [45][46][6]. The country's geography supports three key hydrogen production resources: solar, biomass, and wind. The northern and central regions, especially Agadez and Tahoua, are known for the highest solar irradiation. The southern areas include Maradi, Dosso, and Zinder. Those that are more agriculturally active offer abundant crop residues and organic waste, which are suitable for biohydrogen production. This study explores the economic viability of producing green hydrogen from solar and biomass sources in Niger, along with the associated costs of storage and export logistics to European markets. The potential export route via neighboring coastal countries, especially Benin, is analyzed. Transportation options are a pipeline network for compressed or liquefied hydrogen for maritime shipping.

With Europe aiming to diversify its green hydrogen imports under its climate neutrality objectives, Niger offers a strategic opportunity to position itself as a competitive supplier in the global hydrogen market [6]. This evaluation assesses cost-competitiveness, investment needs, and policy implications, while also highlighting the potential socio-economic benefits for Niger in terms of energy access, industrial development, economic desertification, and increased international collaboration. Appendix H, highlighting the eight regions of Niger

II.2 Resources and Feedstock Selection

This initial phase of the methodology concentrates on thoroughly identifying and describing the renewable energy feedstocks selected for hydrogen production in Niger. The focus is on three primary resources: solar energy, agricultural biomass, and animal blood from abattoirs. This step lays the groundwork for assessing the technical and economic feasibility of these hydrogen production methods within Niger's specific context.

II.2.1 Identification of Available Biomass

Farming plays a vital role in Niger's economy, with over 80% of the working population involved [56]. It is primarily dependent on rain-fed agriculture due to climatic variability. The figure in (Appendix E) shows agricultural output in Niger. Production data for Niger from 2019 to 2023 are available [19].

II.2.1.1 Selected Agricultural Residues

The selected feedstocks for biohydrogen production include sugar cane, sweet potatoes, rice, groundnuts, and cassava, chosen based on their local availability, energy potential, abundance of agricultural residues, and alignment with sustainability principles for diverse biomass production or advanced bioenergy generation. This approach ensures a sustainable and reliable feedstock supply chain for hydrogen production in Niger.

Table 5: Selected crop residues

Feedstock	Specified Type
MSW	OFMSW
Cassava	Peels
	Stalks
Sugar cane	Tops/leaves
	Bagasse
Groundnut (Peanut)	Shells
	Straw
Sweet potatoes	peels
Rice	Straw
	Husk

II.2.2 Slaughterhouse Blood

Slaughterhouse blood is a valuable organic waste stream with high potential for methane production through anaerobic digestion (AD). Its composition, rich in proteins and nitrogenous compounds, makes it an ideal substrate for biogas generation, especially when co-digested with carbon-rich agricultural residues to balance the carbon-to-nitrogen (C/N) ratio. This study uses national slaughterhouse datasets of 2019 from eight (8) regions in Niger to estimate the annual volume of blood waste. This data forms the basis for calculating the biochemical methane potential (BMP) of slaughterhouse blood, using a standard conversion factor and literature-based yield. The data were collected from the Livestock Ministry.

II.2.3 Solar Potential Assessment in Niger

The solar assessment of Niger indicates a higher potential for photovoltaic (PV) energy production. The specific yield reaches 1,812.6 kWh/kWp per year [47], reflecting strong annual energy generation per installed kilowatt of PV capacity.

Key solar irradiation values are as follows:

- Direct Normal irradiation (DNI): 1825.9 kWh/m^2/year
- Global Horizontal irradiation (GHI): 2271.3 kWh/m^2/year
- Diffuse Horizontal Irradiation (DIF): 973.9 kWh/m^2/year
- Global Tilted Irradiation at Optimum Angle (GTI): 2390.2 9 kWh/m^2/year

The ideal tilt angle for a PV module is 21°, which improves solar energy collection throughout the year. The average ambient temperature is 29.4°C, and the site elevation is 459 meters above sea level, both of which affect PV module performance and thermal behavior. These conditions confirm that Niger is highly suitable for solar projects, especially for green hydrogen production.

II.3 Methods

The methodology of this research was divided into four main steps: production, storage, transport, and techno-economic analysis.

II.4 Secondary Data Collection and Compilation

To meet the research objectives, data were collected from FAOSTAT (Food and Agriculture Organization Corporate Statistical Database), articles from sources such as Scopus and ScienceDirect databases, as well as reports from companies and NGOs, press articles, and official publications from the Niger Ministry of Agriculture, the Ministry of Livestock, Atlas, and the Ministry of Energy. Research Rabbit is an advanced online tool used to map literature through citations, helping to identify and shortlist the latest articles. The keywords ‘Green Hydrogen’, ‘economic’, ‘transport’, ‘storage', and Niger were used to search for relevant articles (Appendix D).

II.5 Production

In this methodology section, the focus is on the processes used to produce hydrogen from five selected agricultural feedstocks. These feedstocks were categorized into two main conversion pathways: gasification and dark fermentation, both of which enable hydrogen production using locally abundant agricultural residues in Niger. Additionally, a separate production route was developed to utilize slaughterhouse blood as a resource. Instead of relying on fossil-based methane,

methane was recovered from slaughterhouse blood through anaerobic digestion and subsequently used in a solar steam methane reforming (SSMR) process to generate hydrogen. Thus, the methodological approach combines a route (retrofit crude oil pipeline): the valorization of agricultural residues through gasification and dark fermentation, and the production of hydrogen from slaughterhouse blood-derived methane using solar steam methane reforming. This innovative strategy leverages local resources to produce green hydrogen in a sustainable and context-specific way.

II.5.1 Biohydrogen Production from Biomass

Regarding the first objective, data collected from FAOSTAT (the Food and Agriculture Organization's Corporate Statistical Database) and the Niger Ministry of Agriculture are analyzed and adapted for this study. The relevant data are entered into Excel to generate the curve that shows the share of biomass potential in Niger. Additionally, QGIS (Quantum Geographic Information System) software is used to locate biomass sources according to Niger's regions. First, the shapefiles of Niger are downloaded from FAOSTAT and uploaded to QGIS to assign the different regions based on biomass type. Finally, the map is exported and analyzed.

This study focuses on two complementary pathways based on feedstock fit, technology readiness, and cost in Niger.

- Gasification: for dry lignocellulosic residues (groundnut shells, rice straw, sugarcane tops); mature, scalable, and yields H_2-rich syngas upgraded via standard clean-up + WGS.
- Dark fermentation: for wet, starch/sugar-rich residues (cassava/sweet-potato peels, sugarcane streams); low-temperature, simpler equipment, and decentralizable near farms.

II.5.1.1 Biomass Potential Estimation

Once the data collection process is complete, the next step is to estimate the available biomass for hydrogen production. To achieve this, Equation 1 was used as a description [48].

$$B = P \times R \quad \text{(E1)}$$

Where: B refers to the total biomass potential (tons), P refers to the annual crop production (tons), and R refers to the residue-to-crop ratio (without unit).
Then, since not all biomass can be recovered due to environmental and economic constraints, the sustainably recoverable biomass fraction was calculated using equation 2.

$$Sr = B \times F \quad \text{(E2)}$$

Where: Sr refers to sustainably recoverable biomass (tons), and F refers to the sustainable recovery factor, which is 0.25% [49].

The sustainable recovery factor considers aspects like greenhouse gas emissions, soil health, water use, and ecological sustainability to ensure the recovery process is environmentally friendly. [50]. Additionally, this study emphasizes the importance of identifying and assessing the various competing uses of these residues. Recognizing these competing uses helps prioritize the most sustainable and beneficial options, such as green hydrogen production. Therefore, this study adopted a sustainable recovery factor of 0.25 %. This estimate provides a realistic assessment of the biomass resources available for biohydrogen production without damaging the environment.

II.5.1.2 Physical and Chemical Characterization of Biomass

The physical and chemical properties of biomass determine its suitability for biohydrogen production. This study analyzes residues like rice husk, rice straw, cassava, sugarcane, groundnuts, and sweet potatoes. Lignocellulosic residues (see Appendix G) (rice husk and straw, cassava stalks, sugarcane tops, groundnut shells) are suitable for gasification. Gasification uses high temperatures (800–1000 °C) to convert dry biomass into hydrogen-rich syngas. Starch- and sugar-rich residues (cassava peels, bagasse, groundnut straw, sweet potato peels) suit for dark fermentation. This classification is supported by established research [51], such as studies on dark fermentation [61] and gasification.

The ultimate composition, which consists of carbon (C), hydrogen (H), and oxygen (O) percentages, is the most important aspect that can affect the energy content and conversion efficiency of biomass for hydrogen production.

Table 6:The ultimate composition

Crop	Type of residue	C (%)	H (%)	O (%)	References
Rice	Husk	47.84	6.29	45.19	[52]
Rice	Straw	48.09	5.86	43.64	[52]
Groundnut	shells	46.86	6.16	46.20	[53]
sugarcane	Tops/leaves	43.90	6.10	44.00	[54]
Cassava	stalks	48.20	5.49	31.74	[54]

CxHyOz:

$$x = \left(\frac{m_C}{M_C \times s}\right) \times f \quad \text{(E3)}$$

$$y = \left(\frac{m_H}{M_H \times s}\right) \times f \quad \text{(E4)}$$

$$z = \left(\frac{m_O}{M_O \times s}\right) \times f \quad \text{(E5)}$$

Where: M refers to the molar mass of an ultimate content (Carbon, Hydrogen, or Oxygen) (g/mol), m refers to the percentage of an ultimate content relative to its mass (g) by assuming 100g of total biomass, s refers to the smallest molar ratio, and f refers to the adjustment factor, which was set at 2 for this study.

II.5.1.3 Theoretical and Practical Biohydrogen Potential Estimation

The hydrogen potential of crop residues was evaluated using theoretical calculations based on stoichiometry. This section focuses on the gasification process to estimate the hydrogen potential. Each process, whether theoretical or practical, is analyzed separately to determine its hydrogen production capacity in both cases.

According to this study [33], the bio-hydrogen yield was 29.5%, and CO_2 was 23.6%. The CO concentration at this condition was only 10.9%, and the carbon conversion efficiency (CCE) was 75.01% [33].

II.5.2 Dark Fermentation

Dark fermentation is a biochemical process in which microorganisms break down organic matter in anaerobic conditions to produce hydrogen. The microorganisms involved in this process can include Clostridium, Enterobacter, and Escherichia, which convert organic matter into valuable products such as hydrogen and methane [33].
Hydrogen production from lignocellulosic biomass through dark fermentation involves an initial hydrolysis step, serving as a pretreatment (Appendix G), to break down cellulose and hemicellulose into glucose (equation 6) and xylose (equation 7), respectively, prior to the fermentation process.

$$(C_6H_{10}O_5)_n + nH_2O \xrightarrow{\text{yeast}} n(C_6H_{12}O_6); \text{assuming } n = 1 \quad \text{(E6)}$$

$$(C_5H_8O_4)_n \ + nH_2O \xrightarrow{\text{yeast}} n(C_5H_{10}O_5); \text{assuming } n = 1 \qquad (E7)$$

From the equations above, the amount of glucose and xylose that can be produced is calculated using the following formulas (equations 8 and 9, respectively), considering the maximum efficiency of 80% [33], for the hydrogen production and 33% efficiency for the conversion :

$$Q_{Glucose} = \frac{M_{Glucose}}{M_{Cellulose}} \times Q_{Cellulose} \times \eta \qquad (E8)$$

$$Q_{Xylose} = \frac{M_{Xylose}}{M_{Hemicellulose}} \times Q_{Hemicellulose} \times \eta \qquad (E9)$$

Here: $\mathbf{Q_{Glucose}}$, refers to the amount of glucose produced (Ton), $\mathbf{Q_{Xylose}}$, refers to the amount of xylose produced (Ton), $\mathbf{M_{Glucose}}$, refer to the molar mass of glucose (g/mol), $\mathbf{X_{ylose}}$, refers to the molar mass of xylose, $\mathbf{M_{Cellulose}}$, refers to the molar mass of Cellulose (g/mol), $\mathbf{M_{Hemicellulose}}$, refers to the molar mass of Hemicellulose (g/mol),$\mathbf{Q_{Cellucose}}$, refers to the amount of cellulose (Ton), $\mathbf{Q_{Hemicellulose}}$, refers to the amount of Hemicellulose (Ton), and $\boldsymbol{\eta}$, the efficiency of the process.

Theoretically, assuming an efficiency of 12 moles of hydrogen can be produced during dark fermentation of 1 mole of glucose from cellulose, as shown in equation 10, and up to 10 moles of hydrogen can be produced during dark fermentation of xylose from hemicellulose, as shown in equation 11. Additionally, in this study, an efficiency of 33% was assumed for the hydrolysis step.

$$C_6H_{12}O_6 + 6H_2O \xrightarrow{H_2ase} 12\ H_2 + 6CO_2 \qquad (E10)$$

$$C_5H_{10}O_5 + 5H_2O \xrightarrow{H_2ase} 10\ H_2 + 5CO_2 \qquad (E11)$$

Thus, based on equations 10 and 11, the quantity of hydrogen produced can be calculated using the following formulas (equations 12 and 13, respectively):

$$\mathrm{TQH_{Glucose}} = \frac{12 \times \mathrm{M_H}}{\mathrm{M_{Glucose}}} \times \mathrm{Q_{Glucose}} \quad \text{(E12)}$$

$$\mathrm{TQH_{Xylose}} = \frac{10 \times \mathrm{M_H}}{\mathrm{M_{Xylose}}} \times \mathrm{Q_{Xylose}} \quad \text{(E13)}$$

Here: $\boldsymbol{TQH_{Glucose}}$, refers to the Theoretical amount of hydrogen produced from glucose (Ton), $\boldsymbol{TQH_{Xylose}}$, refers to the theoretical amount of hydrogen produced from xylose (Ton), M_H, refers to the molar mass of hydrogen (g/mol), $\mathbf{M_{Glucos}}$, refer to the molar mass of glucose (g/mol), $\mathbf{M_{Xylose}}$, refers to the molar mass of xylose, $\mathbf{Q_{Glucose}}$, refers to the amount of glucose (Ton), and $\mathbf{Q_{Xylose}}$, refers to the amount of xylose (Ton).

Finally, the theoretical hydrogen potential (TQH) of each crop residue is obtained by combining the amount of hydrogen produced from glucose with the amount produced from xylose, according to the formula below (equation 14):

$$\mathrm{TQH} = \mathrm{TQH_{Glucose}} + \mathrm{TQH_{Xylose}} \quad \text{(E14)}$$

In practice, the performance achieved theoretically is not achievable due to the complexity of the bioprocesses and process efficiency. In the case of dark fermentation, hydrogen is practically produced through the acetate pathway, leading to the production of 4 moles of hydrogen per mole of glucose (equation 15) and 2 moles of hydrogen per mole of xylose (equation 16) in stoichiometry-based terms.

$$\mathrm{C_6H_{12}O_6 + 2H_2O \longrightarrow 2C_2H_4O_2 + 2CO_2 + 4H_2} \quad \text{(E15)}$$

$$\mathrm{C_5H_{10}O_5 + H_2O \longrightarrow 2C_2H_4O_2 + CO_2 + 2H_2} \quad \text{(E16)}$$

Then the efficiency is 32% [33], respectively for cellulose hydrolysis, hemicellulose hydrolysis, and dark fermentation process, the practical amount of hydrogen that can be produced is calculated using the following formulas (equations 17 and 18, respectively):

$$PQH_{Glucose} = \frac{4 \times M_H}{M_{Glucose}} \times Q_{Glucose} \times \eta \tag{E17}$$

$$PQH_{Xylose} = \frac{2 \times M_H}{M_{Xylose}} \times Q_{Xylose} \times \eta \tag{E18}$$

Where: $\boldsymbol{PQH_{Glucose}}$, refers to the amount of hydrogen that can be produced practically from glucose (Ton), $\boldsymbol{PQH_{Xylose}}$, refers to the amount of hydrogen that can be produced practically from xylose (Ton), $\mathbf{M_H}$, refers to the molar mass of hydrogen (H_2) (g/mol), $\mathbf{M_{Glucos}}$, refer to the molar mass of glucose (g/mol), $\mathbf{M_{Xylose}}$, refers to the molar mass of xylose, $\mathbf{Q_{Glucose}}$, refers to the amount of glucose (Ton), $\mathbf{Q_{Xylose}}$, refers to the amount of xylose (Ton), and η, refers to the efficiency.
Finally, the practical hydrogen potential (PQH) of each crop residue is obtained by combining the amount of hydrogen practically produced from glucose with the one produced from xylose, according to the formula below (equation 19):

$$PQH = PQH_{Glucose} + PQH_{Xylose} \tag{E19}$$

II.5.2.1 Economic Analysis for Biohydrogen from Dark Fermentation

A techno-economic evaluation of biohydrogen production from dark fermentation involves assessing the capital expenditure (CAPEX), operational expenditure (OPEX), and the associated hydrogen yields from selected biomass. The following are considered:

Table 7:CAPEX of biohydrogen production from Dark fermentation

Equipment	Specification	Quantity	Cost (USD)	References
Storage	Working capacity: 20 ton	1	15000	[55]
FW grinding	Working capacity: 2 ton/h	1	72000	[55]
Reactors for SSF	Oil jacket	2	24000	[55]
Enzymatic hydrolysis vessel	Oil jacket with stirrer	1	66000	[55]
Heat exchanger	Heat exchanger	1	45000	[55],[56]
Hydrolysate centrifugation and filtration	Working capacity: 670 L/h	1	28200	[55],[57]
Fermentor for H_2 production	Oil jacket with stirrer Working volume: 1000 L	1	60000	[55]
Centrifuge	Working capacity: 3000 L/h	1	51000	[55]
Seed fermentor	Oil jacket with stirrer Working volume: 10 L	2	39000	[55]
Shake flask rack		2	90000	[55]
Purification system	Separation of produced biogas	1	63000	[55],[58]
pH control & nutrient unit	Equipment for maintaining microbial stability	1	35,000	[55],[59]
Installation & civil works	Foundations, wiring, pipelines, and site preparation		98,000	[55],[60]

Table 8:OPEX of Biohydrogen from Dark Fermentation

Components	Unit Cost	Yearly Use	Total cost ($)	References
Feedstock	5 $/ton	277,180,660	1385903300	[61]
Raw Material/Catalyst	$5/L	8000 L	60000	[61]
Electricity	$0.052/kWh	1800 MW	97351	[61]
Heating Mid-Pressure Steam	$3.77/GJ	1904 GJ	7176	[61]
Heating Low-Pressure Steam	$3.57/GJ	3472 GJ	12422	[61]
Cooling by Chilled Water	$1.4/GJ	1804 GJ	2525	[61]
Cooling by Chilled Water (high-scale cooling)	$4/GJ	1754 GJ	7000	[61]
Operator Labor	$30/hr	25200 hrs	630000	[61]
Supervision Labor	$45/hr	8400 hrs	378000	[61]
Wastewater Treatment Cost	$0.88/m³	4488 m³	47398	[61]
Maintenance Cost (3% of CAPEX)	3% of the capital cost		20,586	[61]
Operating Charges (25% of labor cost)	25% of labor cost		252000	[61]
Plant Overhead (50% of maintenance + labor)	50% of (maintenance + labor cost)		650,586	[61]

General and Administrative (8% of CAPEX)	8% of the capital cost	54,896	[61]

II.5.3 Gasification

Gasification is a thermochemical process that converts dry biomass into syngas, a mixture primary consisting of hydrogen (H_2) and carbon monoxide (CO), with a hydrogen content of 25-30% and an efficiency of to 70%, used in this study [33].

In general, the biomass gasification reaction can be expressed as follows (equation 20):

$$nC_xH_yO_z + mH_2O + wO_2 \longrightarrow x_1CO + x_2H_2 + x_3CO_2 + x_4CH_4 + x_5H_2O + x_6O_2 \quad \text{(E20)}$$

Then, if the fractions of CO_2, O_2, and H_2O involved in the process are assumed to be combustion products and CH_4 in the syngas is negligible, equation 20 changes to:

$$nC_xH_yO_z + mH_2O \longrightarrow x_1CO + x_2H_2 \quad \text{(E21)}$$

Also, by associating the water-gas shift reaction with the gasification process, carbon monoxide (CO) produced from equation 21 can be converted into hydrogen (H_2), in order to increase the hydrogen yield, using equation 22 below:

$$x_1CO + x_2H_2O \longrightarrow x_3CO_2 + x_4H_2 \quad \text{(E22)}$$

Therefore, using equations 21 and 22, the hydrogen production from the gasification process involving a water-gas shift reaction is determined by the following formulas (equations 23 and 25):

$$QH_{Gasification} = \frac{x_2 \times M_H}{n \times M_{Biomass}} \times QB \times \eta_{Gasification} \quad \text{(E23)}$$

$$QCO_{Gasification} = \frac{x_1 \times M_{CO}}{n \times M_{Biomass}} \times QB \times \eta_{Gasification} \quad \text{(E24)}$$

$$QH_{WGS} = \frac{x_4 \times M_H}{x_1 \times M_{CO}} \times QCO_{Gasification} \times \eta_{WGS} \quad \text{(E25)}$$

Where: $\boldsymbol{QH_{Gasification}}$, refers to the amount of hydrogen that can be produced through gasification process (Ton), $\boldsymbol{QCO_{Gasificatio}}$, refers to the amount of carbon monoxide that can be produced through gasification process (Ton), $\boldsymbol{QH_{WGS}}$, refers to the amount of hydrogen that can be produced through the water-gas shift reaction (Ton), $\boldsymbol{QB}$, refers to the amount of biomass, with its empirical formula being $C_xH_yO_z$, (ton), $\mathbf{M_H}$, refers to the molar mass of hydrogen (H_2) (g/mol), $\mathbf{M_{CO}}$, refer to the molar mass of carbon monoxide (g/mol), $\mathbf{M_{Biomass}}$, refers to the molar mass of the biomass (g/mol), and $\boldsymbol{\eta_{Gasification}}$, and $\boldsymbol{\eta_{WGS}}$, refer to the efficiency of the gasification process and water-gas shift reaction respectively.

Finally, the total amount of hydrogen that can be produced through the whole process (gasification + water-gas shift) is calculated using the formula below (equation 26):

$$QH = QH_{Gasification} + QH_{WGS} \quad \text{(E26)}$$

Now, regarding the theoretical hydrogen potential estimation, an efficiency of 100% was assumed for each process (gasification and water-gas shift). In contrast, for practical hydrogen potential estimation, efficiencies of 75.01% [33] are assumed for the gasification process

II.5.3.1 Economic Analysis of Gasification

This section presents the methodology adopted for conducting a comprehensive techno-economic analysis of hydrogen production from biomass through gasification. The process integrates an evaluation to assess the viability of this green hydrogen pathway.

The economic analysis includes both capital and operational expenditure CAPEX.

Table 9:CAPEX of Gasification

Equipment	Current year	Current capacity	Current cost ($)	References
Gasifier + gas clean-up	2021	560.56 kW	153135	[62],[63]
Gas cooler	2021	29.61 kW	16848.04	[62]
Hydrogen separator (membrane reactor)	2021	0.0020675 kg H2/s	171202.4	[62],[56]
Plasma gasifier + torch	2021	0.02778 kg biomass/s	715298,20	[62]
Gas cooler	2021	46.48 kW	18618.82	[62]
Hydrogen separator (membrane reactor)	2021	0.0018943 kg H2/s	161728.89	[62],[58]
Gasifier	2021	2000 kg/h	74397,84	[62]
Pump	2021	2000 kg/h	24224,70	[62],[64]
Mixer	2021	2000 kg/h	6377,88	[62]
Gas cooler	2021	40.60 kW	18072,73	[62][65]
Hydrogen separator (membrane reactor)	2021	0.00210811 kg H2/s	173548,24	[62]
Heater	2021	2000 kg/h	104,064,047.41	[62]
Installation and civil works	2021		148,000	[55]
Cryogenic oxygen supply unit		Oxygen flow t/h	168,180,000	[66]

Table 10:OPEX of Gasification

Cost description	Value	Total cost ($)	Reference
Workers' wages	64,050 $/year	75,671.87	[62]
O&M (percentage of CAPEX)	10.4%	178,415.53	[62]
Biomass	0.024 $/kg	2,937,301.68	[62]
Treated water	0.32 $/kg	39164022.4	[62],[55]
Electricity	0.048 $ /kWh	86,400	[62],[55]

II.5.4 Green Hydrogen production Solar steam Methane Reforming

Green hydrogen production through solar steam methane reforming utilizes solar energy to convert methane produced from slaughterhouse blood into hydrogen

II.5.4.1 Methane production from slaughterhouse Blood

Blood from livestock slaughtering generates a high organic pollution load and poses risks. When discharged untreated into sewer systems, it increases the organic pollution load on wastewater treatment plants by 35–50% [29]. This section of the methodology explores the anaerobic digestion of blood from various animals (sheep, cattle, pigs, heifers, goats, camels, and calves). It evaluates the methane potential of blood from animals across eight regions in Niger.

II.5.4.1.1 Feedstock Characterization: Blood Composition

Blood is a slaughterhouse by-product rich in proteins, minerals, and organic matter (See Appendix H) [67]. Its composition makes it a valuable feedstock for bioenergy production, but also creates challenges due to its low C/N ratio and high nitrogen content. Understanding its physicochemical properties is therefore essential for assessing its potential in energy conversion processes [68].

Table 11: Elemental Composition (C, H, O, N, S) and Physicochemical Characteristics of Blood from Various Livestock Species

Animal	C (%)	H (%)	O (%)	N (%)	S (%)	Ts (%)	Vs (%)	references
Sheep	49.1	7.2	23.8	14.4	0.6	19.7	95.6	[69]
Cattle	55.10	7.00	20.00	20	1.00	83.10	70.1	[70][69]

Pig	49.7	9.0	24.8	14.9	0.4	17.9	16.8	[71]
heifers	48	7.77	69.92	1.40	1.26	17	10.6	[72][70]
						71	60	
Goat	42	5.62	39.85	1.45	1.0			[73][70]
						11	9.9	
camel	55.60	24.64	19.35	0.32	0.09			[69]
calves	55.10	7.00	20.00	20	1.00	83.10	70.1	[69][70]

II.5.4.1.2 Process of Methane Production from Slaughterhouse Blood

Methane production from slaughterhouse blood is achieved through anaerobic digestion of its organic content.

II.5.4.1.3 Theoretical Buswell's Equation

The theoretical Buswell's equation, shown in Equation 27 below, was introduced in 1952 and is used to estimate a feedstock's biogas potential from anaerobic digestion. It requires data on the carbon, oxygen, hydrogen, nitrogen, and sulfur content (ultimate analysis) of the specific biomass. To determine the methane potential, both Buswell's equation and the carbon content of the biodegraded material are combined [74][75].

Buswell's Equation

Boyle's modified Buswell equation was used to estimate the theoretical potential of biogas and methane at standard conditions (0°C, 1 ATM), as shown in Equation (27). These equations were applied in conjunction with the chemical composition of market waste organic matter [74].

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right)H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right)CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right)CO_2 + dNH_3 + sH_2S \qquad \textbf{(E27)}$$

To determine the methane and energy yield, the following steps were taken Step One: Theoretical biogas composition

This was calculated using Equation 27 and Equation 28.

• To find the coefficients of carbon dioxide and methane, the elemental values from the ultimate analysis of a specific feedstock were divided by their respective atomic masses.

• The values obtained at this stage were then used in Buswell's equation to determine the previously mentioned coefficients.

• The percentage of methane in the biogas was calculated by dividing the methane coefficient by the sum of the methane and carbon dioxide coefficients, as shown in Equation 28. This value was subtracted from one hundred to find the percentage of carbon dioxide.

Equation 28: Methane percentage

$$CH_4 / (CH_4 + CO_2) = \%CH_4 \quad \textbf{(E28)}$$

Step Two: Methane Yield

• **Conversion of Volume to Mass**

The theoretical potential of animal blood was initially expressed in cubic meters (m^3). Using the average density of animal blood of approximately 994.5 kg/m^3, according to JOHN MACLEOD [94][96], the values were converted into kilograms.

• **Determination of Dry Matter and Moisture Content:**

The converted mass values were multiplied by the moisture content (%) and dry matter (TS/VS) values obtained from proximate analysis of blood. This process allowed the calculation of both the theoretical dry matter and the corresponding moisture fraction.

• **Calculation of Carbon Percentage (Ultimate Analysis):**

The elemental composition of blood (C, H, O, N, S) was determined from ultimate analysis articles. For each element, the elemental fraction was multiplied by its atomic mass. The results were summed, and the carbon fraction was divided by this total, then multiplied by 100 to find the percentage of carbon.

• **Weight of Carbon in the Feedstock:**

The carbon percentage was multiplied by the dry matter content of the blood to determine the weight of carbon in the feedstock.

• **Biodegradable Fraction of Carbon:**

It was assumed that 70% of the total carbon is biodegradable [76]. This fraction was multiplied by the carbon weight, which is used to determine the amount of carbon converted into biogas.

Weight of methane carbon:

The fraction of carbon in methane was calculated by multiplying its percentage in biogas by the total amount of carbon converted into biogas.

Conversion to methane weight:

According to Banks [74], since 1 mol of methane (CH_4) weighs 16 g, the weight of methane was calculated by dividing 16 g by the atomic mass of carbon (12 g/mol) and then multiplying by the number of carbon atoms in methane. This resulted in the weight of methane in kilograms.

Volume of methane (STP conditions):

At standard temperature and pressure (STP), 1 mol of gas occupies 22.4 L, and 16 g of methane is equivalent to 22.4 L. The mass of methane (in grams) was divided by 16 to find the number of moles, which was then multiplied by 22.4 to determine the volume of methane in liters. The result was then converted to cubic meters (m^3) [74].

Conversion to metric tons:

Finally, the weight of methane in kilograms was divided by 1000 to express the value in metric tons.

II.5.4.1.3 Techno-Economic Analysis of Methane from Slaughterhouse Blood

The techno-economic analysis of methane from slaughterhouse blood evaluates both the technical feasibility and the associated costs of its production.

Table 12:CAPEX of Methane from Slaughterhouse Blood

Category	Cost($)	References
Pretreatment	2652.76	[77]
Thermophilic fermentation	944.97	[77]
Anaerobic digestion	1451.86	[77]
Gas upgrading	3100.77	[77]
Total direct cost (TDC)	8150.36	[77]
Other costs	6847.80	[77]

Table 13:OPEX of Methane Production from Slaughterhouse Blood

Cost item	Price ($)	Unit	Total price	References

Feedstock: slaughterhouse blood	88.63	Tonne	683691.8	[77]
Electricity	103.99	MWh	5199,5	[77]
Low-pressure steam (<10 bar)	9.68	Tonne	74,671.52	[77]
Cooling water	0.024	m³	107,712	[77],[62]
Process water	0.21	m³	378.84	[77],[62]
Labour	59085.6	Employee year	177256.8	[55]
Maintenance	2.36	% of fixed capital investment	90,026.19	[77]
Insurance	1.18	% of fixed capital investment	450.12	[77]

II.5.4.2 Production from Solar Steam Methane Reforming

This study investigates the application of solar-assisted steam methane reforming (SMR) for producing green hydrogen. Unlike traditional SMR, which depends on fossil methane, this work considers bio-methane derived from the anaerobic digestion of slaughterhouse blood. This method not only provides a renewable feedstock for hydrogen production but also offers an effective waste management solution. Based on the previously calculated methane potential, the hydrogen yield is estimated through stoichiometric analysis, emphasizing the importance of waste-to-energy strategies in advancing Niger’s green hydrogen plans.

II.5.4.2.1 Determining Solar Irradiation in Niger

To estimate solar irradiation in Niger, data from the Global Solar Atlas were utilized and processed using computational tools. The main steps are summarized below:

▪ Data Collection

Hourly and daily solar radiation data were collected from the Global Solar Atlas. The dataset includes Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), and Diffuse Horizontal Irradiance (DHI), which are important parameters for photovoltaic and solar-thermal applications.

▪ Data Preprocessing

The raw dataset was cleaned and formatted for computational analysis. Missing values or anomalies were checked and corrected where necessary. Time series were aligned to represent typical daily and seasonal solar patterns.

▪ Computational Processing

Commands were executed using the COMANDO libraries to calculate hourly PV output profiles. The analysis converts solar radiation data into normalized PV output curves based on assumed system parameters.

▪ Generation of Representative Profiles

Daily solar irradiation profiles were calculated for each day of the year. Selected representative days were highlighted to show seasonal variations in solar availability.

After establishing Niger's solar irradiation levels, the next step was to integrate this renewable energy source into the steam methane reforming (SMR) process. Solar energy provides the necessary heat for the highly endothermic SMR reaction, substituting fossil fuels and reducing carbon emissions.

II.5.4.2.2 Reaction of SMR

The SMR reaction is endothermic, requiring heat input to maintain reaction temperatures between 900 °C [78]. Theoretical energy needs for methane reforming were calculated using stoichiometric equations.

Stoichiometric Determination of Hydrogen from Solar Steam Methane Reforming (SMR)

Hydrogen production through solar-assisted steam methane reforming follows two main reactions [78]:

Reforming:

$$CH_4+H_2O \rightarrow CO+3H_2 \quad (E29)$$

Water–gas shift reaction:

$$CO+H_2O \rightarrow CO_2+H_2 \quad (E30)$$

Overall balance:

$$CH_4+2H_2O \rightarrow CO_2+4H_2 \quad (E31)$$

Therefore: 1mol CH_4 (16 g) → 4 mol H_2 (8 g). That means 1 kg CH_4 → 0.5 kg H_2 (theoretical).

Real Yield (with efficiency factors)

$$mH_2, real=0.5 \times mCH_4 \times X\ ref \times \eta\ shift \times \eta\ PSA \quad (E32)$$

Where:

X ref = reforming conversion (≈ 0.95) [79].

η shift = water-gas shift efficiency (≈ 0.98) [80].

η PSA= hydrogen recovery (≈ 0.88) [81].

II.5.4.2.3 Techno-Economic Analysis of Green Hydrogen Production from Solar Steam Methane Reforming (SMR)

The techno-economic analysis of green hydrogen production from solar steam methane reforming (SMR) evaluates both the technical performance and the associated costs of this pathway.

Table 14:CAPEX of Solar Steam Methane Reforming (SMR)

Equipment	**Costs ($)**	References
A100: Hydrogen production	307888	[82],[60]
A200: Steam production	23608	[82],[83],[84]
A300: Hydrogen purification	102747	[82]
A400: Feed intake	12347	[82]
Total installed equipment costs	446590	[82]
Total direct costs	526976	[82]
Total indirect costs	316186	[82],[58]
Fixed capital investment	843162	[82],[85]

Table 15:OPEX of Solar Steam Methane Reforming (SMR)

Cost description	**Cost ($)**	References
Feedstock	121,977	[82],[86]
Ru–Ni/Al_2O_3 catalyst	462	[82]
Cu/Fe_3O_4–Cr_2O_3 catalyst	513	[82],[87]
Adsorbent	1,776	[82]
Electricity	6,215	[82]
Cooling water	834	[82]
Deionized water	13,652	[82],[88]
CO_2 emission allowances -		[82]
CO_2 capture -		[82]
Fixed operating costs	35,634	[82],[89]

II.6 LCOH Analysis of the Production

The key performance indicators (KPIs) [90] for economic assessment are :

Levelized Cost of Hydrogen (LCOH) is calculated by using this formula:

$$\text{LCOH} = \frac{\text{Total Annualized Cost (USD/year)}}{\text{Annual Hydrogen Production (kg)/year}} \qquad \text{(E33)}$$

Where:

- Total Annualized Cost includes CAPEX (converted to annual cost using capital recovery factor), OPEX (Operating Expenditures, any other recurring costs).
- Annual Production: is the expected output of hydrogen per year in kilograms.

II.7 Hydrogen Storage

Efficient hydrogen storage is crucial in the green hydrogen value chain because it enables a continuous supply and supports large-scale transportation to end-users. Due to the intermittent nature of renewable energy sources and varying geographic conditions, hydrogen must be stored in a way that is both technically feasible and cost-effective [91]. This study investigates the storage methods of compressed gaseous hydrogen and Liquid Hydrogen Storage. These methods are among the most advanced and promising options for linking hydrogen production facilities in Niger to potential export routes to Europe.

II.7.1 Compressed gaseous hydrogen storage

In this study, the compressed hydrogen approach stores hydrogen at high pressures, typically 500 bar (see Appendix F) [92], in specially designed composite tanks (Type IV) [93]. This method is technically mature, relatively energy-efficient compared to liquefaction, and, although it requires reinforced safety systems in hot climates such as Niger.

Table 16:Key Parameters for Compressed Hydrogen Storage

Parameters	Description / Details	References
Storage Pressure	500 bar	[92]
Tank Materials	Type IV	[93]
Storage Temperature	Ambient temperature (29°C)	[94]
Safety Systems	Pressure relief valves: H2STAR Leak Detection OHC-800 of RIKEN KEIKI sensors, cooling systems: 15 to 16°C	[95] [96] [97]
Volumetric Energy Density	5.6 MJ/L	[98]

Tanks capacity	13.61 kg	[99]
Monitoring & Maintenance	Continuous monitoring of pressure and temperature, with regular inspections of tank integrity and materials.	[100]
Tank IV Lifetime	15–20 years or 5,000–10,000 cycles	[101]
Infrastructure Compatibility	Type of tank (IV): It can be integrated with an adapted infrastructure.	[102]
Climatic Considerations	High ambient temperatures (29 °C in Niger), 15°C for cooling.	[97]
Regulations & Standards	International hydrogen storage standards and safety certifications (ISO 19881, ISO 21010:2017, SAE J2601.	[103]

In this study, compressed hydrogen storage at 500 bar using Type IV composite tanks . This approach is selected for its technical maturity, safety features (relief valves, leak detection, and cooling), and proven durability of 15–20 years or 5,000–10,000 cycles. With a volumetric energy density of 5.6 MJ/L and compliance with international standards (ISO 19881, SAE J2601), it provides a reliable, efficient, and climate-friendly storage solution, ensuring compatibility with existing infrastructure while minimizing operational risks.

II.7.1.1 Economic Analysis of Compressed Storage Method

The economic analysis of the compressed storage method focuses on assessing the costs associated with equipment, operation, and overall efficiency.

Table 17:CAPEX of Compressed Storage Method

Cost Description Study Case	Cost H2 ($)	References
Main equipment cost (Compressors, tank, and heat exchangers)	747072	[104],[105]
Equipment installation	149414	[104]
Instrumentation and control systems	119532	[104]
Gas piping	254004	[104]
Electrical systems	37354	[104]
Industrial warehouse	37354	[104]
Service center	74707	[104]
Total fixed costs	1419437	[104]
Engineering and supervision	37354	[104]
Building costs	74707	[104]

Legal costs	22142	[104]
Administrative fees	14941	[104]
Contingencies	74707	[104]
TOTAL VARIABLE COSTS	224122	[104]

Table 18:OPEX Compressed Storage Method

Cost items	**45 MPa-90K**	**Total cost** (USD)	**Refereces**
Maintenance costs (%)	4%	65742.32	[110],[111]
Other operating costs (%)	1%	16435.58	[110],[62]
SPC (kWh/kg)	4.716	586122783.7	[110]

II.7.2 Liquid Hydrogen Storage

The second option is liquid hydrogen storage, achievable through cryogenic liquefaction (cooling hydrogen to -150 °C (123 K (see Appendix F) [40]. These methods significantly improve hydrogen's volumetric energy density and are more suitable for long-distance transportation.

Table 19:Key Parameters for Liquid Hydrogen Storage

Parameters	**Description / Details**	**References**
Storage Pressure	1 bar	[40]
Tank Materials	Steel tank with vacuum insulation	[106]
Storage Temperature	-150 °C	[40]
Safety Systems	safety valves and venting systems gas detectors.	[107]
Energy Density	67.76 kg/m^3	[107]
Tanks capacity	4 732 m^3	[108]
Monitoring & Maintenance	Continuous monitoring of tank pressure, insulation performance, and boil-off rate	[109]
Tank IV Lifetime	20 to 30 years	[110]
Infrastructure Needs	Requires specialized cryogenic infrastructure; integration possible with LOX/LNG terminals	[111]
Climatic Considerations	Sensitive to ambient heat; high boil-off losses in hot climates like Niger, unless advanced insulation is used.	[97]

Regulations & Standards	International hydrogen storage standards and safety certifications (ISO 19881, ISO 21010:2017, SAE J2601)	[112] [112]
Boil-off Management	Boil-off gas recovery systems are needed to minimize hydrogen losses due to heat ingress.	[113]

This study examines an option for long-distance transport. Storage takes place at 1 bar and 150 °C in steel tanks with vacuum insulation, which provide high volumetric energy density (67.76 kg/m³) compared to compressed storage. These tanks, with lifespans of 20–30 years, are equipped with safety valves, venting systems, and H_2 gas detectors, and require ongoing monitoring of insulation performance and boil-off rates. While liquid hydrogen storage needs specialized cryogenic infrastructure and is sensitive to ambient heat, especially in hot climates like Niger, advanced insulation and boil-off gas recovery systems can help minimize losses. Compliance with international standards (ISO 19881, ISO 21010:2017, SAE J2601) ensures safety and operational reliability. Overall, cryogenic rail tankers provide a technically feasible and energy-dense method for integrating hydrogen into large-scale export supply chains.

II.7.2.1 Economic Analysis of Liquid Hydrogen Storage

The economic analysis of liquid hydrogen storage examines the investment and operational costs required to maintain hydrogen at cryogenic conditions.

Table 20: CPEX of Liquefied Hydrogen Storage

Component	Details	Estimated Cost (USD)/ton	Reference
Cryogenic Tank	Comprised a series of components to liquefy 500 tons of hydrogen per day	35000	[114]
Vertical Vessels	Safety valves, venting, gas detectors, and boil-off recovery systems	810000	[115]
Coldboxes	integration, LOX/LNG compatibility	1090000	[115]

Table 20:OPEX Liquid Hydrogen Storage

OPEX Component	Annual Cost (USD)/year	References
Maintenance cost	4590000	[114]
COL	942720	[114]

other DMC	13315920	[114]
CUT	68712504	[114]
GE	26466864	[114]
FMC	8440000	[114]
Liquefaction	1870000	[114]

II.8 LCOS Analysis of the Two Storage Methods (Liquefied Hydrogen Storage and Compressed Storage Method)

To evaluate the economic performance of the two hydrogen storage options, a Levelized Cost of Storage (LCOS) analysis was conducted. This Equation is used [116],[117]; this approach enables a consistent economic comparison between the two storage technologies.

$$\mathrm{LCOS} = \frac{\mathrm{CAPEX} + \sum_{n=1}^{t=n}\left(\frac{OPEX}{(1+i)^n} + \frac{\mathrm{ReCAPEX}}{(1+i)^n} + \frac{\mathrm{Charge\ Cost}}{(1+i)^n}\right)}{\sum_{n=1}^{t=n}\frac{Electricity_{generated}}{(1+i)^n}} \quad \text{(E34)}$$

where:

- CAPEX ($) =Total capital expenditure
- OPEX ($) =Costs associated with the operation and maintenance of the systems.
- ReCAPEX ($) =Reinvestment in the equipment that requires it. –
- Charge Cost ($) =this value refers to the cost of the load, in this case, electricity.
- The cost of electricity varies over time and depends on the market; for simplicity of calculations, an average value has been assumed.
- Energy discharged (MWh) = The amount of electricity discharged in megawatt-hours (MWh) each year.
- i (%) =The discount factor.
- n (year)= considers the total number of years (5) the storage system has been in operation

Table 21:Electricity price

Storage methods	Electricity price($)	conversion USD par kWh	Elc price pour le strorage USD par kWh	Reference
Liquefied Hydrogen Storage	6,215	0.162	1006.83	[118]
Compressed Storage Method	37354	0.162	6051.348	[118]

II.9 Hydrogen transportation from Niger to Europe

II.9.1 Retrofitting the Existing Crude Oil Pipeline

As part of this methodology, a thorough evaluation is carried out to determine the feasibility of repurposing the existing NigerHydrogen transportation from Niger to Europe. This involves exploring the logistical routes, costs, and infrastructure needed to export hydrogen to European markets.

-Benin crude oil pipeline, which currently connects the Agadem oil fields in Niger to the Sèmè-Kpodji terminal in Benin for transporting green hydrogen. This analysis focuses on five key areas: This study will consider:

- Steel grade used in Niger's pipeline (API 5L Grade B and API 5L X52) [119].
- Hydrogen operating pressure in the pipeline [92].
- Temperature of the gas (affects diffusion and solubility) [94].
- Wall thickness (affects diffusion depth)= 250 mm [119].
- Transport duration (affects total uptake) = 27 hours according to the pipeline length and flow

By analyzing these factors using the equations below and reference values from the literature, the study will assess the risk level and determine the need for retrofitting.

- Hydrogen Diffusion in the pipelines

$$\frac{\partial \mathbf{C_L}}{\partial t} = D \frac{\partial^2 \mathbf{C_L}}{\partial x^2} \quad \text{(E35)}$$

Where:

C_L: Concentration of diffusible hydrogen (mol/m³)

D: Diffusion coefficient of hydrogen in steel (10^{-9} to 10^{-7} m²/s depending on temperature) x: Thickness coordinate (m)

t: Time (s)

This law will be conceptually used to explain how hydrogen moves through pipeline steel walls during transport.

II.9.2 Economic analysis for hydrogen transportation by pipeline

This section describes the methodology used to simulate transporting green hydrogen through the existing crude oil pipeline connecting Niger and the Port of Benin, along with the cost estimates for retrofitting the pipeline for hydrogen compatibility using:

Aspen HYSYS is used to determine the parameters of each equipment for the techno-economic analysis.

Pipeline Model Setup:

The pipeline layout, length (1900 km), and diameter (as per the Niger–Benin pipeline specifications) were modeled.

Material properties of hydrogen were imported from the Aspen physical property database.

A steady-state flow regime was assumed under isothermal conditions for simplification.

Operation Conditions:

Inlet pressure: 500 bar

Temperature: Ambient (29 °C for Niger)

Flow rate: Based on projected hydrogen production from upstream facilities (10,000 kg/day)

Transport Parameters Calculated

- Pressure drops along the pipeline
- Compressor power requirements
- Temperature profile
- Linepack storage capacity

Economic Evaluation Using Capcost for Retrofitting Analysis

To estimate the capital cost associated with retrofitting the existing oil pipeline for hydrogen service, the Capcost Process Economics Program was utilized. The following procedures were followed:

Component Identification:

Components required for safe hydrogen transport were identified, including:

- Hydrogen-compatible compressors
- Purge and inerting Systems
- Leak detection sensors
- Hydrogen-rated valves and gaskets

II.9.3 Data Input and Assumptions

Reference cost data from Capcost was used based on U.S. Gulf Coast prices and adjusted with location factors for West Africa.

Equipment sizing was based on flowrate and pressure values derived from HYSYS simulation.

Installation and commissioning costs included.

Cost Scaling and Estimation:

Equipment costs were scaled using the six-tenths rule and the Cost of Engineering and Construction Products Index (CEPCI) [120].

Total Installed Cost (TIC) was estimated and broken down into:

- Direct material cost
- Instrumentation and controls
- Installation and civil works
- Safety systems

Table 22:Costs for Hydrogen Transport (Truck, Railway, Pipeline) and Storage (CGH_2, LH_2)

Type of cost	Technology	Costs	Unit	Comment	References
Transport	Truck	0.0018	€/kg/km	-	[121]
Transport	Railway	0.01–0.03	€/kg/km	depending on the number of railway cars	[121]
Transport	Pipeline	0.0016	€/kg/km	repurposed Pipelines	[121]
Storage	CGH_2	0.04–1.3	€/kg	for a storage capacity between 11 - 101 t H_2	[121]
Storage	LH_2	0.016–1.15	€/kg	for a storage capacity between 11 - 101 t H_2	[121]
Conversion processes	H_2 – conversion	1.47	€/kg	conversion from gaseous H2 to liquid H_2	[121]
Conversion processes	H_2 – reconversion	0.33	€/kg	reconversion from liquid H2 to gaseous H_2	[121]

II.10 Exportation of hydrogen from Port of Sèmè (Benin) to Europe

This section outlines the methodology for exporting green hydrogen from Sèmè port (Benin) to Europe exclusively via maritime shipping. This methodology excludes transport by pipelines, focusing on the logistics and economic aspects of transporting hydrogen by sea.

Several strategic factors drive the choice of maritime exportation from Benin's ports. Benin's coastal infrastructure and proximity to European shipping routes offer a practical and cost-effective pathway for large-scale hydrogen export. By leveraging existing port facilities, we can streamline the export process and minimize initial capital investments compared to developing new overland infrastructure.

In the following analysis, we provide a detailed overview of the steps involved in the maritime transport chain, including the liquefaction or conversion of hydrogen into suitable carriers, loading operations, and the economic factors influencing the choice of shipping methods. This sets the stage for a comprehensive financial analysis of the chosen export route.

Table 23:CAPEX of shipping

Ship components	Unit	Per unit Cost (USD/unit)	Total cost (Setup 1)	Reference s
W_{hull}	kg	3.49	9500000	[122]
$W_{machine}$	kg	0.014634	33000	[122]
W_{equip} (64%)	kg	0.014634	3500	[122]
W_{sss}	kg	3.49	760000	[122]
LH_2 Cargo based on Wempty cargo - wall material (Aluminium 4.4%) - Insulation foam (rigid closed-wall Polyurethane) - Liner alloy (Aluminium 5086) - Construction alloy - LH_2 storage system and equipment	kg	30	15000000	[122]
LH_2 fuel tank (Wlp)	kg	30	2500000	[122]
Two (15.5 MW) Azimuthal pods electrical propulsion system	2	15000000	300000	[122]
Combined gas and Steam turbine (COGAS)	1	14700000	147000	[122]
Investment and design cost of LH_2 carrying cargo	kg	2.05	1025000	[122]
Annusl Ship CAPEX (Total cost)	USD		280000	[122]
Discount rate	%	5		[122]
Economic life	Year	20		[122]
CRF	%	8.02		[122]

Table 24:OPEX of the shipping

Variables	Value	References
C_Port ($/call)	50,000	[118]
C_PL ($/m³)	21627.88	[123]
C_Canal ($/transit)	400,000	[123]
C_Fuel ($/tonnes)	1.906458e11	[123]
C_CE ($/tonnes of CO_2-eq)	1.001e12	[123]
Boil-off rate (%/day)	2002581.9	[123]
C_SM (% of shipbuilding cost)	2^5	[123]
C_Crew ($/person)	1500000	[123]
C_S_Insurance (% of shipbuilding cost)	10^5	[123]
C_ETM (% of shore tank building cost)	10^2	[123]
C_Labor ($/person)	1500000	[123]
C_ET_Insurance (% of shore tank building cost)	5000000	[123]

II.11 Levelized cost of transportation

The reaction is used in the equation (35) [124] :

:

$$\mathrm{LCOT} = \frac{\mathbf{TCI} - \frac{\mathrm{R}}{(1+i)^{J}} + \sum_{j=i}^{j} \frac{\mathrm{R}}{(1+i)^{J}}}{\sum_{j=i}^{j} \frac{\mathrm{R}}{(1+i)^{J}}} \quad \text{(E36)}$$

In this formula,

- LCOT is the levelized cost of hydrogen transportation,
- TCI is the total investment of the project,
- R represents the residual value of the project after the operating period,
- Aj represents the operating costs of the project in year j,
- Yj represents the quantity of products in the j year,
- K represents the discount rate,
- J represents the service life.

Conclusion of Chapter 2

In summary, this chapter established the methodological foundation of the study by defining the study area, selecting relevant renewable feedstocks (agricultural residues, slaughterhouse blood, and solar energy), and applying a structured multi-step approach for hydrogen production, storage, transportation, and techno-economic assessment. The integration of experimental data, literature values, national statistics, GIS-based spatial analysis, and process modeling tools (Excel, QGIS, HYSYS, CAPCOST) ensures a comprehensive and realistic evaluation.

CHAPTER THREE: RESULTS AND DISCUSSION

This chapter presents the key results of the study and provides a critical discussion of their technical, economic, and contextual implications in relation to the research objectives.

III.1 The Geographic Distribution of Crops in Niger

The distribution of specific crops (sugarcane, groundnut, cassava, sweet potato, and rice) across different regions of Niger. Each color represents an administrative region, while the crop-specific boxes show where these crops are cultivated.

Sugarcane is mainly irrigated along the Niger River, like Tillabery, Niamey, and Dosso, but also in Zinder; groundnut is widely grown in Maradi, Dosso, Zinder, Tahoua, Tillabery, and Niamey; cassava is primarily produced in Dosso, Tillabery, Zinder, and Niamey; sweet potato is cultivated in Dosso, Maradi, Zinder, Tillabery, Tahoua, and Niamey; and rice is limited to irrigated also areas along the Niger River (Tillabery, Niamey, and Dosso), Lake Chad basin (Diffa), and in Maradi, Zinder, and Tahoua [19].

Water-dependent crops are concentrated in irrigated zones, indicating hydrological constraints. In contrast, rain-fed crops like groundnut, cassava, and sweet potato are common across many regions, providing decentralized biomass for energy. These patterns explain that biohydrogen projects should focus on water-rich areas with irrigation and utilize rain-fed crop residues elsewhere to create a resilient supply chain, emphasizing strategic locations for biomass-to-hydrogen facilities.

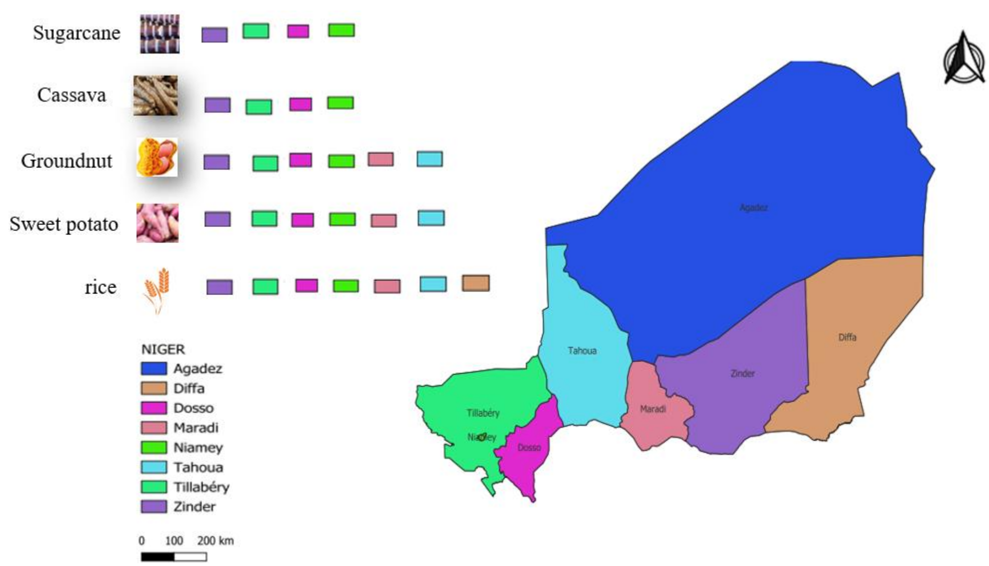

Figure 1:The geographic distribution of crops in Niger

III.1.1 Selected Crops Grown in Niger

Five major crops in Niger: cassava, sugarcane, rice, sweet potatoes, and groundnuts were evaluated as feedstocks for biohydrogen production via gasification and dark fermentation. Data from 2019-2023 show stable annual yields, totaling about 2.39 million tons of cassava, 2.69 million tons of sugarcane, 0.66 million tons of rice, 1.05 million tons of sweet potatoes, and 2.78 million tons of groundnuts, indicating reliable residue availability. Technologically, dry lignocellulosic residues, such as groundnut shells, rice husks, and sugarcane leaves, are well-suited for thermochemical gasification, while moist, starch- and sugar-rich residues from cassava peels, sweet potato vines, and sugarcane are ideal for biological fermentation. Combining both resource types create a system that integrates thermochemical and biological methods, reducing supply risks, supporting continuous operation, and boosting resilience. Using crop residues adds value, increases farmers' income, and reduces greenhouse gases from residue decay.

Overall, the selected crops represent a practical, sustainable, and technically feasible biomass base for developing an integrated biohydrogen production system in Niger.

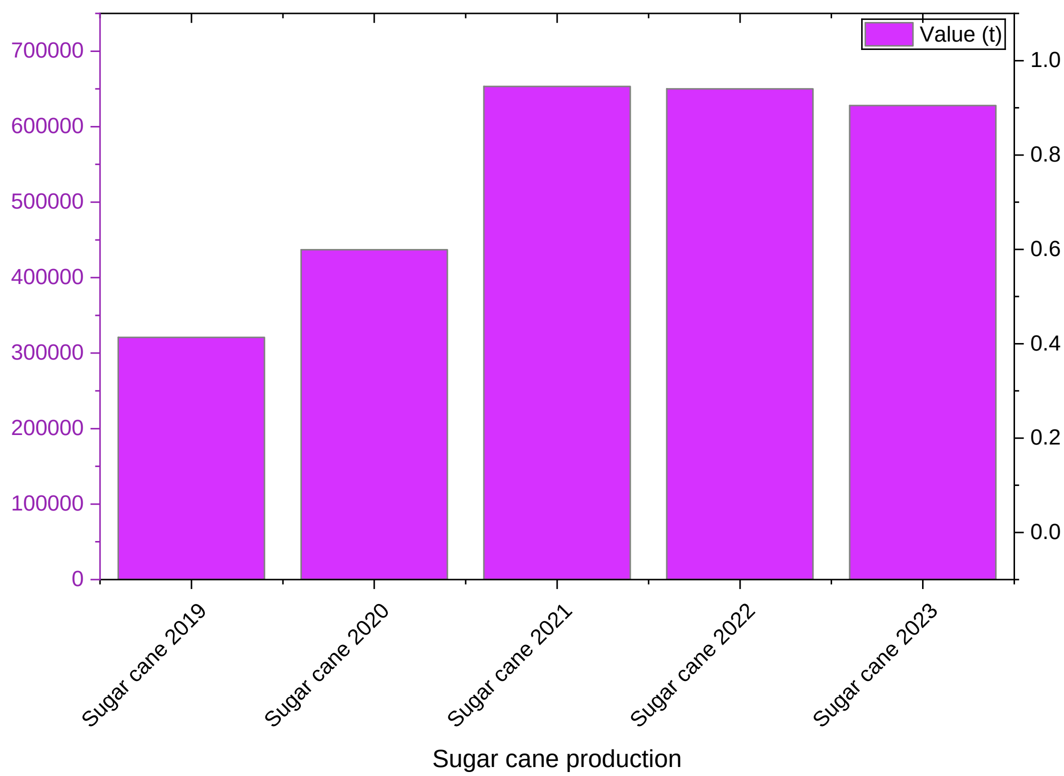

Figure 2:Sugar cane production over 5 years

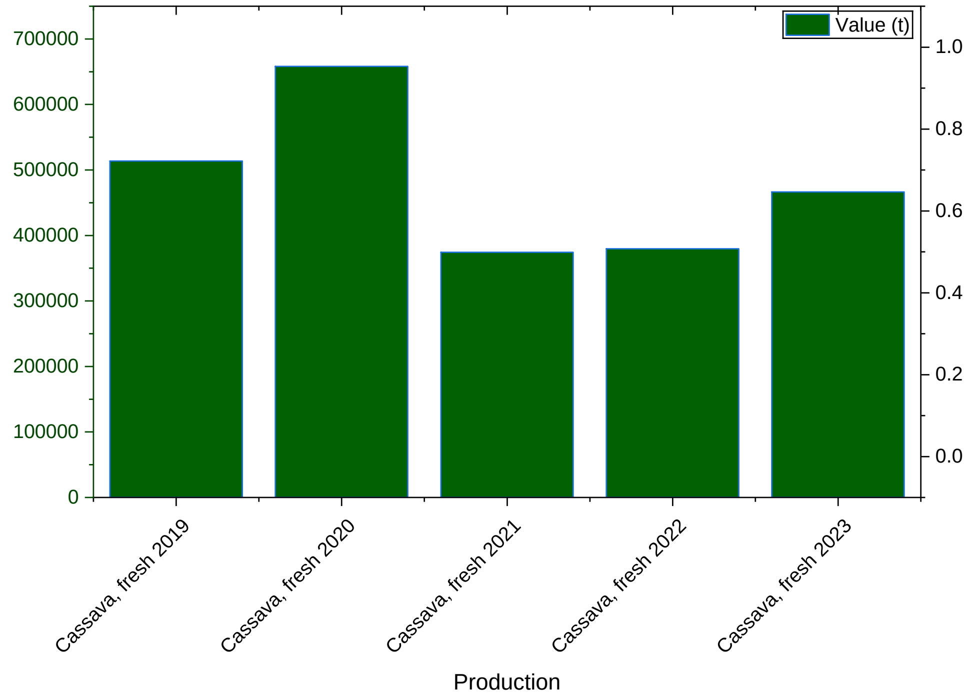

Figure 3:Cassava, fresh production over 5 years

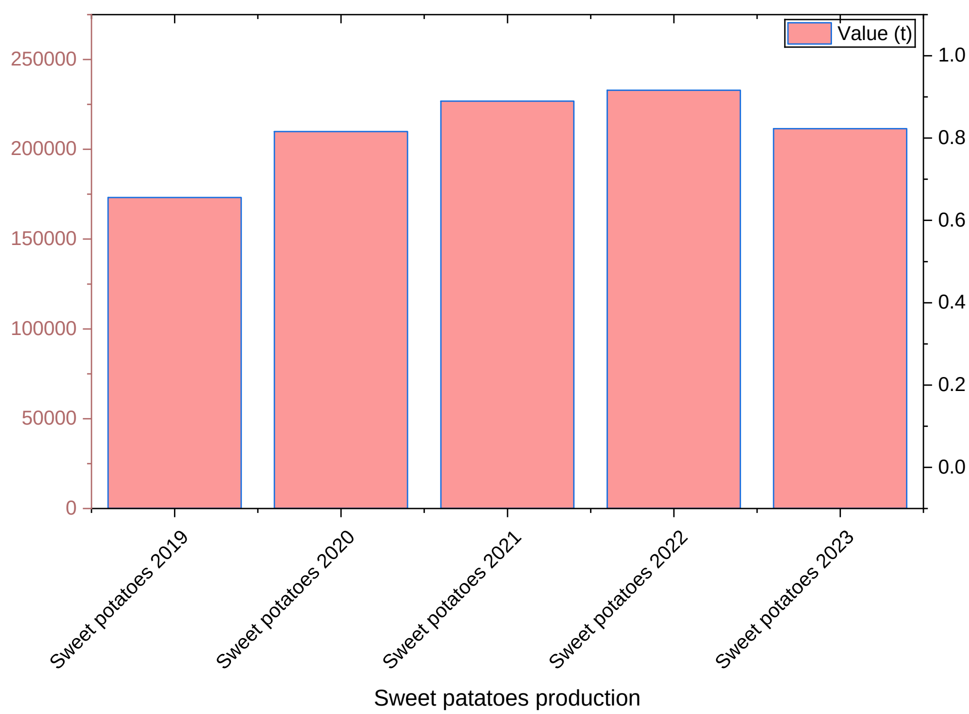

Figure 4:Sweet potatoes production over 5 years

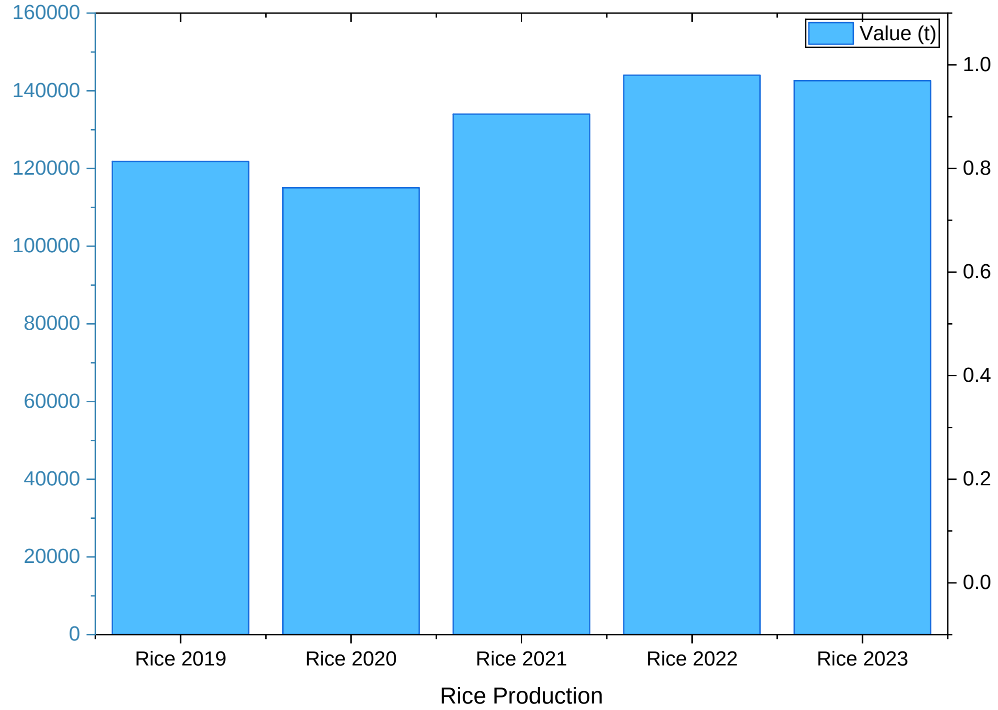

Figure 5: Rice production over 5 years

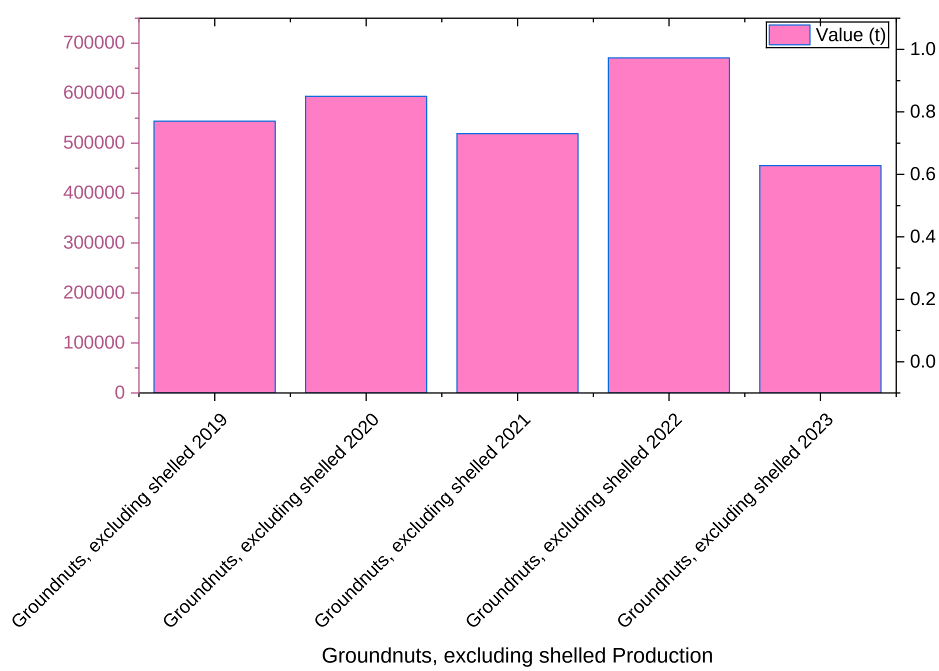

Figure 6: Groundnut, excluding shelled production over 5 years

III.2 Production

This section presents the results of hydrogen production obtained through the different pathways considered in this study, highlighting their technical performance and economic feasibility.

III.2.1 Biohydrogen Production from Dark Fermentation

Figure 3 illustrates hydrogen production potential from dark fermentation using sweet potato peels, cassava peels, sugarcane bagasse, and groundnut stalks. The y-axis shows total hydrogen (tons), and the x-axis shows categories. Groundnut stalks produce the most hydrogen at 525,439.548 tons, primarily due to their high cellulose and hemicellulose content, which aids microbial conversion. Sugarcane bagasse and sweet potato peels yield approximately 327,032.548 and 315,313.8 tons, respectively, demonstrating their potential in agricultural areas. Cassava peels yield about 218,117.088 tons but remain valuable in co-digestion. This highlights the importance of feedstock selection for optimizing hydrogen, with locally abundant residues like groundnut stalks enhancing renewable energy and bioeconomy strategies in Niger. Prioritizing high-yield, local residues helps Niger create a sustainable hydrogen source, supports green energy, reduces emissions, and generates rural jobs.

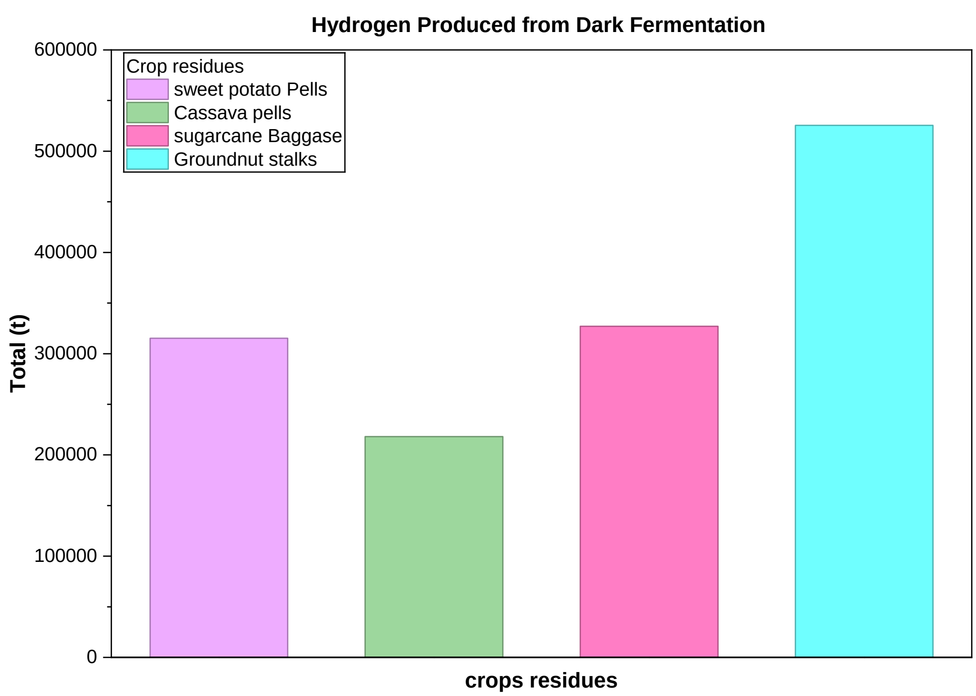

Figure 7:Hydrogen Production from Dark Fermentation

III.2.2 Biohydrogen Production from Gasification

Figure 4 shows hydrogen production from five agricultural residues: rice husk, rice straw, groundnut shells, sugarcane tops, and cassava stalks. The y-axis indicates total hydrogen output (tons), and the x-axis lists residues. Groundnut shells lead with 240,383.65 tons, due to high carbon content and low ash. Rice straw produces over 156,739.36 tons, followed by cassava stalks at 131,417.09 tons, both of which are abundant yet underutilized. Sugarcane tops yield 64,704.06, with higher moisture and a lower carbon-to-hydrogen ratio. Rice husk yields the least at 18,693.69 tons, likely due to high silica and ash content reducing efficiency. The chart shows residue type impacts gasification; prioritizing groundnut shells and rice straw could boost bioenergy in Niger.

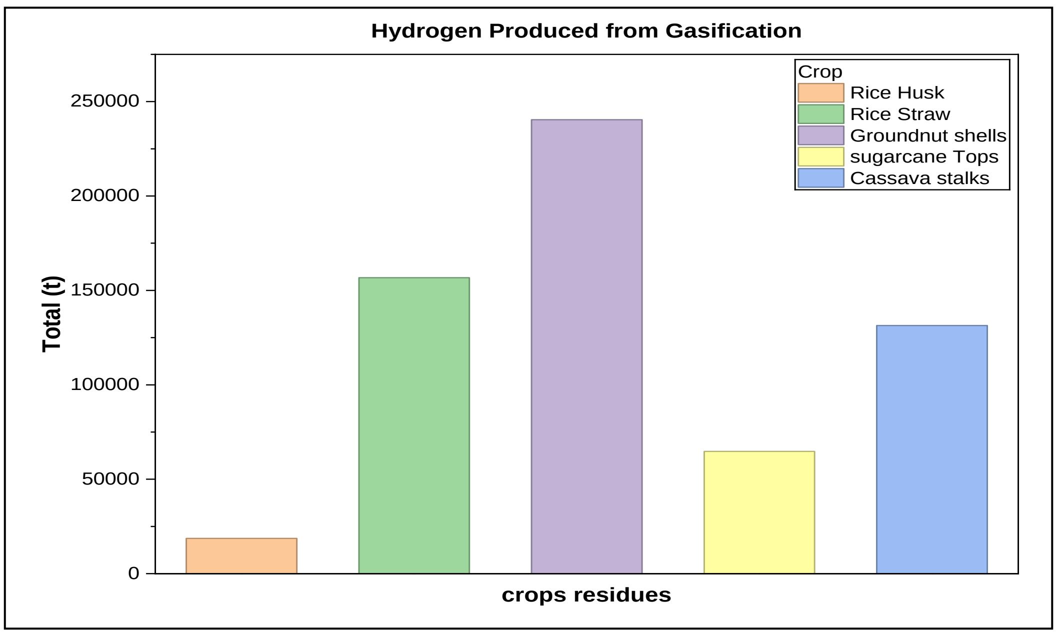

Figure 8:Hydrogen production from gasification

III.2.3 Green Hydrogen Production

This study focuses on 2019 data, which is only available online from the Ministry of Livestock.
The 2019 Niger slaughter data reveal a significant potential for bioenergy from animal waste, especially blood. Goats and sheep are most slaughtered, followed by cattle, with camels and pigs slaughtered less often—slaughter peaks during cultural or religious events. An estimated 3,248,602,500 billion liters of blood came from cattle, 1.7 billion from goats, and smaller amounts from other species, indicating abundant organic waste for energy recovery.

Animal blood, rich in proteins and organic matter, offers high potential for renewable energy production through anaerobic digestion (for biomethane). The involved volumes, especially in major slaughterhouses, justify investment in waste-to-energy systems. Utilizing this resource could help Niger reduce environmental pollution, create local sources, and support its green hydrogen goals as part of a broader circular economy strategy.

Table 25:Monthly Distribution of Slaughtered Animals and Blood Output in Niger (2019)

Month	**Calves**	**Heifers**	**Cattle_Total**	**Sheep_Total**	**Goats_Total**	**Camels_Total**	**Pigs_Total**
January	2691	279	18798	55341	101257	2656	76
February	2632	228	17067	50658	97948	2561	46
March	2478	258	16091	51046	96867	3437	76
April	1987	357	15790	51267	105185	3091	56
May	2098	347	16410	55679	118676	3742	60
June	2201	310	15974	54946	109210	3679	385
July	2338	381	15381	53052	109678	3794	64
August	1820	295	10957	38316	87775	2704	252
September	2153	193	14941	48985	96781	2562	54
October	2495	249	16796	55274	103534	2763	42
November	2439	334	16323	54432	106180	2562	69
December	2221	292	13099	54886	109964	2255	69
Total 2019	28631	3556	196885	618307	1288069	36129	724
blood (Litter)	2.9	12.6	16500	1.5	1320	37.1	2.93
Quantity Of blood (Litter)	83029.9	44805.6	3248602500	927460.5	1700251080	1340385.9	2121.32

The data highlights an underused bioresource. This research shows that anaerobic digestion of slaughterhouse blood can produce methane for hydrogen via solar-assisted SMR. Seasonal patterns indicate a year-round supply for continuous hydrogen production and export. Incorporating this waste-to-hydrogen approach into Niger's renewable energy strategies promotes sustainability, a circular economy, energy transition, and climate resilience by converting animal waste into clean fuel.

III.2.3.1 Production of Biomethane

Figure 5 illustrates the methane production potential from animal blood during slaughter in Niger, with notable differences based on the animal source. Cattle blood has the highest potential, at approximately 811,153 kg, due to its large volume and high organic content. Camel and goat blood also show high potential, with 465,021.77 kg and 375,369.75 kg of methane, highlighting their importance in biomethane strategies in pastoral regions, sheep blood yields around 237,074 kg, contributing when combined with others. Cow/heifer and pig blood yields are much lower at 117.47 kg and 575.13 kg, respectively, due to smaller slaughter numbers.

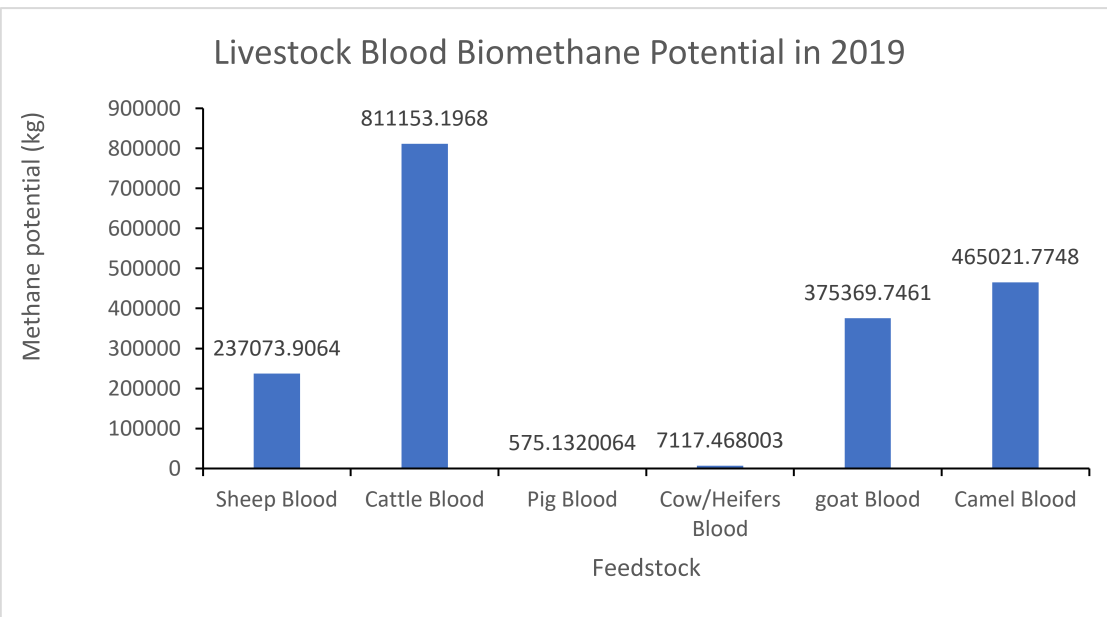

Figure 9:Livestock Blood Biomethane Potential in 2019

Biohydrogen and biomethane from animal blood waste in Niger show that slaughterhouse residues are valuable bioenergy feedstocks. Utilizing anaerobic digestion or integrated SMR promotes energy recovery and waste management, fostering a circular bioeconomy. These findings help in developing methane hubs for hydrogen or renewable electricity, which are crucial for green hydrogen supply chains and rural off-grid energy in West Africa.

III.2.3.2 Solar Potential in Niger

The plot displays normalized daily PV output profiles across Niger, with the x-axis from 0 to 24 hours and the y-axis near 0.85. Each line represents a specific day, with key days highlighted. Bell-shaped curves indicate high solar potential, with PV production starting around 5–6 AM, peaking at noon, and ending around 6–7 PM, following the solar cycle. Slight seasonal variations suggest stable, intense solar irradiation year-round, making it ideal for solar energy, including green hydrogen production. Lower curves show impacts like dust or clouds, which are important for planning. The plotted data demonstrate typical bell-shaped solar profiles with seasonal and atmospheric variations, confirming Niger's high year-round solar irradiation and peak midday output. This supports assessing the potential for solar-assisted hydrogen. The results confirm that solar thermal energy integration is feasible, as consistent year-round output provides a steady heat supply for SMR reactors, improving efficiency and sustainability. These findings highlight Niger's potential in Africa's green hydrogen sector, supplying clean hydrogen locally and for export through infrastructure such as the Niger-Benin pipeline.

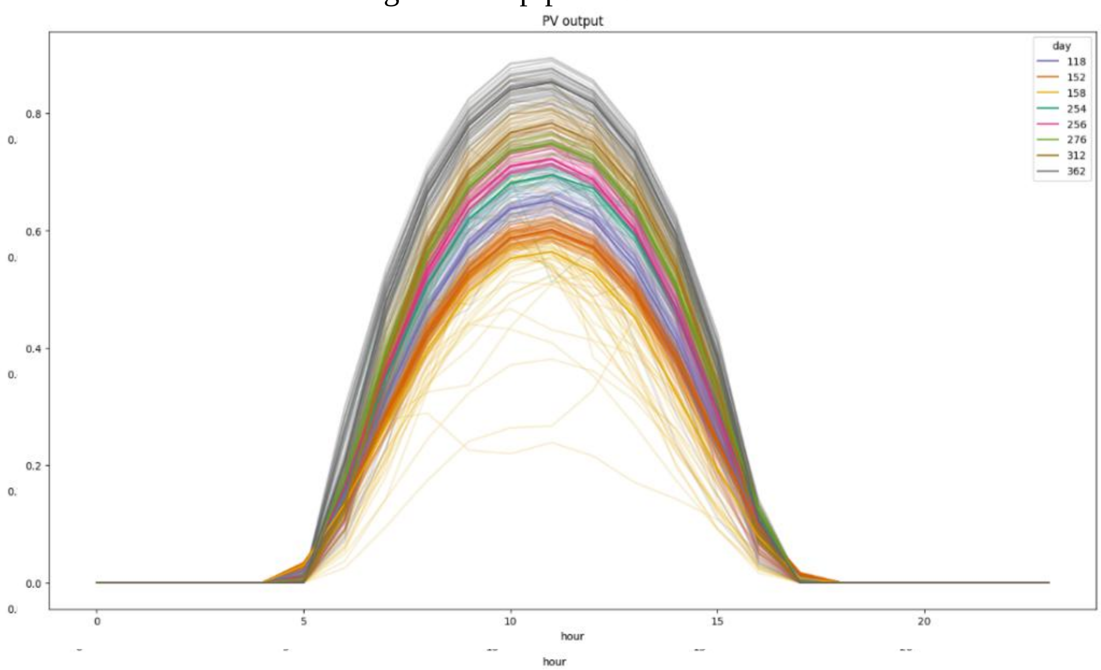

Figure 10:Niger Solar irradiation

III.2.3.3 Green Hydrogen Production from SSMR by using Methane from Slaughterhouse Blood

This research on green hydrogen from biomass residues for export from Niger to Europe highlights the importance of feedstock selection in maximizing output and economic viability. Prioritizing abundant residues like groundnut shells and rice straw can help Niger build a sustainable, cost-effective biohydrogen supply chain supporting circular bioeconomy principles. This promotes waste-to-energy, reduces agricultural waste, and boosts rural energy resilience, positioning Niger in the African hydrogen export market. The analysis also discusses solar-assisted steam methane reforming (SMR), where methane from slaughterhouse blood is converted to green hydrogen using solar thermal energy. The process involves high-efficiency hydrogen extraction, CO_2 capture, and methane recirculation, providing a decentralized renewable hydrogen solution for regions such as Niger.

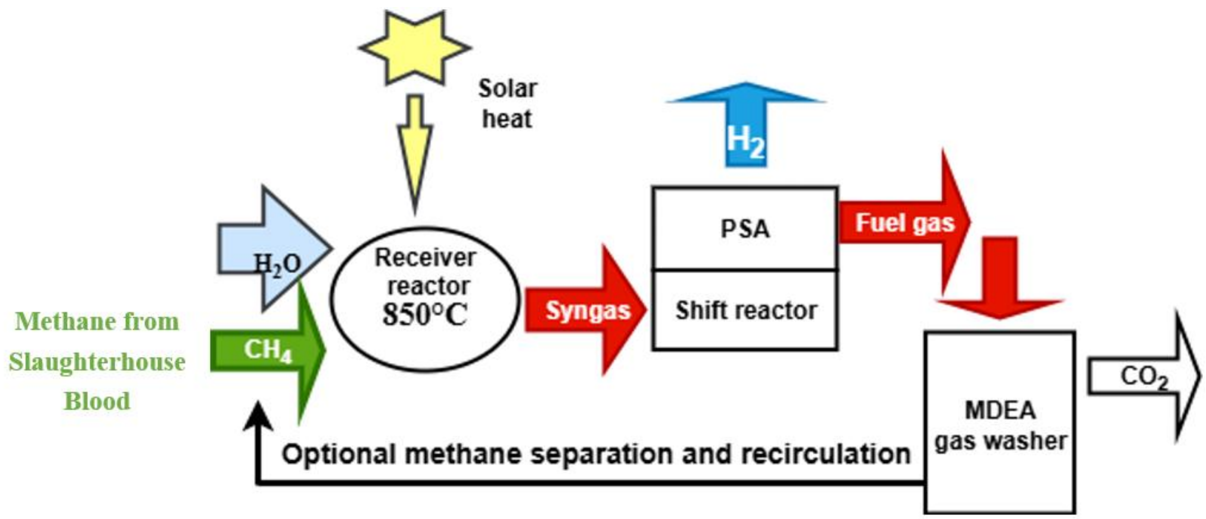

Figure 11:Methane Assessment for SSMR

III.2.3.4 Green Hydrogen Produced from SSMR

The bar chart 8 shows hydrogen potential from livestock blood via SMR or anaerobic pathways. The y-axis measures hydrogen in kg; the x-axis shows different blood types. Cattle blood is most promising, producing over 405,576 kg in 2019 due to high methane and slaughter volume. Camel and goat blood follow with 232,511 kg and 187,685 kg, respectively, indicating pastoral byproduct potential in dry regions like Niger. Sheep blood contributes 118,537 kg, while pig and cow blood produce less due to limited availability. This supports research on green hydrogen from slaughterhouse waste in Niger, highlighting animal blood's bioenergy potential as a hydrogen feedstock. Combining slaughterhouse waste with solar-assisted SMR could create a low-cost, circular biohydrogen model, reducing waste, improving sanitation, boosting energy security, lowering emissions, and aiding rural growth, aligning with Niger's renewable hydrogen export goals.

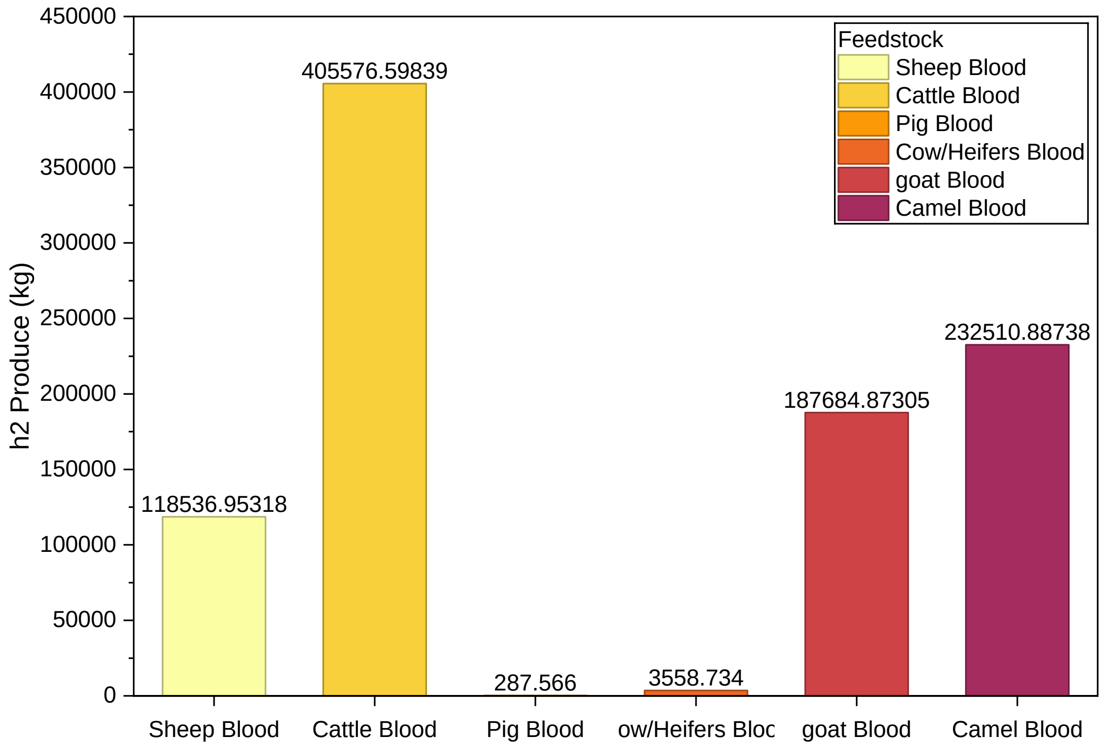

Figure 12:Green hydrogen production from SSMR.

III.2.4 Total Hydrogen Produced from three (3) Methods

The five-year assessment highlights two methods for converting agricultural waste into hydrogen: dark fermentation and gasification. Dark fermentation produces the most hydrogen (1,385,903.3 tons) by transforming wet, sugar-rich biomass like cassava peels at low temperatures (30–37°C). It is cost-effective, simple, and quick, ideal for rural areas, but needing extra purification. Gasification yields 611,937.85 tons of hydrogen from dry residues like groundnut shells, rice husks, and bagasse. Although its yield is lower, it produces high-purity, hydrogen-rich syngas and can handle large volumes of solid residues unsuitable for biological methods. Operating at 800–1000°C, it requires high energy, infrastructure, and skilled operators, leading to higher costs. Its maturity and scalability make it suitable for industrial systems. In summary, dark fermentation suits small-scale, low-cost applications, while gasification is better for larger, centralized facilities processing dry biomass. Combining both could optimize Niger's agricultural resources by using high yields from wet biomass and high purity from dry residues. Unlike these, solar steam methane reforming (SSMR) uses biomethane from slaughterhouse blood and solar thermal energy. SSMR produced 948,155.6 kg of hydrogen per year, demonstrating a high yield and purity suitable for long-term use. It offers a low-carbon, export-oriented option aligned with Niger's solar resources but needs significant infrastructure, a steady biomethane supply, and reliable solar energy, making it more suitable for centralized, high-capacity use rather than rural areas.

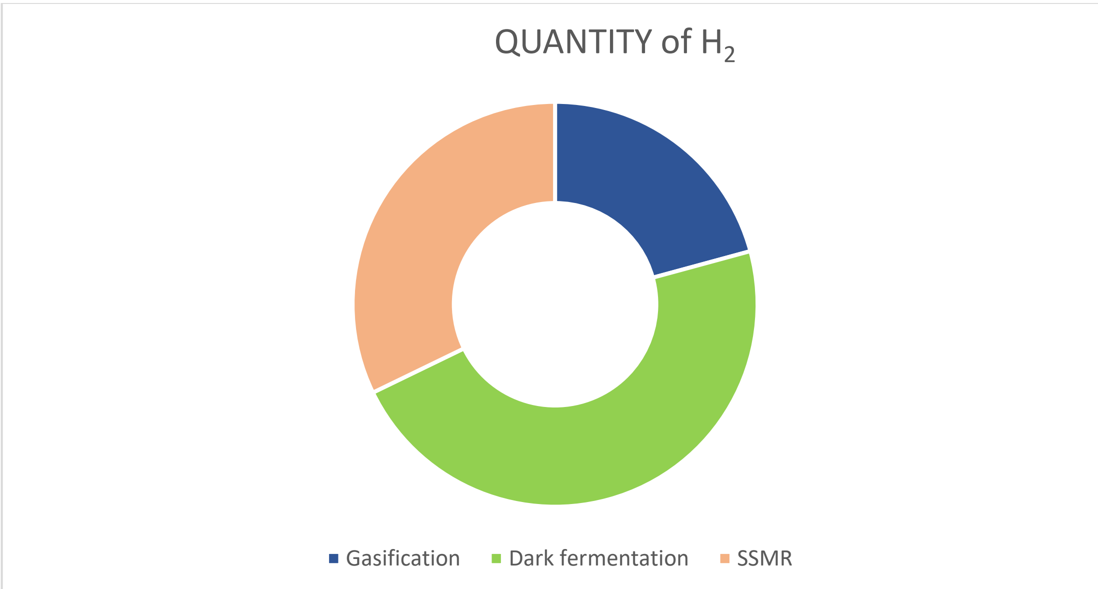

Figure 13:Hydrogen produced from gasification, Dark fermentation, and SSMR

III.3 LCOH Analysis Result of the Production

This techno-economic comparison reveals that gasification is the most cost-effective pathway for hydrogen production, characterized by moderate CAPEX, manageable OPEX, and the lowest LCOH (2.59 USD/kg H_2), despite producing less hydrogen than dark fermentation. Dark fermentation, while achieving the highest hydrogen output, suffers from very high operating costs, resulting in the highest LCOH (5.01 USD/kg H_2). SSMR shows low CAPEX and OPEX, but its low production volume increases its LCOH (4.14 USD/kg H_2).

Overall, gasification is the most economically viable option for large-scale production, while SSMR is promising for small-scale solar-powered units, and dark fermentation requires significant cost reductions to become competitive.

Table 26:Techno-Economic Results of Hydrogen Production Pathways

Production methods	Total Hydrogen(kg)/year	total CAPEX ($)	total OPEX ($)	total annualised cost in (USD/year)	LCOH (USD/kg h2)
Gasification	122,387,570	273,994,520.2	42,441,811.48	316,436,331.6	2.585526713
SSMR	948,155.6	2,602,652.52	1,320,450	3,923,102.52	4.13761467
Dark Fermentation	277,180,660	686,200	1,388,123,240	1,388,809,440	5.010484642

The obtained results indicate levelized hydrogen costs of 2.59 USD/kg H_2 for gasification, 4.14 USD/kg H_2 for solar steam methane reforming (SSMR), and 5.01 USD/kg H_2 for dark fermentation. The cost of hydrogen from gasification (2.59 USD/kg H_2) falls within the typical range of thermochemical pathways and demonstrates competitive performance compared to other renewable production methods. These values are consistent with the ranges reported in the literature [125]. conventional SMR typically yields 1.25–3.50 USD/kg H_2 [126][127], while biohydrogen from dark fermentation is estimated around 5 USD/kg H_2 [127], [128]. The higher cost of SSMR compared to fossil-based SMR is mainly due to the integration of solar energy and the use of slaughterhouse-derived methane as a renewable feedstock, which increases CAPEX but ensures a low-carbon pathway[129]. Overall, these results confirm the robustness of the developed model and demonstrate good alignment with international benchmarks

III.4 Storage Methods

This analysis compares compressed and liquefied hydrogen storage, highlighting their benefits and trade-offs. Compressed hydrogen is a mature, low-cost technology suitable for small-scale use, but has moderate efficiency and safety risks due to high pressure. Its operational costs are high for continuous compression and monitoring. Liquefied hydrogen offers higher density and is ideal for large-scale transport, requiring higher initial investment and energy for liquefaction but providing safer storage at lower pressures. Challenges like boil-off and maintenance costs, especially in hot climates such as Niger, must be managed.

III.4.1 LCOS Analysis Results of the Storage

The obtained LCOS values indicate 1.25 USD/kg for liquefied hydrogen storage and 2.58 USD/kg for compressed hydrogen storage. The liquefied hydrogen cost falls within the range reported in the literature (0.02–1.25 USD/kg) [122], confirming the competitiveness of cryogenic storage solutions. By contrast, the compressed storage method yields higher costs than the typical range of 0.05–1.4 USD/kg reported in previous studies [121], mainly due to elevated OPEX requirements associated with large-scale compression. These results are consistent with international benchmarks such as the Norwegian hydrogen hub projections, where storage costs could drop as low as 0.183 USD/kg [Ref.]. Overall, the findings suggest that liquefied hydrogen storage offers a more cost-effective pathway for large-scale applications. In contrast, compressed storage remains better suited to smaller-scale or short-term uses.

Table 27:Analysis of CAPEX, OPEX, and LCOS for Liquefied vs. Compressed Hydrogen Storage

Storage method	Total Hydrogen(kg)/year	Total capex ($)	Total opex ($)	LCOS ($/kg)
Liquefied Hydrogen Storage	400516385.6	1,935,000	124338008	1,252
Compressed Storage Method		5041751	586204961.6	2,575

III.5 Transportation by Retrofitted Pipeline

This map shows the oil pipeline from Koulele in eastern Niger through Zinder to Benin's port, with strategically placed pumping and control stations for monitoring, pressure, and flow. It connects Niger's southern corridor to Benin, forming a continuous route.

This map is especially relevant for hydrogen transport via a retrofitted pipeline. With modifications like ensuring material compatibility, sealing, and hydrogen sensors, it could support large-scale hydrogen from renewable sources (solar-SMR or biomass) in Niger to international markets via Benin’s port. Its existing design, regional coverage, and logistic hubs make it ideal for retrofit projects, aiding the Africa-Europe hydrogen trade.

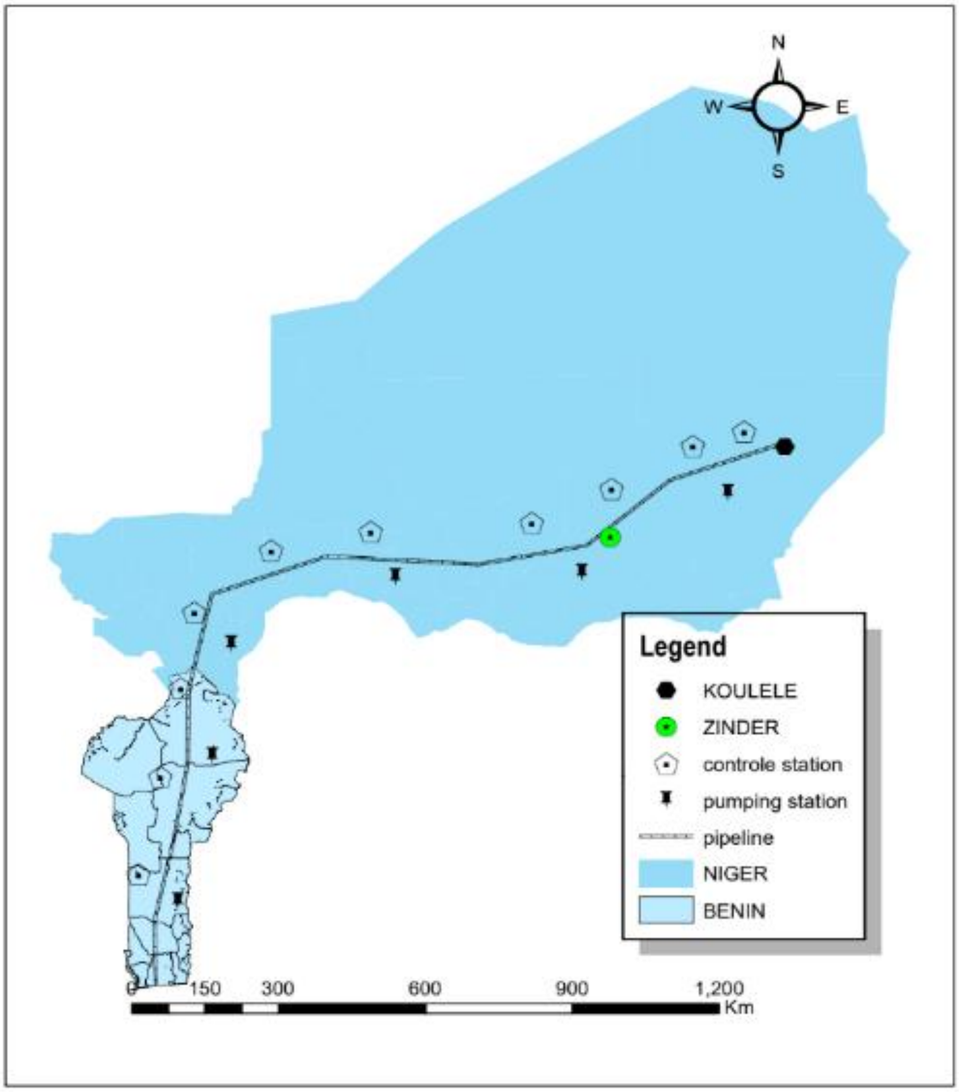

Figure 14:Pipeline transport option

Table 28:Leading Equipment Required for Retrofitting Petroleum Pipelines to Hydrogen Transport

Equipment	Main Specifications	Function in Hydrogen Pipeline Conversion
Centrifugal Pump (P-101)	5 kW, 3 units, discharge pressure 5 bar, carbon steel	Maintains hydrogen flow and compensates for pressure losses along the pipeline.
Jacketed Non-Agitated Reactor (R-101)	Volume 10 m³, carbon steel	Conditions or purifies hydrogen before injection, with temperature control for stability.
Distillation Tower (T-101)	23 m height, 2.1 m diameter, 32 stainless steel sieve trays	Separates and removes impurities (e.g., CO_2, H_2O, hydrocarbons) from the hydrogen stream.
Horizontal Vessel (V-101)	6 m length, 1.8 m diameter, 5 bar, carbon steel	Provides buffer storage of hydrogen to regulate flow and support maintenance operations.
Leak Detection & ESD Safety System (Z-101)	Detection sensors and emergency shut-down (ESD)	Ensures safety by detecting hydrogen leaks and initiating automatic emergency shutdown.

III.5.1 Cash Flow Analysis

Figure 11 illustrates the Cash Flow Diagram derived from the techno-economic (CAPCOST) analysis of a green hydrogen production and export project from Niger, which initially has negative values during the first two years, reaching about –150 million USD. This is due to high upfront capital expenditures (CAPEX) and start-up costs. By year four, the project reaches the break-even point, meaning revenues start to surpass costs and the investment begins generating a positive net return. From year five onward, the cash flow steadily increases, eventually reaching around 400 million USD by year twelve. This indicates strong long-term profitability and confirms the project’s economic viability. However, the early negative phase emphasizes the importance of solid financial planning to absorb initial losses until profitability is achieved.

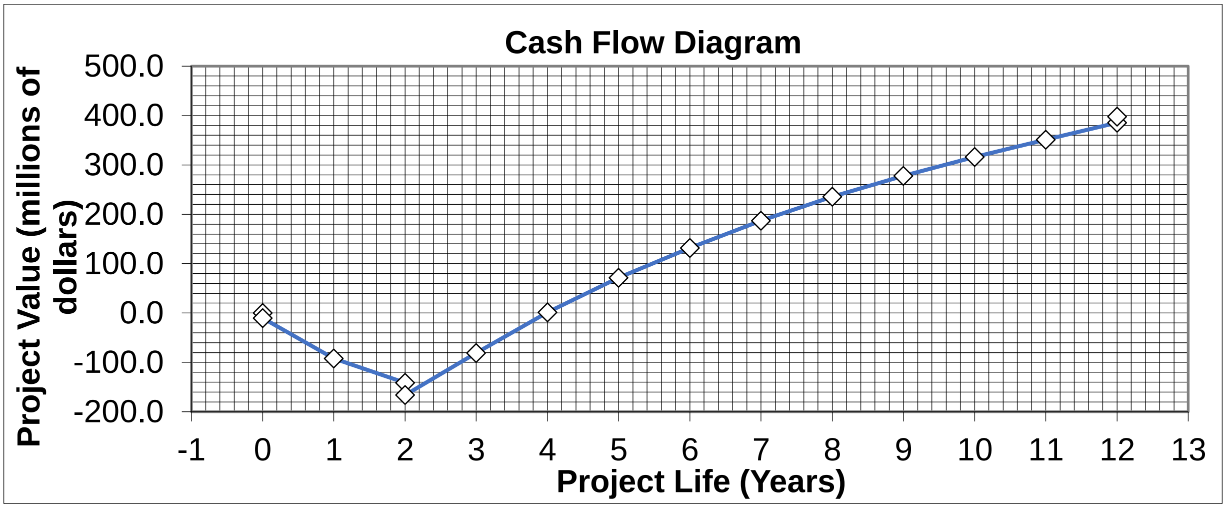

Figure 15:Project Cash Flow Evolution over 12 Years

The 12-year horizon is chosen to reflect a realistic life-cycle from construction to mature operations while keeping financial assumptions credible:

- Construction + Ramp-up (≈ 2 years) – The first two years cover EPC, commissioning, and ramp-up, which explains the negative cash flows at the start.
- Stable Operations (≈ 10 years): A ten-year operating window captures steady-state performance, learning effects, and gradual optimization of OPEX and capacity factors.
- Financing Tenor Alignment – Typical debt tenors and offtake/hedging contracts for energy/industrial assets run about 10–12 years, so a 12-year model aligns repayments and contracted revenues.
- Asset Life & Major Overhauls Core equipment (compressors, Type-IV tanks, cryogenic units, reforming trains) has economic lives of 10–20 years, with significant inspections/overhauls often planned around year 10–12. Stopping the base case at year 12 avoids adding speculative post-overhaul costs.
- Policy & Market Visibility: Price, incentive, and regulatory visibility is strongest over the next decade; extending far beyond 12 years would add uncertainty that can distort NPV/IRR.
- Conservative Valuation: Limiting the horizon to 12 years provides a prudently conservative NPV. Residual value can be recognized separately without assuming aggressive late-life cash flows.

In sum, twelve years include the full investment ramp, the break-even period, and a long enough steady phase to demonstrate sustained profitability (as shown in Figure 15), while staying aligned with financing practice, equipment life-cycle, and policy visibility.

III.5.2 Profitability Criteria of the Hydrogen Project

For the non-discounted profitability criteria, the project reaches a cumulative cash position of 921.52 million USD, demonstrating strong liquidity generation throughout its lifetime. The return on investment (61.43%) emphasizes the project's high profitability. At the same time, the payback period of 3.9 years indicates that the initial investment is recovered in less than four years, which is notably quick for a large-scale energy infrastructure project.

Regarding the discounted profitability criteria, the project has a Net Present Value (NPV) of 397.98 million USD, confirming its economic viability even when considering the time value of money. The discounted rate of return (12.10%) exceeds the standard benchmark of 8–10%, making the project appealing to investors. The discounted payback period of 5.9 years also shows that profitability is achieved before half of the project's lifetime.

III.5.3 Profitability Criteria of the Hydrogen Project

Discounted Profitibility Criterion

Net Present Value (millions)	397.98
Discounted Cash Flow Rate of Return	12.10%
Discounted Payback Period (years)	5.9

Non-Discounted Profitibility Criteria

Cumulative Cash Position (millions)	921.52
Rate of Return on Investment	61.43%
Payback Period (years)	3.9

Figure 16: Profitability Criteria of the Hydrogen Project

III.6 LCOT Analysis of hydrogen shipping

The calculated pipeline transport cost of 0.857 USD/kg/km for hydrogen export from Benin to Europe is significantly higher than literature values (0.0016–0.01 USD/kg/km),[123]. This discrepancy reflects the higher capital and operational requirements for hydrogen infrastructure in West Africa. When extrapolated to intercontinental distances, the cost exceeds international benchmarks for delivered hydrogen, suggesting that pipelines may be more suitable for regional transport to coastal hubs, with maritime shipping remaining the most competitive option for long-distance exports.

Table 29:Pipeline Transport Cost for Hydrogen Export

Type of cost	Technology	Costs($/kg/km)
Transport	Pipeline	0,857

III.6 Integrated Hydrogen Supply Chain: Niger to Europe

This schematic representation highlights the integrated hydrogen value chain from Niger to Europe, showing how locally produced green hydrogen can be exported and utilized across multiple end-use sectors, thereby supporting both energy transition in Europe and economic opportunities in Niger.

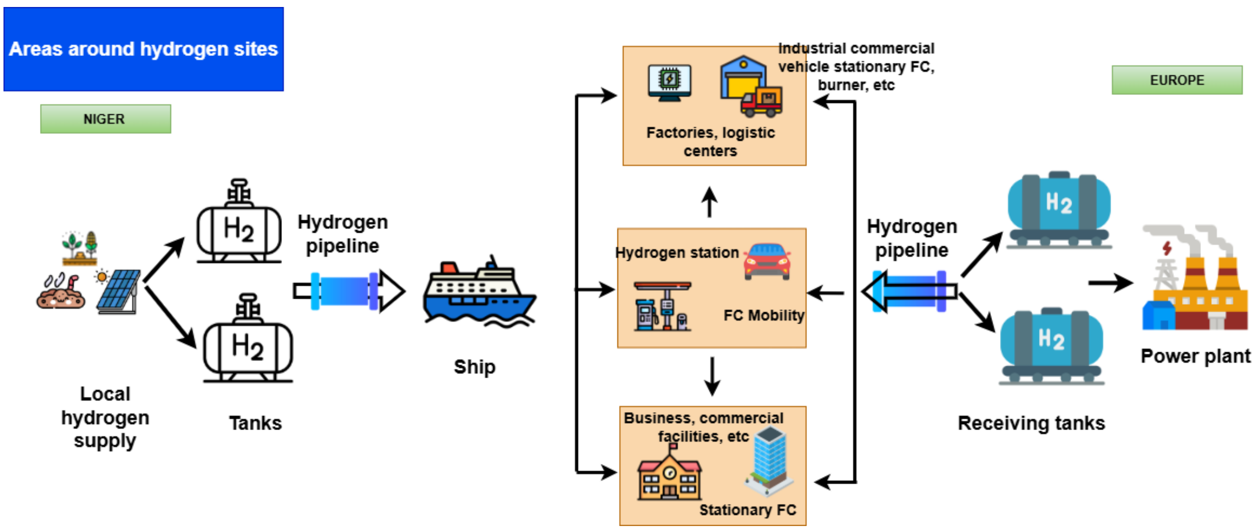

Figure 17: Hydrogen Value Chain from Niger to Europe

III.7 Discussion

In this section, the main findings are critically examined to highlight their significance, limitations, and real-world relevance.

III.7.1 Political Situation in Niger

However, the successful implementation of green hydrogen projects in Niger also depends on the current political situation. Since the 2023 military coup, Niger has been under a transitional military government, resulting in institutional changes, international sanctions, and the suspension of democratic processes. This political instability may affect foreign investments, financing availability, infrastructure development, and partnerships with European stakeholders. Additionally, security challenges in certain regions can disrupt biomass supply chains or hinder infrastructure deployment. Therefore, while the technical and economic results of this study are promising, a stable political and regulatory environment will be essential to ensure long-term project viability and international collaboration.

III.7.2 Integrated Discussion of Hydrogen Production, Storage, and Export Potential in Niger

This study's results show that Niger has significant potential for producing green hydrogen due to its abundant sunlight and agricultural waste. Three different methods were evaluated through a techno-economic assessment: biomass gasification, dark fermentation, and solar steam methane reforming (SSMR) using methane from slaughterhouse blood. Each approach demonstrated its unique advantages. Gasification provides a scalable solution capable of supporting large-scale hydrogen production. Dark fermentation offers a decentralized option suitable for local applications. Meanwhile, SSMR is effective when sunlight exceeds 2,000 $kWh/m^2/year$, especially during sunny periods.

Cost analyses further reveal that hydrogen production in Niger is highly competitive. The levelized cost of hydrogen (LCOH) from biomass ranges from $2.50 to $ 5.10 per kilogram. When conditions are optimal, solar-assisted SSMR yields the lowest costs. For storage, compressed hydrogen is preferable for small to medium-scale needs, whereas liquefied hydrogen is ideal for long-distance exports, despite its higher cost of 5.98 USD/kg. Export analyses indicate that retrofitted oil pipelines are the most cost-effective long-term option, at $ 0.85/ton/km, while railway transport, although more adaptable, is more expensive. These findings directly address the main research question by confirming that producing, storing, and exporting hydrogen from Niger to Europe is economically feasible. They also highlight Niger's potential to diversify energy supply chains and strengthen its economy.

CONCLUSION AND PERSPECTIVES

This research highlights Niger's potential to produce and export green hydrogen by utilizing its abundant solar energy and underused agricultural and livestock waste. Combining various hydrogen production technologies enables better feedstock use and adaptation to local environmental conditions. Among the methods studied, dark fermentation emerged as the most promising over five years, yielding high hydrogen outputs from biomass residues like groundnut stalks and sweet potato peels. Simultaneously, solar steam methane reforming (SSMR) using methane from slaughterhouse blood offers a unique, locally adapted solution for short-term, high-yield production, demonstrating innovation in bio-waste utilization.

For storage and transport, liquefied hydrogen proved to be the best choice for large-scale export despite its technical challenges and energy demands, primarily because of its higher volumetric density and safer low-pressure storage for shipping. Retrofitting the existing Niger-Benin oil pipeline for hydrogen transport presents a cost-effective option by using existing infrastructure, which further cuts down capital costs for export logistics.

The cash flow analysis over a 12-year lifecycle reveals a robust return on investment, with significant profitability achieved after the third year. This supports the financial viability of scaling up green hydrogen operations in Niger, provided that initial funding and technical training are secured. Ultimately, this project contributes to the country's renewable energy goals, offers a model for circular economy development, and provides a strategic export opportunity aligned with Europe’s RE Power EU and green transition objectives.

Perspectives

The study offers significant insights; however, several limitations must be recognized. First, the analysis is based on theoretical and modeled data, which may not accurately reflect real-world operational conditions. Second, the study is limited by the lack of local data on the composition of feedstock, process efficiencies, and infrastructure costs, which could make the results less accurate. Third, the scope is limited to specific options for production, storage, and transportation, which means that other possible technologies have not been looked into. Lastly, external factors like policy frameworks, geopolitical dynamics, and market fluctuations were not taken into account, even though they could have a significant effect on whether or not the project would work.

To be sure, they need to be tested in the real world. The dark fermentation and SSMR models assume that the feedstock is always available and of good quality, but this may not always be the case. Economic evaluations rely on projected CAPEX/OPEX and market prices, which may vary due to geopolitical and macroeconomic influences. The retrofitted pipeline model assumes that hydrogen can be used with the materials that are already there. This needs to be proven through metallurgical testing and compliance with international safety standards (for example, ASME B31.12). Future work should include pilot-scale demonstration projects with local cooperatives and businesses, a lifecycle assessment (LCA) to find out how much good the projects do for the environment, policy suggestions for investment incentives and infrastructure support, and a study of the water supply needs for electrolysis and what that means for dry areas.

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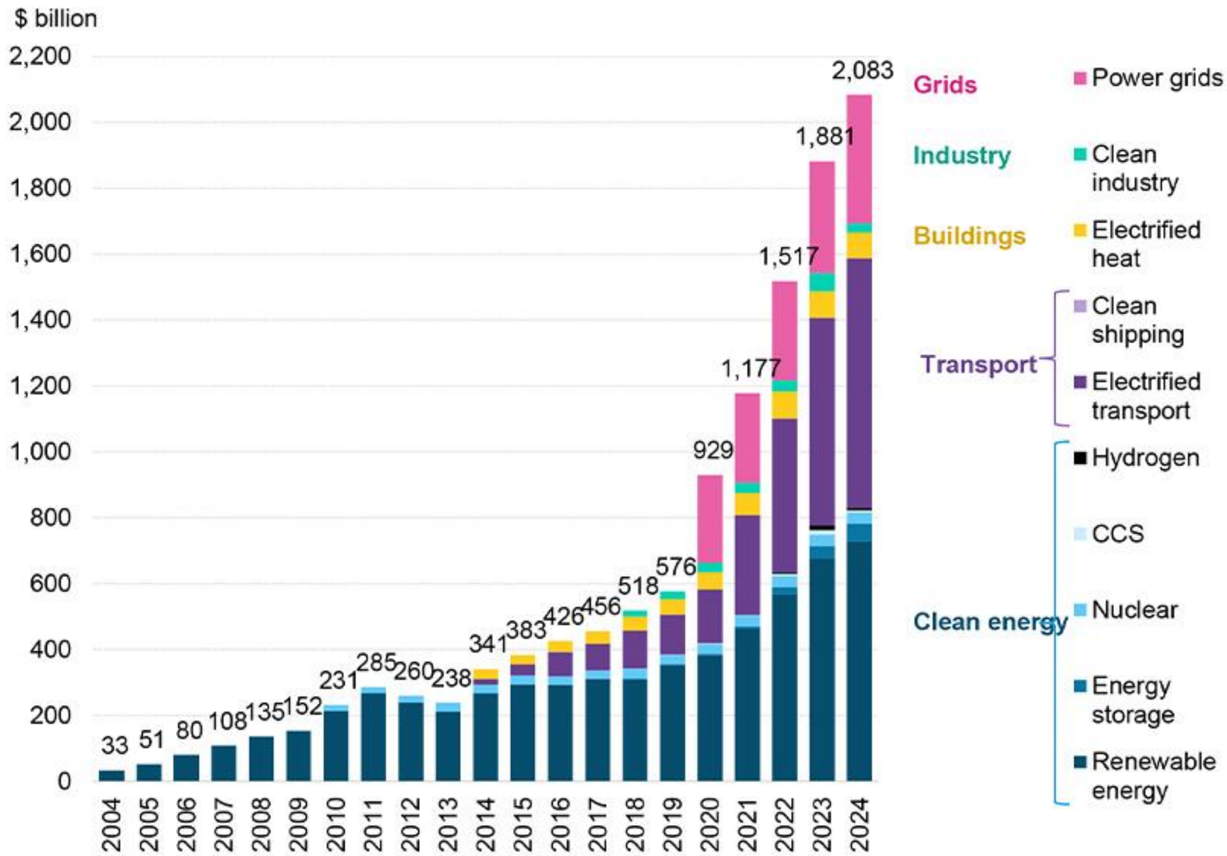
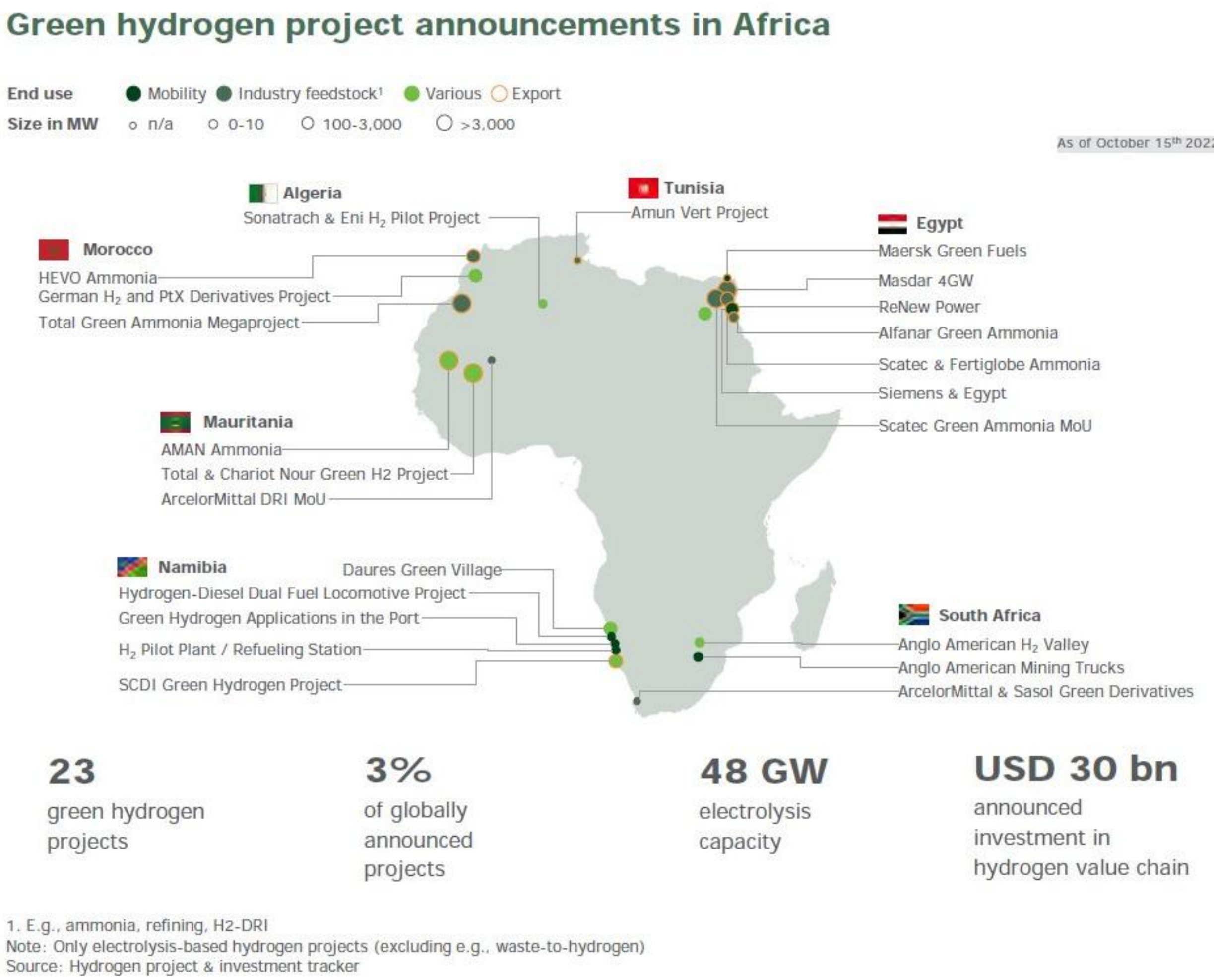
Appendices

Appendix A: Global energy transition. Adapted from Hydrogen



Appendix B: Green Hydrogen project announcements in Africa



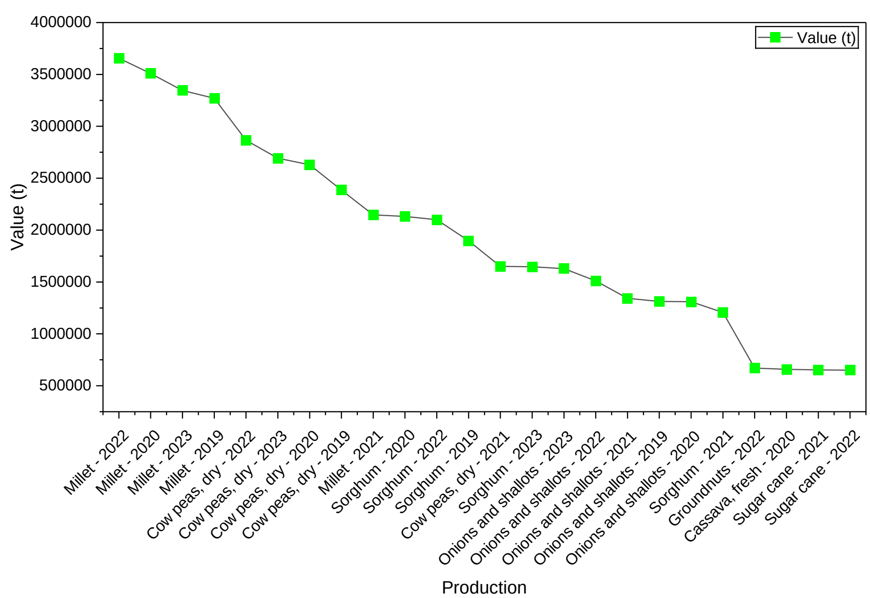
Appendix C: Biomass Potential in Africa

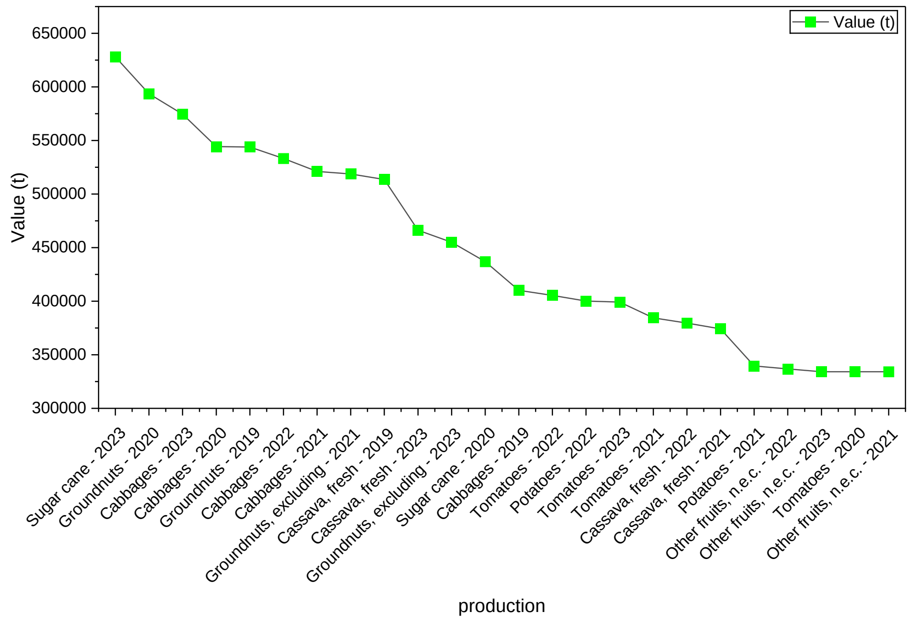
Country	1990 Population (thousands)	2025 Population (thousands)	Calorie Multiplier	Multiplication of Food Supply (MFS)
Algeria	24960	51830	1	2.08
Angola	9194	26619	130	3.76
Benin	4622	12354	1.02	2.73
Botswana	1238	2853	1	230
Burkina Faso	8993	22633	1.04	2.62
Burundi	5492	13392	1.16	2.84
Cameroon	11524	29262	1.05	2.67
Cape Verde	363	74	1	213
Chad	5553	12907	132	3.06
Comoros	543	1646	1.23	3.74
Congo	2229	5757	1	2.58
Cote d'Ivoire	11980	37942	1	3.17
Djibouti	440	1159	1	2.63
Equat. Guinea	352	798	1	227
Ethiopia	49831	130674	143	3.75
The Gambia	861	1875	101	2.2
Ghana	15020	37988	1.02	2.58
Guinea	5755	15088	1.05	2.76
Guinea-Bissau	964	1978	1	2.05
Kenya	23585	63826	1.08	291
Lesotho	1747	3783	1	217
Liberia	2515	7234	1	281
Libya	4545	12873	1	283
Madagascar	12010	33746	1.04	2.93
Mali	9214	24580	1.05	281
Mauritania	2024	4993	1	247
Mauritius	1075	1397	1	130
Morocco	25061	47477	1	1.89
Mozambique	14200	36290	141	3.6
Namibia	1439	3751	1.16	3.03
Niger	7731	21287	1.02	281
Rwanda	7027	20595	119	3.49
Senegal	7327	17078	1	233
Sierra Leone	4151	9800	1.25	295
Somalia	8677	23401	119	3.21
Sudan	25203	60602	1.16	2.8

Swaziland	751	1739	1	232
Tanzania	25993	74172	1.05	3
Togo	3531	9377	1.08	2.86
Tunisia	8057	13425	1	1.67
Uganda	17560	45933	1.09	2.84
Zaire	37391	104530	112	3.14
Zambia	8138	20981	1	258
Zimbabwe	9947	22889	1.04	2.4
Africa Total	641549	1580726	1.09	2.65

Appendix D: The various steps of the literature review

Appendix E: Agricultural Products of Niger Over Five Years




Value (t)
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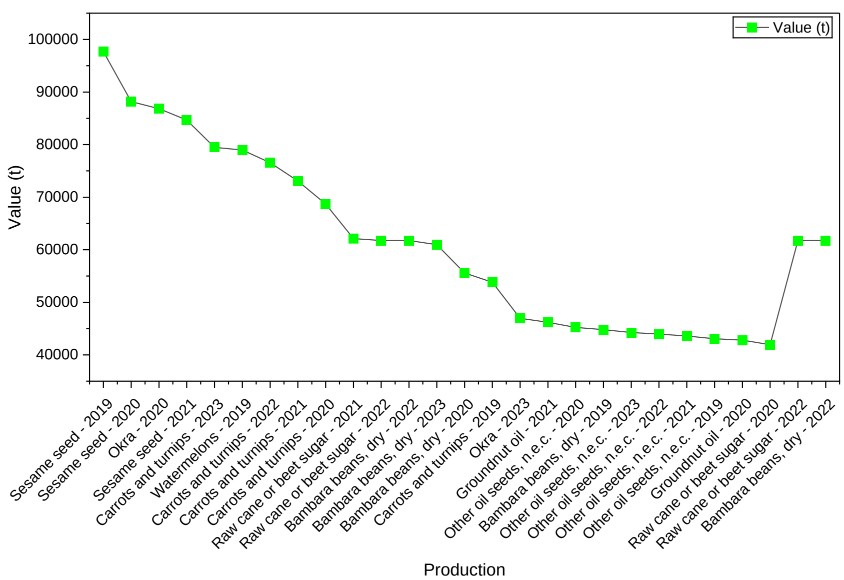
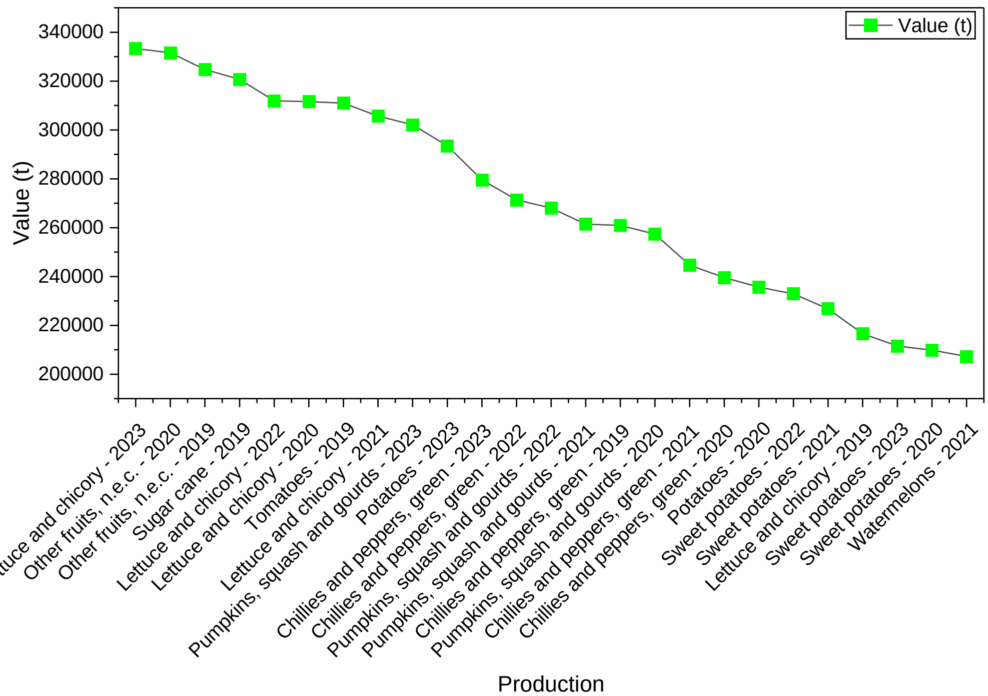
600000
550000
500000
450000
400000
350000
300000
Sugar cane - 2023
Groundnuts - 2020
Cabbages - 2023
Cabbages - 2020
Groundnuts - 2019
Cabbages - 2022
Cabbages - 2021
Groundnuts, excluding - 2021
Cassava, fresh - 2019
Cassava, fresh - 2023
Groundnuts, excluding - 2023
Sugar cane - 2020
Cabbages - 2019
Tomatoes - 2022
Potatoes - 2022
Tomatoes - 2023
Tomatoes - 2021
Cassava, fresh - 2022
Cassava, fresh - 2021
Potatoes - 2021
Other fruits, n.e.c. - 2022
Other fruits, n.e.c. - 2023
Tomatoes - 2020
Other fruits, n.e.c. - 2021
production


Value (t)
100000
90000
80000
70000
60000
50000
40000
Sesame seed - 2019
Sesame seed - 2020
Okra - 2020
Sesame seed - 2021
Carrots and turnips - 2023
Watermelons - 2019
Carrots and turnips - 2022
Carrots and turnips - 2021
Carrots and turnips - 2020
Raw cane or beet sugar - 2021
Raw cane or beet sugar - 2022
Bambara beans, dry - 2022
Bambara beans, dry - 2023
Bambara beans, dry - 2020
Carrots and turnips - 2019
Okra - 2023
Groundnut oil - 2021
Other oil seeds, n.e.c. - 2020
Bambara beans, dry - 2019
Other oil seeds, n.e.c. - 2023
Other oil seeds, n.e.c. - 2022
Other oil seeds, n.e.c. - 2021
Other oil seeds, n.e.c. - 2019
Groundnut oil - 2020
Raw cane or beet sugar - 2020
Raw cane or beet sugar - 2022
Bambara beans, dry - 2022
Production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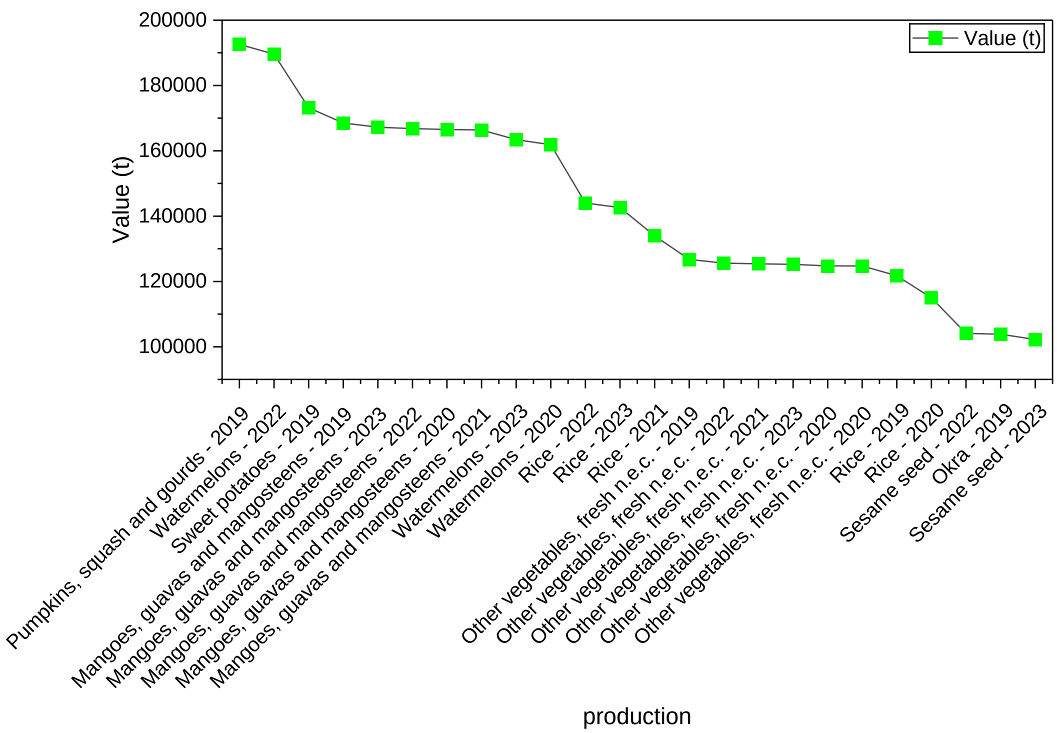
300000
280000
260000
240000
220000
200000
Value (t)
Lettuce and chicory - 2023
Other fruits, n.e.c. - 2020
Other fruits, n.e.c. - 2019
Sugar cane - 2019
Lettuce and chicory - 2022
Lettuce and chicory - 2020
Tomatoes - 2019
Lettuce and chicory - 2021
Pumpkins, squash and gourds - 2023
Potatoes - 2023
Chillies and peppers, green - 2023
Chillies and peppers, green - 2022
Pumpkins, squash and gourds - 2022
Pumpkins, squash and gourds - 2021
Chillies and peppers, green - 2019
Pumpkins, squash and gourds - 2020
Chillies and peppers, green - 2021
Chillies and peppers, green - 2020
Potatoes - 2020
Sweet potatoes - 2022
Sweet potatoes - 2021
Lettuce and chicory - 2019
Sweet potatoes - 2023
Sweet potatoes - 2020
Watermelons - 2021
Production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120000
100000
Value (t)
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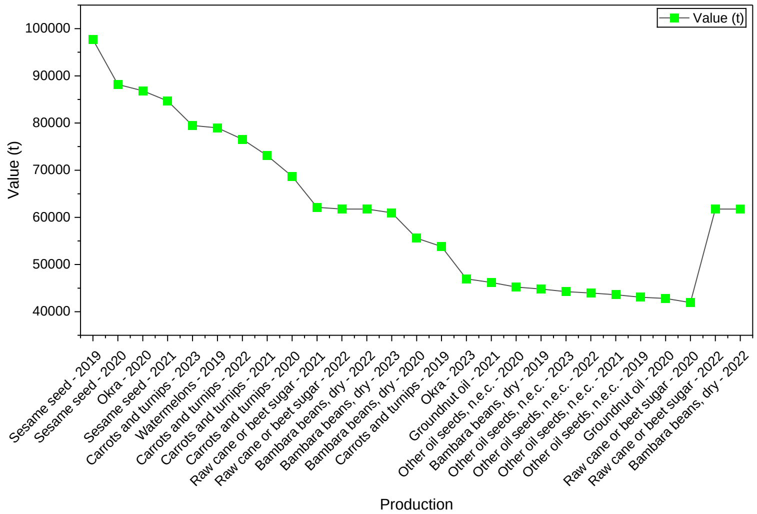
Watermelons - 2022
Sweet potatoes - 2019
Mangoes, guavas and mangosteens - 2019
Mangoes, guavas and mangosteens - 2023
Mangoes, guavas and mangosteens - 2022
Mangoes, guavas and mangosteens - 2020
Mangoes, guavas and mangosteens - 2021
Watermelons - 2023
Watermelons - 2020
Rice - 2022
Rice - 2023
Rice - 2021
Other vegetables, fresh n.e.c. - 2019
Other vegetables, fresh n.e.c. - 2022
Other vegetables, fresh n.e.c. - 2021
Other vegetables, fresh n.e.c. - 2023
Other vegetables, fresh n.e.c. - 2020
Other vegetables, fresh n.e.c. - 2020
Rice - 2019
Rice - 2020
Sesame seed - 2022
Okra - 2019
Sesame seed - 2023
production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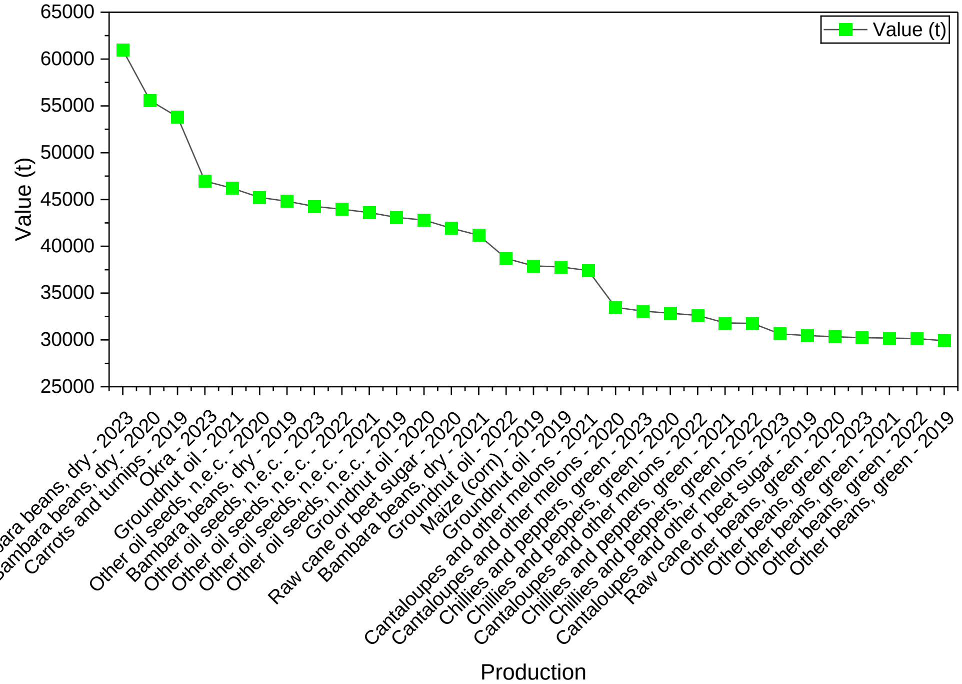
40000
Value (t)
Sesame seed - 2019
Sesame seed - 2020
Okra - 2020
Sesame seed - 2021
Carrots and turnips - 2023
Watermelons - 2019
Carrots and turnips - 2022
Carrots and turnips - 2021
Carrots and turnips - 2020
Raw cane or beet sugar - 2021
Raw cane or beet sugar - 2022
Bambara beans, dry - 2022
Bambara beans, dry - 2023
Bambara beans, dry - 2020
Carrots and turnips - 2019
Okra - 2023
Groundnut oil - 2021
Other oil seeds, n.e.c. - 2020
Bambara beans, dry - 2019
Other oil seeds, n.e.c. - 2023
Other oil seeds, n.e.c. - 2022
Other oil seeds, n.e.c. - 2021
Other oil seeds, n.e.c. - 2019
Groundnut oil - 2020
Raw cane or beet sugar - 2020
Raw cane or beet sugar - 2022
Bambara beans, dry - 2022
Production


Value (t)
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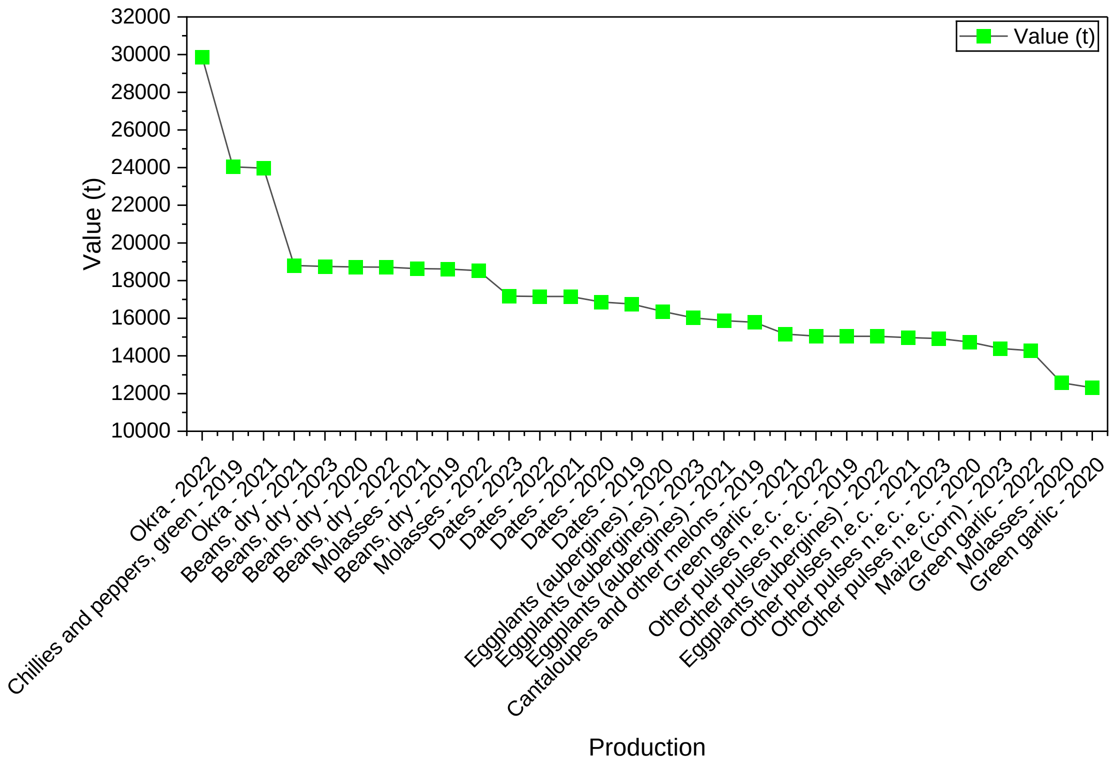
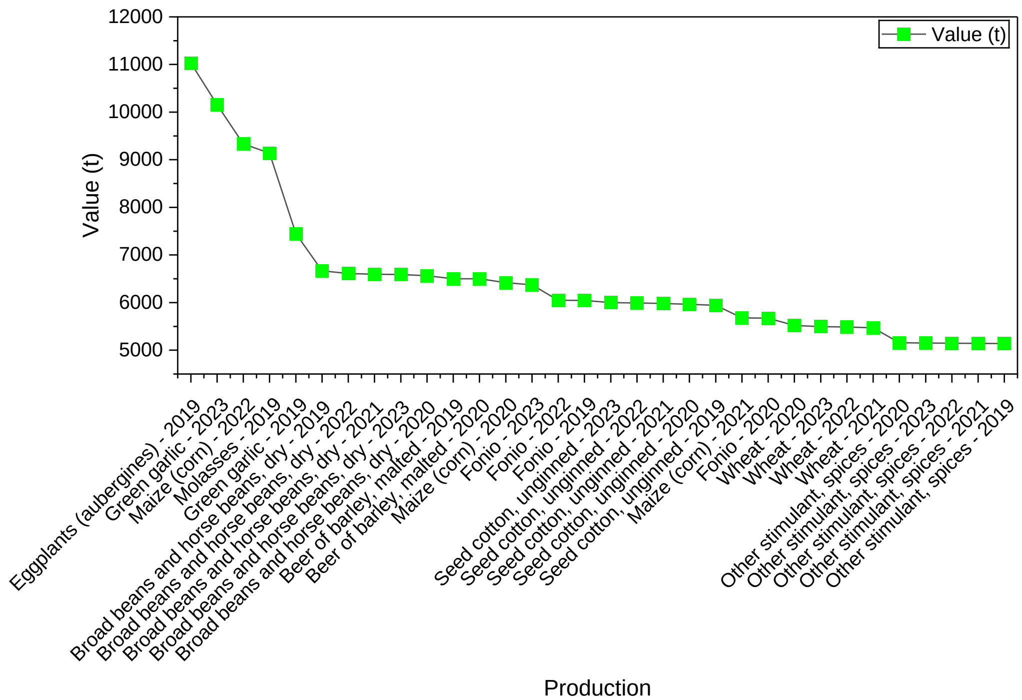
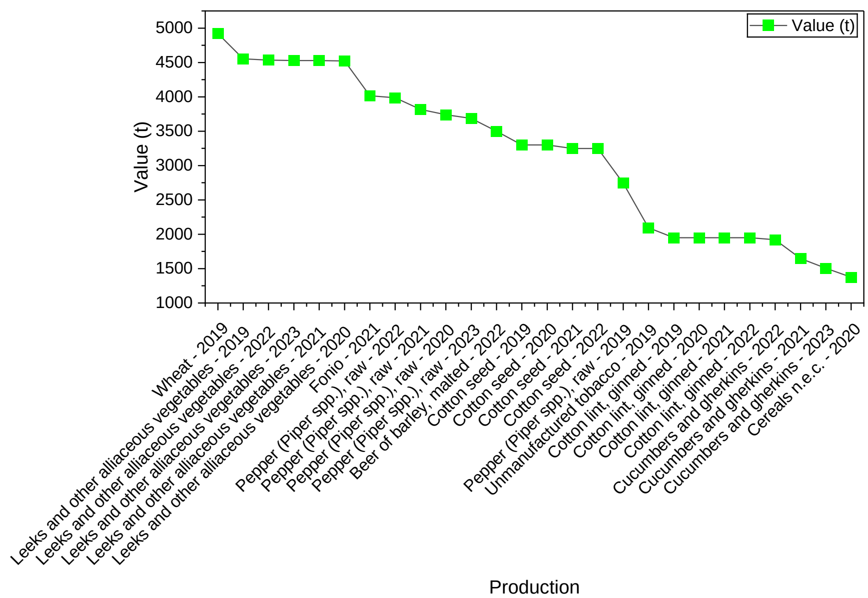
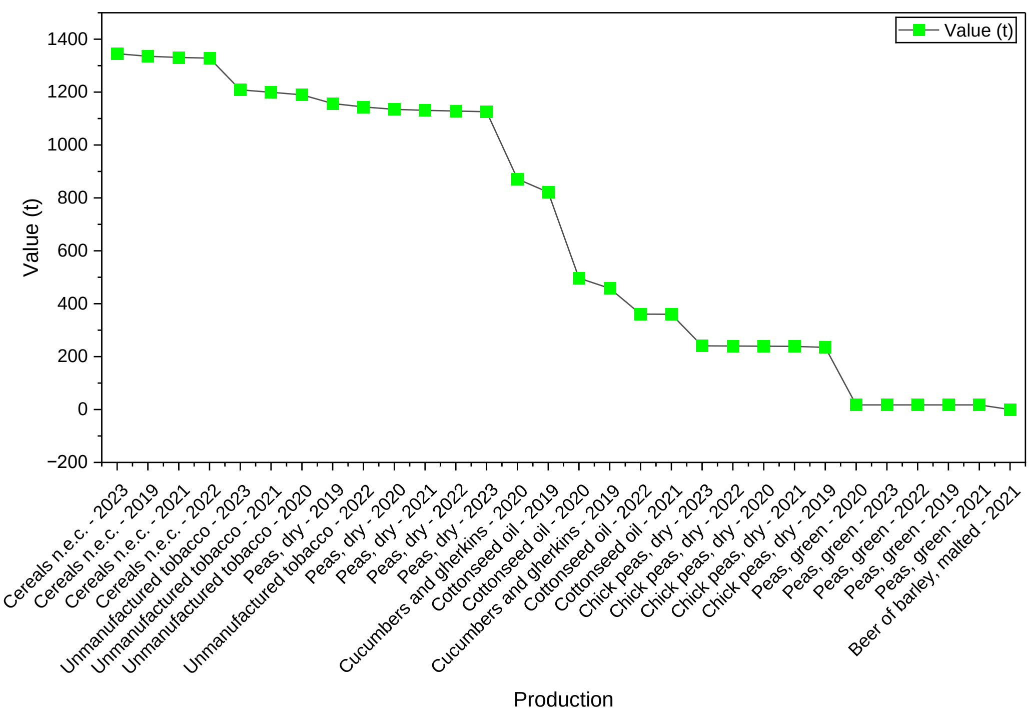
55000
50000
45000
40000
35000
30000
25000
Value (t)
Bambara beans, dry - 2023
Bambara beans, dry - 2020
Carrots and turnips - 2019
Okra - 2023
Groundnut oil - 2021
Other oil seeds, n.e.c. - 2020
Bambara beans, dry - 2019
Other oil seeds, n.e.c. - 2023
Other oil seeds, n.e.c. - 2022
Other oil seeds, n.e.c. - 2021
Other oil seeds, n.e.c. - 2019
Groundnut oil - 2020
Raw cane or beet sugar - 2020
Bambara beans, dry - 2021
Groundnut oil - 2022
Maize (corn) - 2019
Groundnut oil - 2019
Cantaloupes and other melons - 2021
Cantaloupes and other melons - 2020
Chillies and peppers, green - 2023
Chillies and peppers, green - 2020
Cantaloupes and other melons - 2022
Chillies and peppers, green - 2021
Chillies and peppers, green - 2022
Cantaloupes and other melons - 2023
Raw cane or beet sugar - 2019
Other beans, green - 2020
Other beans, green - 2023
Other beans, green - 2021
Other beans, green - 2022
Other beans, green - 2019
Production


Value (t)
Value (t)
Production
Okra - 2022
Chillies and peppers, green - 2019
Okra - 2021
Beans, dry - 2021
Beans, dry - 2023
Beans, dry - 2020
Beans, dry - 2022
Molasses - 2021
Beans, dry - 2019
Molasses - 2022
Dates - 2023
Dates - 2022
Dates - 2021
Dates - 2020
Dates - 2019
Eggplants (aubergines) - 2020
Eggplants (aubergines) - 2023
Eggplants (aubergines) - 2021
Cantaloupes and other melons - 2019
Green garlic - 2021
Other pulses n.e.c. - 2022
Other pulses n.e.c. - 2019
Eggplants (aubergines) - 2022
Other pulses n.e.c. - 2021
Other pulses n.e.c. - 2023
Other pulses n.e.c. - 2020
Maize (corn) - 2023
Green garlic - 2022
Molasses - 2020
Green garlic - 2020


Value (t)
Value (t)
Production
Eggplants (aubergines) - 2019
Green garlic - 2023
Maize (corn) - 2022
Molasses - 2019
Green garlic - 2019
Broad beans and horse beans, dry - 2019
Broad beans and horse beans, dry - 2022
Broad beans and horse beans, dry - 2021
Broad beans and horse beans, dry - 2023
Broad beans and horse beans, dry - 2020
Beer of barley, malted - 2019
Beer of barley, malted - 2020
Maize (corn) - 2020
Fonio - 2023
Fonio - 2022
Fonio - 2019
Seed cotton, unginned - 2023
Seed cotton, unginned - 2022
Seed cotton, unginned - 2021
Seed cotton, unginned - 2020
Seed cotton, unginned - 2019
Maize (corn) - 2021
Fonio - 2020
Wheat - 2020
Wheat - 2023
Wheat - 2022
Wheat - 2021
Other stimulant, spices - 2020
Other stimulant, spices - 2023
Other stimulant, spices - 2022
Other stimulant, spices - 2021
Other stimulant, spices - 2019


Value (t)
Production
Wheat - 2019
Leeks and other alliaceous vegetables - 2019
Leeks and other alliaceous vegetables - 2022
Leeks and other alliaceous vegetables - 2023
Leeks and other alliaceous vegetables - 2021
Leeks and other alliaceous vegetables - 2020
Fonio - 2021
Pepper (Piper spp.), raw - 2022
Pepper (Piper spp.), raw - 2021
Pepper (Piper spp.), raw - 2020
Pepper (Piper spp.), raw - 2023
Beer of barley, malted - 2022
Cotton seed - 2019
Cotton seed - 2020
Cotton seed - 2021
Cotton seed - 2022
Pepper (Piper spp.), raw - 2019
Unmanufactured tobacco - 2019
Cotton lint, ginned - 2019
Cotton lint, ginned - 2020
Cotton lint, ginned - 2021
Cotton lint, ginned - 2022
Cucumbers and gherkins - 2022
Cucumbers and gherkins - 2021
Cucumbers and gherkins - 2023
Cereals n.e.c. - 2020


Value (t)
Production
Cereals n.e.c. - 2023
Cereals n.e.c. - 2019
Cereals n.e.c. - 2021
Cereals n.e.c. - 2022
Unmanufactured tobacco - 2023
Unmanufactured tobacco - 2021
Unmanufactured tobacco - 2020
Peas, dry - 2019
Unmanufactured tobacco - 2022
Peas, dry - 2020
Peas, dry - 2021
Peas, dry - 2022
Peas, dry - 2023
Cucumbers and gherkins - 2020
Cottonseed oil - 2019
Cottonseed oil - 2020
Cucumbers and gherkins - 2019
Cottonseed oil - 2022
Cottonseed oil - 2021
Chick peas, dry - 2023
Chick peas, dry - 2022
Chick peas, dry - 2020
Chick peas, dry - 2021
Chick peas, dry - 2019
Peas, green - 2020
Peas, green - 2023
Peas, green - 2022
Peas, green - 2019
Peas, green - 2021
Beer of barley, malted - 2021

Appendix F: Hydrogen Properties

Table 2. **Hydrogen Properties**

	U.S. Units	SI Units
Chemical formula	H_2	H_2
Molecular weight	2.016	2.016
NFPA rating	Health=0 Flammability=4 Instability=0	
DOT classification	2.1	
EPA list of lists	No	
Vapor pressure at −423°F (−252.8°C)	14.69 psia	101.283 kPa
Density of the gas at boiling point and 1 atm	0.083 lb/ft^3	1.331 kg/m^3
Specific gravity of the gas at 32°F and 1 atm (air=1)	0.0696	0.0696
Specific volume of the gas at 70°F (21.1°C) and 1 atm	192.0 ft^3/lb	11.99 m^3/kg
Specific gravity of the liquid at boiling point and 1 atm	0.0710	0.0710
Density of the liquid at boiling point and 1 atm	4.23 lb/ft^3	67.76 kg/m^3
Boiling point at 14.69 psia (101.283 kPa)	−423.0°F	−252.8°C
Melting point at 14.69 psia (101.283 kPa)	−434.5°F	−259.2°C
Critical temperature	−399.8°F	−239.9°C
Critical pressure	188 psia	1296.212 kPa, abs
Critical density	1.88 lb/ft^3	30.12 kg/m^3
Triple point	−434.8°F at 1.021 psia	−259.3°C at 7.042 kPa, abs
Latent heat of fusion at triple point	24.97 Btu/lb	58.09 kJ/kg
Latent heat of vaporization at boiling point	191.7 Btu/lb	446.0 kJ/kg
Specific heat of the gas at 70°F (21.1°C) and 1 atm		
C_p	3.425 Btu/(lb)(°F)	14.34 kJ/(kg)(°C)
C_v	2.418 Btu/(lb)(°F)	10.12 kJ/(kg)(°C)
Ratio of specific heats	1.42	1.42
Solubility in water vol/vol at 60°F (15.6°C)	0.019	0.019
Flammable limits in air	4% to 75%	
Air required for combustion	-	
Autoignition temperature	752°F	400°C

[107]

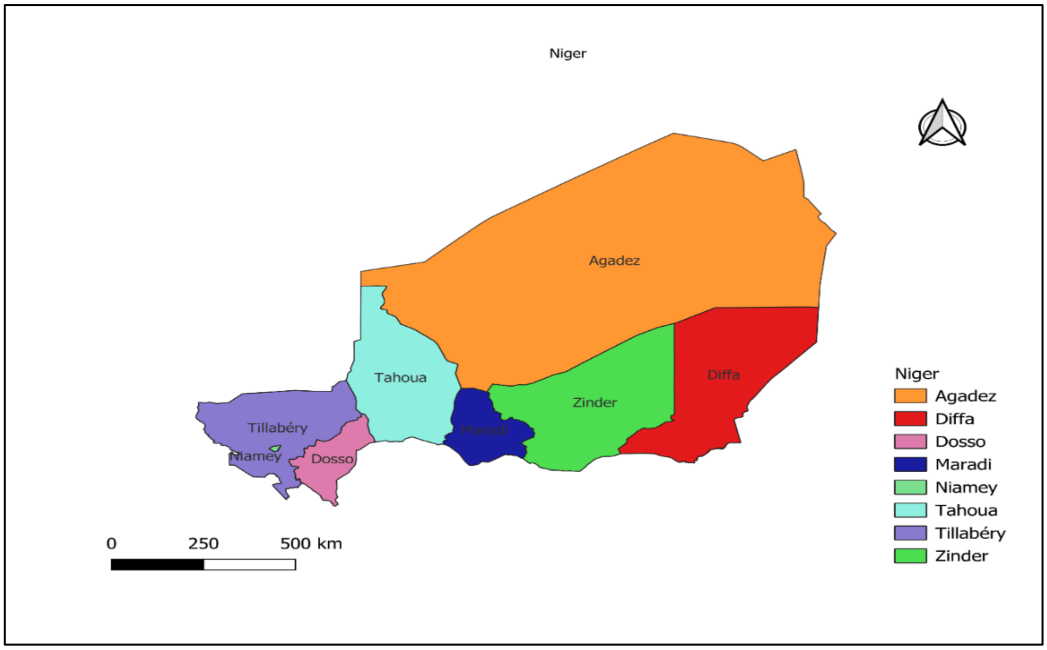
Appendix G: Cellulose, Hemicellulose, and Lignin Content of Selected Crops

Crop	Biomass residue	Type of residue	cellulose (%)	Amount of cellulose	Hemicellulose (%)	Amount of hemicellulose	lignin (9 %)	Amount of lignin	References
sweet potato	901310.28	Pells	33.00 %	297432.3924	0.33	297432.3924	11.7	10545330.3	[130]
Cassava	1148126.47	pells	37.90 %	435139.9321	0.37	424806.7939	7.5	8610948.53	[22]
sugarcane	1230217.54	Baggase	50.00 %	615108.77	0.23	276798.9465	21	25834568.3	[131]
Groundnut	2086512.74	stalks	36.28 %	756986.8221	0.32	676030.1278	20.12	41980636.3	[132]

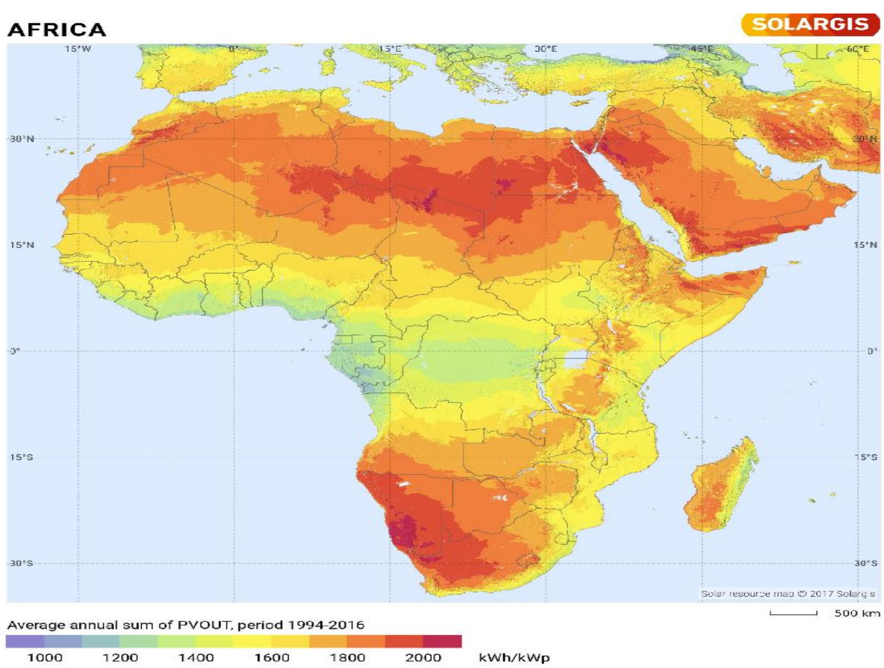
Appendix H: Annual Livestock Slaughter and Blood Yield per Animal (2019)

Month	Calves	Heifers	Cattle_Total	Sheep_Total	Goats_Total	Camels_Total	Pigs_Total
Total 2019	28631	3556	196885	618307	1288069	36129	724
blood (Litter)/ animal	2.9	12.6	16500	1.5	1320	37.1	2.93
refferences	[133]	[133]	[134]	[134]	[134]	[135]	[136]

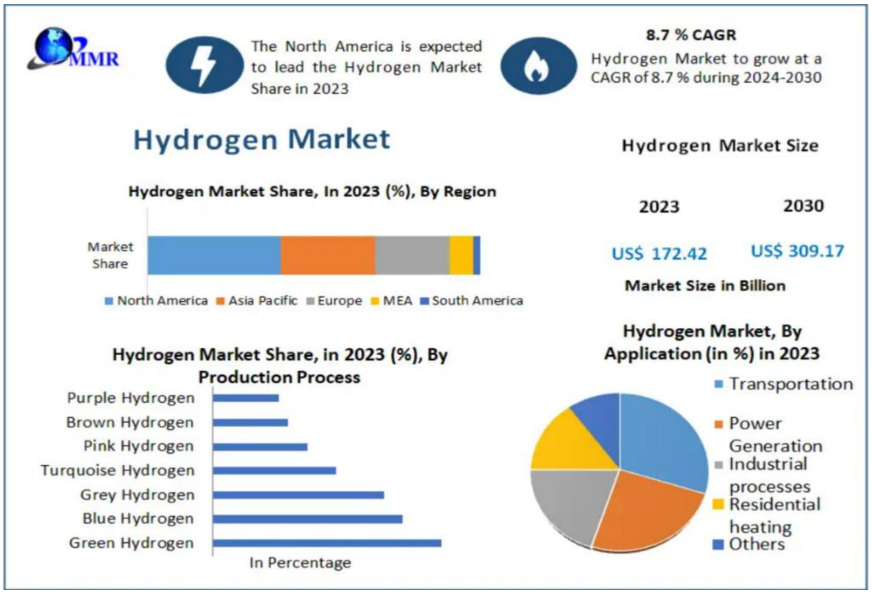
Appendix I: Administrative Regions of Niger



Appendix J: Africa's Solar Potential



Appendix K: Global Hydrogen Market Outlook in 2023



Appendix L : African countries that include hydrogen in their NDCs under the Paris Agreement and ongoing or planned hydrogen projects adapted to [137].