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SPECIALITY: BIOENERGY BIOFUELS AND GREEN HYDROGEN TECHNOLOGY

MASTER THESIS

STRATEGY DEVELOPMENT BASED ON THE HYDROGEN BUSINESSES IN CÔTE D'IVOIRE

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

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DEDICATION

First and foremost, I dedicate this work to God, who has blessed, protected, and bestowed upon me the strength to accomplish it.

Additionally, I wholeheartedly dedicate this work to my mother Ama, and father Koffi for their continuous support, encouragement, valuable advice, and prayers throughout my academic journey.

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DECLARATION

I declare that this work has been carried out by me and all data derived from the literature has been duly acknowledged and referenced.

ABSTRACT

Côte d'Ivoire has substantially neglected crop residues from farms in rural areas. This study aims to provide strategies for the sustainable conversion of crop residues to hydrogen. Using existing data and theoretical approaches, up to 16,801,306 tons of crop residues of 11 crop types were available in Côte d'Ivoire in 2019. These residues are dominated by the cashew sector in the northern regions with Béré region (929,200 tons) and Gbeke region (652,800 tons), Follow by cocoa in the West and Southwest regions. Guémon and San Pedro regions have the highest cocoa residues and account for 1,841,700 tons and 1,820,000 tons respectively. A theoretical energy and hydrogen potential of 273,387,320 gigajoules and 1,296,424.84 tons were respectively estimated from the crop residues. Technically, 907,497.39 tons of hydrogen is expected each year. Three scenarios of hydrogen project implementation have been developed and indicate that the Ivorian industries can be supplied with 9,026,635 gigajoules of heat. Moreover, 17,910 cars and 4,732 buses can be supported in the transport sector. It is estimated that 817,293.95 tons of green ammonia for farmers can be supply. Five million, seven hundred twenty-seven thousand, nine hundred ninety-two (5,727,992) households are expected to have access to 1,718.40 gigawatts of electricity. Due to these changes in transport, energy, industry and agricultural sectors, a reduction of 1,644,722.08 tons of carbone dioxide per year can be achieved theoretically. With the scenarios, some 263,276.87 tons of hydrogen are exportable to other countries. Conversion of crop residues to hydrogen is a promising opportunity with environmental and socio-economic impact. Therefore, the usage of these residues in Côte d'Ivoire requires further extensive research.

Keywords: Côte d'Ivoire; strategy; business; hydrogen; crop residues.

RESUMÉ

La Côte d'Ivoire possède d'importants résidus de cultures négligés provenant des fermes des zones rurales. Cette étude vise à proposer des stratégies pour la conversion durable des résidus de culture en hydrogène. En utilisant les données existantes et les approches théoriques, jusqu'à 16.801.306 tonnes de résidus émanant de 11 types de cultures étaient disponibles en Côte d'Ivoire en 2019. Ces résidus sont diversifiés et dominés par le secteur de l'anacarde dans les régions du nord avec la région de Béré (929.200 tonnes) et la région de Gbeke (652.800 tonnes). Suivi par le cacao dans les régions de l'Ouest et du Sud-Ouest. La région du Guémon et de San Pedro ont les résidus de cacao les plus élevés et représentent respectivement 1.841.700 tonnes et 1.820.000 tonnes. Un potentiel théorique d'énergie et d'hydrogène de 273.387.320 giga joules et 1.296.424,84 tonnes ont été estimés respectivement à partir des résidus de culture. Techniquement, 907.497,39 tonnes d'hydrogène sont attendus chaque année. Trois scénarios de mise en œuvre du projet hydrogène ont été développés et indiquent que les industries ivoiriennes peuvent être approvisionnées avec 9.026.635 giga joules d'énergie calorifique. En outre, 17.910 voitures à hydrogène et 4.732 bus à hydrogène peuvent être pris en charge dans le secteur du transport. Un approvisionnement de 817.293,95 tonnes d'ammoniac vert (engrais) est possible pour les agriculteurs. Cinq millions sept cent vingt-sept mille neuf cent quatre-vingt-douze (5.727.992) foyers devraient avoir accès à 1.718,40 gigawatts d'électricité. Suite à ces changements dans les secteurs du transport, de l'énergie, de l'industrie et de l'agriculture, il est possible théoriquement d'avoir une réduction de 1.644.722,08 tonnes de dioxyde de carbone par an. Avec les scénarios, quelque 263.276,87 tonnes d'hydrogène sont exportables vers d'autres pays. La conversion des résidus de culture en hydrogène est une opportunité prometteuse avec un impact environnemental et socio-économique. Par conséquent, l'utilisation de ces résidus en Côte d'Ivoire nécessite des recherches approfondies.

Mots-clés : Côte d'Ivoire; stratégie; entreprise; hydrogène; résidus agricoles.

ACRONYMS AND ABBREVIATIONS

AGHA	Africa Green Hydrogen Alliance
CH_3COOH	Acetic acid
CCS	Carbon Capture and Storage
CH_4	Methane
CO_2	Carbon dioxide
COP21	Conference of the Parties 21
ECOWAS	Economic Community of West African States
EU	European Union
FCA	African Financial Community
FCEVs	Fuel Cell Electric vehicles
GDP	Gross Domestic Product
GJ	Gigajoule
GW	Gigawatts
GWh	Gigawatts-hour
H_2	Hydrogen
IPCC	Intergovernmental Panel on Climate Change
Kg/m^3	kilogram per cubic meter
LHV	Lower heating value
MJ/L	Mega joule per liter
MtH_2	Million tons of Hydrogen
N_2O	Nitrous Oxide
NGO	Non-Governmental Organization
NH_3	Ammonia
QGIS	Quantum Geographic Information System
SIFCA	International Society of Plantations of Rubber and Oils of Côte d'Ivoire
SMR	Steam Methane Reforming
SODEN	New Energies Society
TWh	Terawatt hour
UK	United Kingdom
US	United States
WASCAL	West African Science Service Centre on Climate Change and Adapted Land Use

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INTRODUCTION

Energy is an essential and indispensable element for humans as it contributes significantly to sustainable development. It is involved in all sectors of activity such as education, health, access to water, infrastructure, agriculture, livelihoods, and the environment. Energy stimulates the development of nations and increases economies. According to IRENA. (2023), global energy demand is rapidly increasing and the actual energy consumption is heavily governed by the use of fossil fuels such as oil, coal, natural gas, etc. These primary sources of energy are depleting due to their constant exploitations. In addition, their utilization has dramatically changed the climate patterns leading to global warming that has a negative impact on planet Earth. In fact, along the value chain of fossil fuels, from extraction to end use, there is a considerable stock of greenhouse gas emissions such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emitted into the atmosphere. To date, frequent floods, droughts, heatwaves, severe hurricanes, and rising sea levels are increasing public health risks, water crises, food insecurity, perturbation in natural ecosystems, and displacement of people, etc. (Dhakal et al., 2022). Climate change is an issue for all the nations in the world and dramatically affects the environment, society, and worldwide economy (Abbass et al., 2022; Feliciano et al., 2022; Leal Filho et al., 2021).

The need for innovation in the global energy system has been revealed by scientific communities since. Therefore, the use of clean, affordable, and reliable energy sources will cope with the aforementioned disasters and provide a better life. To achieve this, 194 countries decided to tackle climate change during the Paris Agreement in 2015 at the Conference of the Parties (COP21) by limiting global warming to 1.5°C (Riester et al., 2022). Thus, renewable energies have become an indispensable subject of discussion in the energy sector nowadays. Renewable energies are naturally available, clean, environmentally friendly, and continuously replenished at the human scale after their consumption. Solar energy, wind energy, hydro energy, tidal energy, geothermal energy, and biomass energy are the most popular sources that are currently in progressive implementation around the world. Meanwhile, these non-conventional energy sources although clean and limitless, face huge impediments in their rapid deployment. These challenges are at technological, financial, social, and political levels. For example, the high investment cost of setting up a wind or solar farm prevents people, particularly in Africa, from moving away from fossil fuels. Moreover, most renewable energy operates intermittently. By way of example, the sun does not shine during the night for this reason there is a need for a storage system when relying on solar energy (Wells et al., 2022).

Alternatively, hydrogen as a vital energy carrier can be produced using solar energy (photovoltaic system), biomass or other renewable energy sources. The hydrogen generated can be stored and used at anytime and anywhere in industries, transport, buildings etc. Hydrogen is expected to be the main energy carrier of a sustainable energy system for tomorrow's society. There are many ways to produce hydrogen, however, currently, worldwide hydrogen production depends on the steam methane reforming (SMR) process. This usually involves the use of fossil fuels with their devastating impact on the environment (Moorea et al., 2022). Yet, biomass is a promising source that has the potential to speed up the development of hydrogen as a key fuel for the future. Because it is abundant, renewable, and environmentally friendly. Biomass is defined as the fraction of biodegradable products, waste, and residues from agriculture, plants, animal substances, households, industries etc. (Kalak, 2023). The conversion of biomass into hydrogen can be done through biological or thermochemical processes.

Different countries including Germany, the United Kingdom, the United States, European countries, South Africa etc. are developing hydrogen economies in their national strategies in order to foster and meet the net zero target (Umbach & Pfeiffer, 2020). Hydrogen-related activities have a wide range of opportunities such as the creation of new jobs, research and development, capacity development, technology transfer, public-private partnerships, and even the attraction of many investors. Furthermore, hydrogen can decarbonize the electricity, transport, and industrial sectors.

Like other countries, Côte d'Ivoire seeing that its energy consumption is strongly dependent on fossil fuels has taken a commitment to sustainable development. The potential of renewable resources for hydrogen production is highly available. The country could build a solid economy around the development of the hydrogen market, not only boosting the growth of its economy but also reducing the dependence on fossil fuels. For instance, recently many events regarding the renewable energies sector were held in the country. This is to help raising awareness and take some important decisions about the deployment of hydrogen. Among those events, the Africa Green Hydrogen Forum organized on 26 and 27 September 2022 in Abidjan gathered governments, stakeholders, experts, and international private companies from Egypt, Kenya, Mauritania, Morocco, Namibia, South Africa, and other countries across the world to discuss the policies, technological aspects, export opportunities, market potential and the role of green hydrogen in Africa (African Development Bank Group, 2022).

Problem statement

Although, Côte d'Ivoire has potential resources (hydroelectricity, biomass, solar radiation, etc.) for hydrogen production however, its energy capacity still depends mainly on fossil fuels. The four major thermal power plants installed in Azito, Ciprel, Aggreko and Vridi accounts for about sixty-one percent (61%) of total energy production. Therefore, carbon dioxide emissions will continue to increase. In addition, there is no a comprehensive strategy for the development of hydrogen companies. First, news about hydrogen to the general public is not disseminated. Therefore, hydrogen is almost unknown in Côte d'Ivoire. Media, stakeholders, and decision-makers hardly talk about hydrogen. Currently, the country does not have a solid and concrete policy adapted to the development of hydrogen companies. This does not encourage investors to come and build industries. One can only mention iH2-IVOIRE, a private company specializing in the development of hydrogen in Africa. There is a lack of real public-private partnerships in the hydrogen field. Furthermore, the absence of hydrogen production infrastructure, storage infrastructure, refueling stations and distribution networks is also a fundamental issue. This constitutes a major obstacle to the development of hydrogen technologies. Beyond all these challenges, Côte d'Ivoire does not have a skilled workforce of local talent with expertise in hydrogen-related fields. Apart from the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL), which has been training a few young students since 2021 in its international master program in energy and green hydrogen technology. In general, there is a lack of skills training programs, technical education initiatives and knowledge sharing platforms that enable youth to learn about technology. Besides, the universities in Côte d'Ivoire have not yet integrated the hydrogen track into their program hence, lack of research and development. On top of that though the country's economy is strongly based on agriculture yet crop residues are not valorized. The lack of local industries for the transformation of raw products prevents the farmers from fully processing the agricultural wastes. In most cases, after harvesting the main crops, the residues are abandoned in the different fields. Addressing all these challenges is crucial to an efficient and sustainable energy plan.

Research objectives

This study aims to propose a comprehensible strategic plan for the sustainable conversion of biomass to hydrogen in Côte d'Ivoire.

Specifically:

- To assess the potential of biomass resources in Côte d'Ivoire.
- To evaluate the energy and hydrogen potential of available biomass in Côte d'Ivoire
- To develop scenarios based on the utilization of hydrogen in Côte d'Ivoire
- To analyze the impact of the scenarios.

Research questions

To reach these objectives, four research questions are to be addressed:

- ✓ What is the biomass potential in Côte d'Ivoire?
- ✓ Will biomass generate enough energy and hydrogen?
- ✓ What are the different scenarios?
- ✓ What will be the impacts of the scenarios?

Structure of the study

The study is organized into three main chapters. The first part of the work is dedicated to the introduction where the state of the current energy demand and consumption is highlighted. The emissions of greenhouse gases and their consequences are shown. Moreover, alternative solutions are presented. This part encompasses the problem, the objectives of the study, and the research questions. Chapter one defines what is hydrogen and its properties, the different routes of production, the storage and distribution mode along with the various sectors of utilization. It ends up with an overview of the current hydrogen strategies and projects in some countries across the world as well as the state of the art of hydrogen development in various sectors in Côte d'Ivoire. In the chapter two, the methodology used to conduct this study is presented. Moreover, chapter three highlights the results found according to the different objectives followed by important discussions. Finally, the conclusion, and recommendations are drawn in the last part of the work.

CHAPTER 1: STATE OF KNOWLEDGE

1.1. Introduction

This chapter will first show the value chain of hydrogen from production to end used. Secondly it gives a global review of the current strategies and projects of hydrogen developed or in development across the world. Finally, the advancement of hydrogen related businesses in Côte d'Ivoire will be presented.

1.2. Definition and properties of hydrogen

Hydrogen is a chemical element with the symbol H and occupies the first position in the periodic table. Being constituted of one electron and one proton, hydrogen is the lightest and the most abundant element in the universe. It is an energy carrier, not an energy source and forms a diatomic gas H_2 which is highly colorless, tasteless, odorless, combustible, nontoxic, and non-metallic. Apart from that, hydrogen does not exist alone in nature, it always binds with other chemical compounds such as oxygen, carbone, nitrogen etc. (Mäkelä, 2021). The extraction of hydrogen requires various technics. The physical properties of hydrogen are depicted in Table 1.

Table 1: Physical properties of hydrogen. Adapted from (IEA, 2019)

Property	**Hydrogen**
Density (gaseous)	0.089 kg/m^3 (0°C,1bar)
Density (liquid)	70.79 kg/m^3 (-253°C, 1 bar)
Boiling point	-252.76°C (1 bar)
Energy per unit of mass (LHV)	120 MJ/kg
Energy density (ambient cond., LHV)	0.01 MJ/L
Specific energy (liquefied, LHV)	8.5 MJ/L
Flame velocity	346 cm/s
Ignition range	4-77% in air by volume
Auto ignition temperature	585°C
Ignition energy	0.02J

1.3. Hydrogen production pathways

Hydrogen production requires different methods depending on the energy source used, whether renewable or fossil. According to IRENA. (2022), global hydrogen production is dominated by the use of fossil fuels, which accounts for about 95 percent. Specifically, almost 47% from natural gas, 21% from oil, 27% from coal. Consequently, only approximately 5% comes from water electrolysis. Hydrogen from fossil fuels costs 0.8-2.7 €/kg while renewable hydrogen costs 2.5-6.3 €/kg. The global production sits at around 75 MtH2/year as pure hydrogen and another 45 MtH2/year in mixing gases.

The production routes are referenced in various color-codes, green hydrogen is the cleanest and most environmentally friendly that is produced through renewable energy. Based on fossil fuel there is grey hydrogen which is from natural gas, or methane, using steam methane reforming process without capturing the carbon dioxide, but becomes blue hydrogen when the carbon is captured and stored (CCS). Furthermore, there is turquoise hydrogen from solid carbon through the methane pyrolysis process. Besides, black or brown hydrogen is generated by the use of black coal or brown coal (lignite) gasification process respectively, and pink hydrogen when nuclear energy is used as a source of electricity. Finally, hydrogen that occurs naturally from underground is assigned white hydrogen (Arcos & Santos, 2023). This natural hydrogen is discovered in many countries but in Africa it is found in Mali. Figure 1 summaries different pathways for hydrogen production.

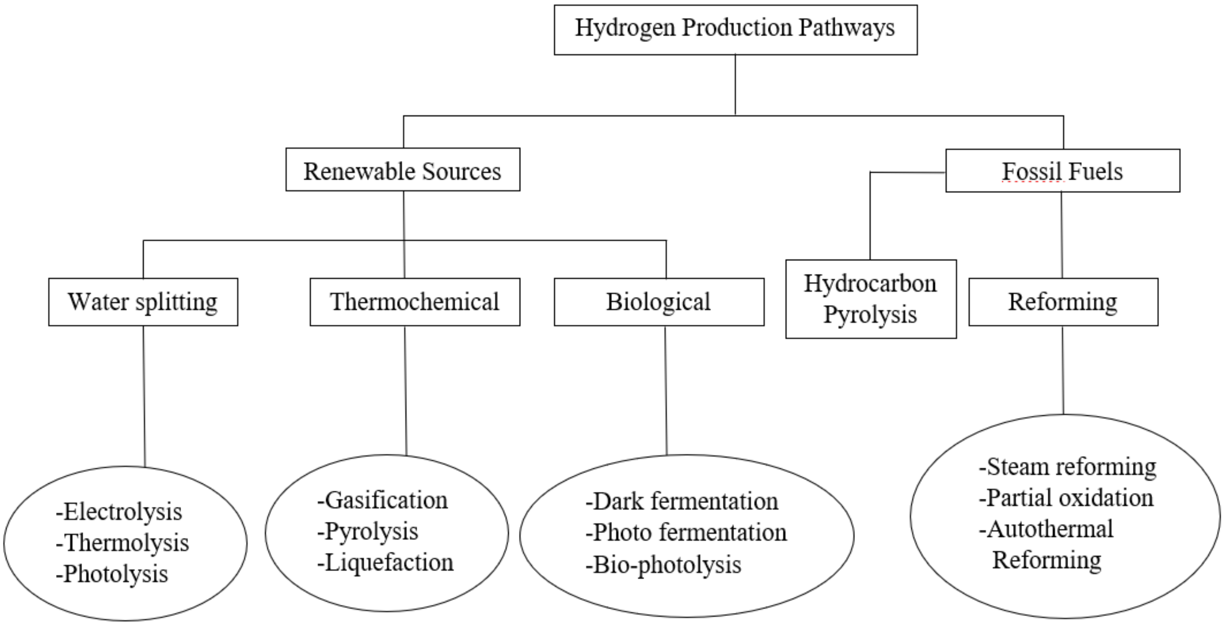


Figure 1: Hydrogen production pathways Adapted from (Strømholm & Rolfsen, 2021)

1.4. Hydrogen storage and distribution

Hydrogen gas has properties that require a suitable storage system at the production, transport, and end-use site. Although the hydrogen molecule has the highest energy value (LHV) (120 MJ/kg) on a mass basis, it is the lightest, and has high buoyancy and a very low density. For example, at room temperature and atmospheric pressure, 1 kg of hydrogen gas fills over 11 m^3 of tank , tubes or cylinder (Andersson & Grönkvist, 2019). In general hydrogen storage can be performed in two different categories. The first is the physical storage of hydrogen in the gaseous state. (Compressed gas at high-pressure 350-700 bar in a tank with a pressure of 350-1000 bar) or liquid state (cryogenic liquid with a temperature below −252.8°C, the boiling point of hydrogen). The liquid state occupies less space than compressed gas but require high energy for the liquefaction. On the other hand, the second category under which hydrogen can be stored is material based, including solid state compounds like porous materials, metal hydrides, and complex. Hydrogen can also be stored in chemical compounds such as ammonia and methanol. Besides that, there is a geological way in which hydrogen is stored underground in salt caverns (Yadav et al., 2022).The various options for hydrogen storage are illustrated in Figure 2.

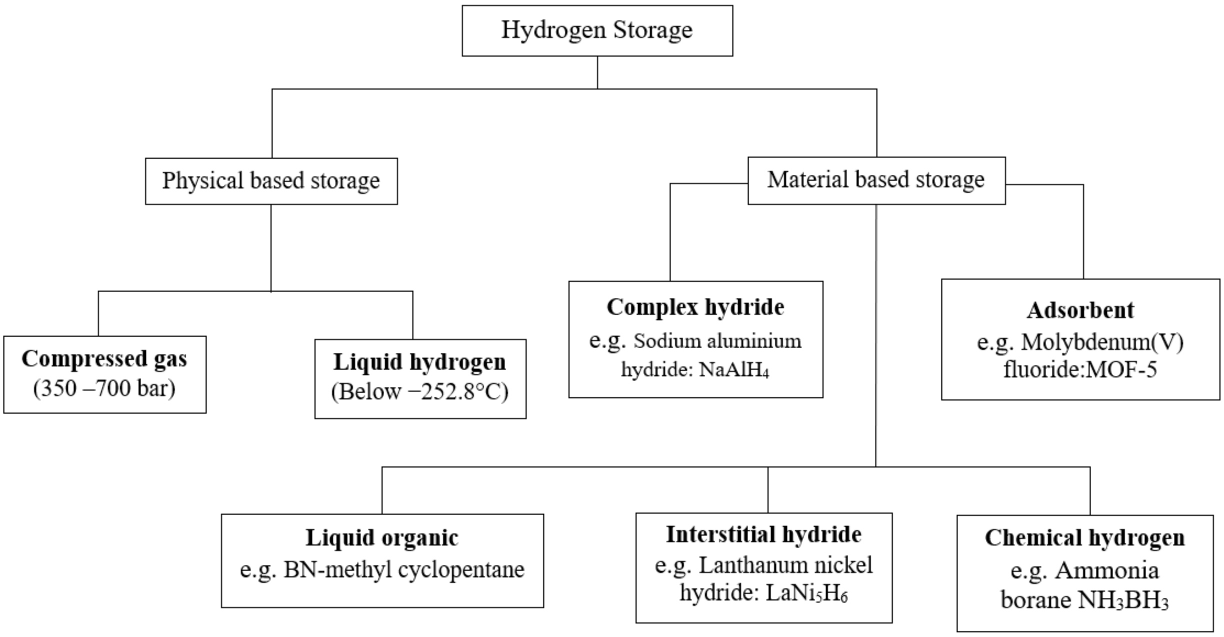


Figure 2: Different methods for hydrogen storage. Adapted from (Jain & Kandasubramanian, 2020)

Hydrogen transportation modes depend on the distance. For relatively short distances, gaseous and liquid hydrogen are stored in small or large containers and transported by road and rail from one place to another using trailers or trucks. But, for very long distances, hydrogen can be transported by ship or pumped through a pipeline. Though it is possible currently only ten percent of hydrogen can be injected into the existing pipeline of natural gas. The hydrogen pipelines are not yet widely developed and require special materials. There is also a refueling station where hydrogen can be used (Faye et al., 2022).

1.5. Hydrogen utilization

Hydrogen has a multitude of applications in many sectors including, industries, transport, power, households, etc. In the transport sector for example hydrogen can be used as a fuel for vehicles, either in fuel cell electric vehicles (FCEVs) where oxygen and hydrogen combine in the fuel cell to generate electricity by releasing heat and water vapor as exhaust or in internal combustion engines. The use of hydrogen to power cars, trains, forklifts, buses, trucks, ships etc. does not emit any greenhouse gases into the atmosphere and thus is environmentally friendly. In the power generation sector, hydrogen fuel is used in stationary fuel cells such as solid oxide fuel cells and has the potential to yield power that could be injected into the grid to increase electricity generation. In addition, hydrogen can also be used for backup power and in gas turbines to generate electricity. Moreover, hydrogen is used as a feedstock or fuel in a wide range of industrial processes, notably chemical production, metallurgy and oil refining. In ammonia, methanol, and others chemicals production, hydrogen can also be used (Whitehead et al., 2023).

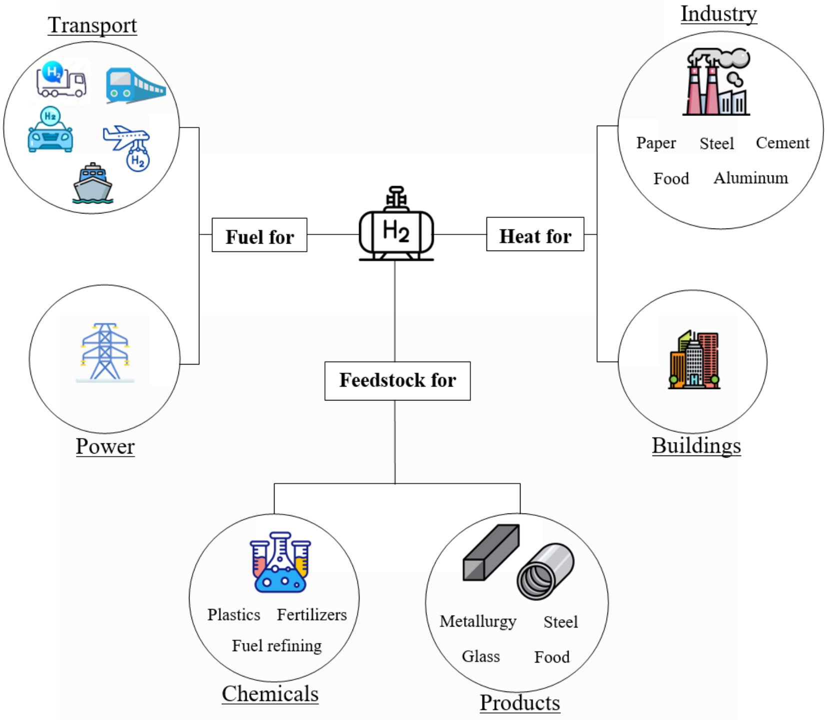


Figure 3: Hydrogen utilization in different sector. Recreated from (Hassan, 2021)

1.6. Overview of global hydrogen strategies

Hydrogen as an energy carrier is crucial to accelerate the global energy transition. Hydrogen can easily decarbonize hard-to-debate sectors. In addition, hydrogen can be used when other renewable energies are not efficiently operating. For more than a decade now, several countries have developed their national hydrogen strategies to phase out the use of fossil fuel. These strategies focus in most cases on the industrial sector, the electricity generation sector, the transport sector, etc. The following paragraphs will examine some strategies.

The European Union (EU), while considering the temporary use of low-carbon hydrogen, has set a goal of achieving climate neutrality between 2030 and 2050. This strategy is divided into three phases. The first phase involves decarbonizing existing hydrogen production industries by producing 1 million tons of renewable hydrogen and installing 6 gigawatts (GW) of electrolyzer by 2024. Phase two focuses on installing at least 40 GW of the electrolyzer and generating renewable hydrogen up to 10 million tons by 2030. This tends to promote and integrate new end-use applications of hydrogen such as trucks, rail, maritime transport and the aviation sectors etc. In the last phase planned for the period 2031-2050, The EU wants to produce large-scale renewable hydrogen to decarbonize all hard-to-decarbonize sectors (Marques & Kempener, 2021).

In particular, national hydrogen strategies vary across EU countries. To name a few, Germany aims to invest €9 billion and build 5 GW of electrolyzer capacity by 2030. Similarly, Spain has the ambition to invest €9 billion and provide 4 GW of electrolyzer capacity in its national hydrogen strategy. On the contrary, France plans to reach 6.5 GW of electrolyzer capacity by 2030 with an investment of 7 billion euros compared to the aforementioned countries.

On the other hand, The United Kingdom (UK) plans to reach 5 GW of low-carbon hydrogen capacity by 2030. Then contribute 20 to 35% of the country's energy consumption by 2050 and provide up to 100,000 jobs (Garcia-Herrero et al., 2021). Several countries such as Australia, Japan, India, South Korea etc. have also strong strategies.

Unlike the EU and the UK, the United States (US) with an investment of $9.5 billion has launched three scenarios to achieve the hydrogen strategy. The first "Strategic Target" is to have a significant impact on the uses of clean hydrogen and reach 10 million tons of clean hydrogen per year by 2030. Secondly, to reduce the cost of clean hydrogen and allow $2 per kilogram per electrolysis by 2026 and $1 per kilogram by 2031. Finally, focus on regional networks to enable large-scale production and end-use of clean hydrogen (US Department of Energy, 2022). China being the world's largest producer of hydrogen (coal based) has targets to increase the share of renewables-based hydrogen to 50% of total hydrogen production by 2030. The country aims to use carbon capture and storage (CCS) technology to decarbonize the current hydrogen production and also strongly applies hydrogen in the transportation sectors.

In the same way, some African countries have already developed their national hydrogen strategy. South Africa has targeted to deploy 10 gigawatts (GW) of electrolysis capacity and generate about 500 kilotons of hydrogen annually by 2030. This growth could create 20,000 jobs per year by 2030 and 30,000 by 2040 (Salma & Tsafos, 2022). In its strategy, Egypt plans to be the regional center for green hydrogen and export about 10 million tons of renewable hydrogen to Europe by 2030 (Esily et al., 2022).

1.7. Hydrogen Business in Africa

Africa has a huge green hydrogen potential. According to H_2 Atlas Africa, west Africa alone can generate approximately 120,000 TWh of green hydrogen per year, using wind and solar energy. The cost of production is estimated at 2.50 €/kg. Mukelabai et al. (2022) have shown that the regional biohydrogen potential ranges from 0.03 to 0.06 Gt/year. The Africa Green Hydrogen Alliance (AGHA), which brings together Egypt, Kenya, Mauritania, Morocco, Namibia and South Africa, was set up in May 2022. The goal is to enhance collaboration on capacity building, financing, policy design and certification in the hydrogen sector. Further, to make the African continent the hub of green hydrogen (Beaucamp & Nforngwa, 2022). Several countries have ongoing and upcoming projects.

Mauritania has launched a green hydrogen mega-project which will make it the hub for green hydrogen on the continent. Thanks to a 15 GW electrolyzer supplied with 30 GW of solar and wind power. The Aman project, estimated to cost $40 billion, will have an annual capacity of 1.7 million tons of hydrogen. In addition, there is also the Nour Electrolyzer project with 1.2 million tons of hydrogen per year and the Masdar-Infinity-Conjuncta green hydrogen project, with a capacity of 1.36 million tons of hydrogen per year (Klein, 2023).

Namibia is also developing a number of key projects to make full use of its hydrogen potential. Hyphen Hydrogen Energy, developed the project called Tsau Khaeb with a capacity of 3 GW which could generate 300,000 tons per year with an overall cost of 9.4 billion dollars. Other projects include the 2.5 GW Tumoneni project, the 50 MW Swakopmund project and the 42 MW Daures Green Hydrogen Village project. The country also aims at the development of three hydrogen valleys in Kharas, the port of Walvis Bay, and Kunene.

South Africa is already in the midst of series of projects. An environmentally friendly ammonia facility of 780,000 tons per year is being developed by Hive Hydrogen. The estimated cost is 4.6 billion dollars with a German subsidy of 15 million euros for the HySHiFT renewable hydrogen project (Hollands, 2023).

Egypt presently has twenty-one green energy projects under development which shows the country's desire to become a global energy hub. There is a development of 3 million tons per year of green ammonia plant. In addition, a 4 GW electrolyzer plant developed by Masdar and Hassan Allam Holding Group and the 3.6 GW electrolyzer project developed by Globeleq etc.

Morocco has a series of green hydrogen initiatives on its agenda. The biggest is the project of 900,000 tons per year, developed by CWP Global and other companies. Aside from that, there are also projects such as a 710,000 tons a year of green hydrogen production. (Hollands, 2023).

1.8. State of art of Hydrogen in Côte d'Ivoire

At present, in Côte d'Ivoire the government has not yet implemented a green hydrogen project. Meanwhile, iH2-IVOIRE HYDROGENE, a small private company is firmly engaged in the development of hydrogen projects in Africa, with a particular focus on implementing hydrogen facilities. The company is working on a project to install the first green hydrogen demonstrator in Côte d'Ivoire at the Africa Cup of Nations in 2024. This project encompasses three innovative scenarios related to the use of an electrolyzer, fuel cell, and hydrogen bus. According to iH2-IVOIRE HYDROGENE, the project expects 6000 visitors from all the countries. In addition, during the competition, students from different schools and universities will be trained (iH2-IVOIRE HYDROGENE, 2023).

CHAPTER 2: MATERIAL AND METHODS

2.1. Study area

Côte d'Ivoire is a country located in West Africa, between longitudes 8°30' and 2°30' West and latitudes 4°30' and 10°30' North, in the intertropical zone, it has a shape like a square whose area is estimated at 322,460 km^2 or about 1% of the African continent with an estimated population of 28,262,050 inhabitants. It is limited by the Gulf of Guinea in the south, Burkina Faso in the north, Liberia and Guinea in the west, Mali, and Ghana in the east. Abidjan represents its economic capital with a large demographic. There are two capital cities, Yamoussoukro and Abidjan and 31 regions. The official language is French, with more than 60 ethnic groups spread over the territory and the CFA franc is its currency. The country is a member of the African Union and the Economic Community of West African States (ECOWAS). Two dry seasons, November to March and July to August and two rainy seasons, June to October and March to May are encountered throughout the year. These seasons are generally felt on the territory of the country but depend specifically on the different locations. Its economy is based on agriculture (Kouassi et al., 2022). The agricultural sector contributes approximately 23 percent to Côte d'Ivoire's overall GDP and accounts for more than two-thirds of its exports. Agro-industries make up around 7 percent of the total GDP and 50 percent of the manufacturing sector. Côte d'Ivoire holds the title of the world's largest cocoa producer, representing 40 percent of global production. Additionally, it has become the leading global producer of raw cashew nuts and maintains its position as the largest exporter of rubber, palm oil, bananas, pineapple. In Africa, it stands as the second-largest producer of coffee. However, rice remains an exception as the country imports 50 percent of its domestic demand (Worldbank, 2019).

Figure 4: Presentation of the study area (Côte d'Ivoire)

Côte d'Ivoire is one of the countries in West Africa with highest electricity networks. Despite this record, the Ivorian government is working effectively to push the country to the top-notch level and make it a hub for West African electricity. In 2022, the country's installed energy capacity is estimated at 2,369 MW. The target set aims to reach 4000 MW in 2025 and 5000 MW in 2030 while increasing the share of renewable energy to 42% in the energy mix. The ambition is to reach 100% access to electricity across the territory. The current national electricity access rate is 64%, and that is disproportionately shared. While urban areas represent 92%, rural areas remain very limited with only 38% access to electricity. In addition, the energy sector is governed by the use of fossil-based energy with approximately 61% from thermal power plants and the remaining 39% from hydroelectric dams. The data from IEA. (2020) shows that In 1990 hydropower and oil were the primary sources of energy. Then, from 2000 to 2020, natural gas became the most widely used energy source in the electricity sector.

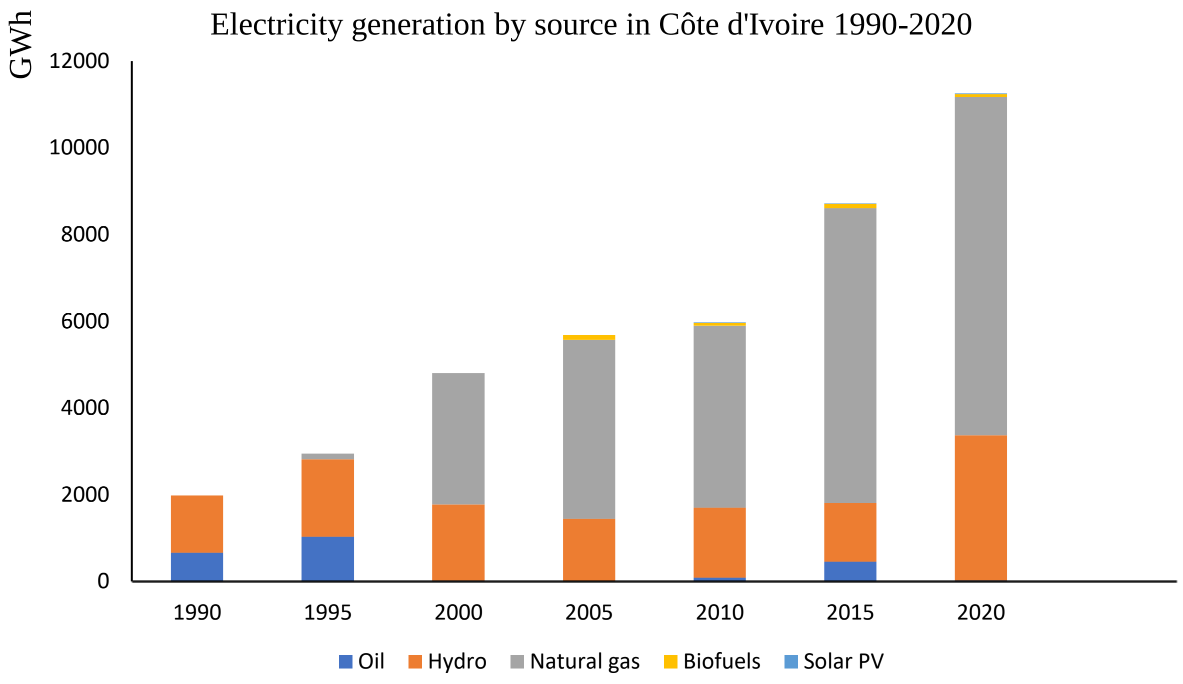


Figure 5: Electricity generation by source in Côte d'Ivoire 1990-2020. Recreated from (IEA, 2020)

2.2. Data collection

The study is carried out using existing high-quality data (secondary data). This method is efficient and reliable to the extent that it reduces time in data collection and saves costs. Existing data are extracted from journal articles such as Scopus, Science Direct databases, Elsevier, google scholar, company and NGO reports and press articles. Research Rabbit, an innovative citation-based literature mapping tool available online is used to shortlist and find the latest articles. The key words 'Hydrogen', 'Strategy', 'Business', and Côte d'Ivoire are used to search for the articles.

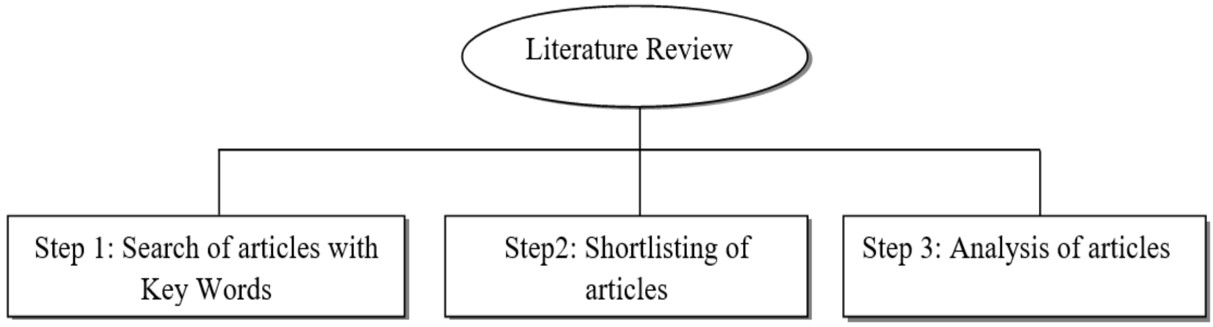


Figure 6: Different steps of literature review

2.3. Data processing and analysis

Regarding the first objective, data collected from a study done by Guero et al. (2021) and the German Agency for International Cooperation (GIZ) on the biomass potential in Côte d'Ivoire are analyzed and adapted to this study. The appropriate data are inserted in Excel to release the curve that describes the share of biomass potential in Côte d'Ivoire. In addition, QGIS (Quantum Geographic Information System) software is used to locate biomass according to Côte d'Ivoire's regions. Firstly, the shapefiles of both Côte d'Ivoire and Africa are downloaded from the Diva-GIS website and uploaded in QGIS to allocate the different regions with respect to the type of biomass. Finally, exported as an image and analyzed. The theoretical energy potential of each crop residue was estimated using the Equation below

$$\mathrm{E_r = Q_r \times LHV} \tag{1}$$

Where $\mathrm{E_r}$, $\mathrm{Q_r}$, LHV are the theoretical energy potential of residue (in MJ), the quantity of residue (in kg) and the lower heating value (in MJ/kg) respectively (Avcıoğlu et al., 2019). The LHVs are taken from different previous works (see Table 2).

Table 2: Elemental composition and low heating values of crop residues

Crop residues	C (wt%)	H (wt%)	O (wt%)	LHV (MJ/kg)	References
Cocoa pod husk	41.53	5.81	51.61	15.48	(Nelson et al., 2021)
Cocoa bean shell	47.30	5	39.50	14.99	(Pirade et al., 2022)
Cashew Shells	52.20	7.40	38.01	19.92	(Tsamba, 2008)
Cashew Apples	44.89	6.34	44.16	15.24	(Alves et al., 2020)
Palm Oil Empty Fruit Bunches	48.20	6.49	31.74	18.40	(Ninduangdee et al., 2015)
Rubber seeds	48.80	5.90	43.70	23.90	(Mohd Ishak, 2019)
Cotton stalk	48.04	6.82	38.96	15.94	(Rabea et al., 2021)
Coffee Husks	39.70	5.40	51.60	12.77	(Koua et al., 2022a)
Coffee grounds	53.25	6.94	34.25	18.80	(Kang et al., 2017)
Rice Straw	48.09	5.86	43.64	18.44	(Phyllis2, 2021)
Rice bran	47.84	6.29	45.19	17.42	(Phyllis2, 2021)
Maize Cobs	42.70	6.49	50.41	16.13	(Kpalo et al., 2020)
Maize Stalk	46.86	6.16	46.20	18.15	(Phyllis2, 2021)
Sugarcane Bagasse	46.96	5.72	44.05	16.10	(Motta et al., 2019)
Molasses	37.90	5.20	42.60	14	(Dirbeba et al., 2021)
Cassava Peels	47.21	7.74	43.70	14.60	(Fonseca et al., 2018)
Mango peel	43.50	7.36	48.10	17.83	(Nagle et al., 2011)
Mango seeds	45.16	7	46.58	17.62	(Nagle et al., 2011)

The hydrogen potential of biomass is evaluated through theoretical calculation. Various methods to theoretically estimate the hydrogen potential exist in the literature. However, in this study, gasification and dark fermentation processes are promoted. Because, gasification appears to be a promising technology for dry biomass and generates a high hydrogen content (25-30%) and conversion efficiency of up to 85% depending on the feedstock. In fact gasification is a thermochemical process that converts solid biomass into biofuels such as synthesis gas also known as syngas (Maitlo et al., 2022). In general, the biomass gasification reaction can be expressed as follow:

$$nC_xH_yO_Z + mH_2O + wO_2 \rightarrow x_1CO + x_2H_2 + x_3CO_2 + x_4CH_4 + x_5H_2O + x_6O_2 \tag{2}$$

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 negligible. Therefore, the Equation 2 changes to:

$$nC_xH_yO_Z + mH_2O \rightarrow x_1CO + x_2H_2 \tag{3}$$

This equation could be followed by the water-gas shift reaction to enhance the hydrogen potential in practice:

$$x_1CO + x_2H_2O \rightarrow x_3CO_2 + x_4H_2 \tag{4}$$

Using the simplified Equation 3, the carbon, hydrogen and oxygen contents in the biomasses collected from different studies are used to generate the formula for each feedstock on a molar basis. Moreover, the equations are balanced, and the hydrogen potential of each biomass is determined. These approaches are similar to those proposed by Cárdenas et al. (2020) in their study. In the same way, for high moisture biomass such as cashew apples, a dark fermentation process is used to assess the hydrogen potential. Zagrodnik & Seifert. (2020) Demonstrated that in general during the process, glucose ($C_6H_{12}O_6$) reacts with water (H_2O) to yield acetic acid (CH_3COOH), carbon dioxide (CO_2) and hydrogen (H_2). Applying this reaction and the percentage of carbon, hydrogen and oxygen present in the cashew apple (see Table 2), (8) is taken to estimate the theoretical hydrogen potential. The different equations used are as follow:

Cocoa pod husks

$$C_{35}H_{58}O_{32} + 3H_2O \rightarrow 35CO + 32H_2 \tag{5}$$

Cocoa bean shells

$$C_{39}H_{50}O_{25} + 14\,H_2O \rightarrow 39CO + 39H_2 \tag{6}$$

Cashew Shells

$$C_{44}H_{74}O_{24} + 20H_2O \rightarrow 44CO + 57H_2 \tag{7}$$

Cashew Apples	$6C_{37}H_{63}O_{28} + 128H_2O \rightarrow 74CH_3COOH + 74CO_2 + 169H_2$	(8)
Palm Oil Empty Fruit Bunches	$2C_8H_{13}O_4 + 8H_2O \rightarrow 16CO + 21H_2$	(9)
Rubber seeds	$2C_{41}H_{59}O_{27} + 28H_2O \rightarrow 82CO + 87H_2$	(10)
Cotton stalks	$C_{20}H_{34}O_{12} + 8H_2O \rightarrow 20CO + 25H_2$	(11)
Coffee huks	$C_{33}H_{54}O_{32} + 1H_2O \rightarrow 33CO + 28H_2$	(12)
Coffee grounds	$2C_{44}H_{69}O_{21} + 46H_2O \rightarrow 88CO + 115H_2$	(13)
Rice Straw	$2C_{40}H_{59}O_{27} + 26H_2O \rightarrow 80CO + 85H_2$	(14)
Rice bran	$2C_{40}H_{63}O_{28} + 24H_2O \rightarrow 80CO + 87H_2$	(15)
Maize Cobs	$2C_{36}H_{65}O_{32} + 8H_2O \rightarrow 72CO + 73H_2$	(16)
Maize Stalk	$C_{39}H_{62}O_{29} + 10H_2O \rightarrow 39CO + 41H_2$	(17)
Sugarcane Bagasse	$2C_{39}H_{57}O_{28} + 22H_2O \rightarrow 78CO + 79H_2$	(18)
Molasses	$C_{32}H_{52}O_{27} + 5H_2O \rightarrow 32CO + 31H_2$	(19)
Cassava Peels	$2C_{39}H_{77}O_{27} + 24H_2O \rightarrow 78CO + 101H_2$	(20)
Mango peel	$C_{36}H_{74}O_3 + 6H_2O \rightarrow 36CO + 43H_2$	(21)
Mango seeds	$C_{38}H_{70}O_{29} + 9H_2O \rightarrow 38CO + 44H_2$	(22)

Furthermore, the scenarios are based on hypothetical calculations. The following Equation 23 is used to estimate the heat potential:

$$\mathrm{Heat_P} = \mathrm{Q_{H_2}} \times \mathrm{LHV} \tag{23}$$

With $\mathrm{Heat_P}$: the heat potential in MJ; $\mathrm{Q_{H_2}}$: the quantity of hydrogen in kg and LHV: the lower heating value of hydrogen which is 120 MJ/kg. In addition, the electrical potential is given by Equation 24:

$$\mathrm{E_L} = \mathrm{Q_{H_2}} \times \mathrm{LHV} \tag{24}$$

Where $\mathrm{E_L}$: the electrical energy in kWh; $\mathrm{Q_{H_2}}$: the quantity of hydrogen in kg and LHV: the lower heating value of hydrogen which is 33 kWh/kg of hydrogen (Joode & Johan, 2022). To find the number of vehicles, the US Department of Energy and Nekkers et al. (2020) Demonstrated that 1kg of hydrogen can run a fuel cell electric vehicle (FCEV) up to 60 miles (96.56 km) for cars and 10.19 miles (16.4 km) for buses. The fuel cell efficiency considered here is 60%. Therefore, based on these data, it is assumed that the average daily kilometers of cars and buses in Côte d'Ivoire are approximately 100 km and 150 km respectively. Equation 25 below expresses the number of cars and buses in the scenarios:

$$\text{Number of vehicles } = \frac{\mathrm{H_2(kg)} \text{ available per year}}{\text{yearly } \mathrm{H_2(kg)} \text{ required per vehicle}} \tag{25}$$

To obtain the ammonia (NH_3), the Haber-Bosch process with 50% efficiency is used. In presence of an iron catalyzer and under exothermic reaction (- 92.4 kJ/mol) nitrogen captured from the air and hydrogen react at high temperature (300–500 °C) and pressure (140–250 bar) to yield ammonia.

$$3\mathrm{H_2} + \mathrm{N_2} \rightarrow 2\mathrm{NH_3} \tag{26}$$

According to Rivarolo et al. (2019), 177 kg of H_2 and 823 kg of N_2 are theoretically necessary to produce 1 ton of ammonia.

Assuming that the potential of hydrogen was fossil energy, the carbon dioxide that could be emitted is calculated using the IPCC method. This method is also used by Suryati et al. (2021) in their study. For the transport sector, in Côte d'Ivoire most small vehicles consume gasoline, and heavy vehicles such as buses consume diesel (see appendix). Based on that, Equation 27 is used to calculate the carbon dioxide.

$$\text{Emisision of } CO_2 = \text{Number of vehicles} \times \text{Fuel consumption (L)} \times \text{Emission factor } (kgCO_2/L) \tag{27}$$

Considering the fact that natural gas is highly used in the power sector the Equations 28 and 29 are used to calculate the CO_2 in the transport and industrial sectors respectively.

$$\text{Emisision of } CO_2 = \text{Emission factor of natural gas } (kgCO_2/kWh) \times \text{Electricity consumption (kWh)} \tag{28}$$

$$\text{Emisision of } CO_2 = \text{Heat consumption (GJ)} \times \text{Emission factor of natural gas } (kgCO_2/GJ) \tag{29}$$

2.4. Software used

The materials used to conduct this research are Microsoft Office (Excel) and QGIS, a multi-platform, free, open-source desktop geographic information system application that supports visualization, editing, printing and analysis of geospatial data.

CHAPTER 3: RESULTS AND DISCUSSION

3.1. Results

3.1.1. The potential of biomass resources in Côte d'Ivoire

Côte d'Ivoire has an enormous potential for biomass resources that can contribute to the development of a sustainable hydrogen industry. Agriculture in Côte d'Ivoire is one of the key sectors with a large biomass availability. The country's economy is largely based on agriculture for decades (Koua et al., 2022). Côte d'Ivoire has achieved world records in agriculture thanks to its strong agricultural diversity. It is the world's largest producer of cocoa and cashew nuts, and the world's fifth-largest palm oil producer, becoming the second-largest African producer. In addition, statistics have shown that the country is the seventh largest producer of natural rubber in the world, which results into the number one African producer. According to OECD and FAO. (2022), Côte d'Ivoire is the fourth African cotton producer and has significant potential for crop residues in the cashew, cassava, cocoa, oil palm, rubber, mango, rice, etc. value chain. Figure 7 below shows a picture of some byproducts from the agricultural sector in Côte d'Ivoire.

Cashew apple Cocoa pods Cocoa shell

Corn stover Palm empty fruit bunches Sugarcane bagasse

Cassava peels Rice husks Rice straw

Figure 7: Picture of some crop residues in Côte d'Ivoire

The cocoa sector has a huge potential for biomass. In general, 1 ton of dry cocoa beans corresponds to about 7 tons of empty pods. It should be noted that the dry pods represent approximately 30% of the weight of the wet pod. The production of Cocoa is estimated at 2.18 million tons in 2019-2020. As a result, Côte d'Ivoire registered approximately 15 million tons of the wet pod equivalent to 4.36 million tons of dry pod residues. In addition, apart from cocoa pods, there was a certain amount of cocoa shells (43,760 tons) available in a few small local industries (GIZ, 2020). This production has drastically evolved shifting from 2.2 million tons in 2021 to 2.4 million tons of cocoa in 2022. Meaning that there is an estimation of about 4.8 million tons of dry pod residues. Regarding cashew, several residues are also generated from this sector. The apple is unquestionably the greatest portion of the fruit in terms of volume and mass. Approximately 80% of the weight of the whole fruit is made up by the cashew apple. In 2019, the amount of cashew residues was estimated at 5,049,000 tons including its apples with 5,000,000 tons and for shells (49,000 tons). These values have widely increased to an outstanding record. For instance, in 2022 alone, 1,028,172 tons of cashew nuts were recorded and Guehi et al. (2023) have shown that cashew apple account for 9 to 10 times the weight of nuts. This means that about 9 to 10 million tons of cashew apples have been generated. Oil palm has residues like palm empty bunches accounted for 1,542,000 tons. Furthermore, Rice is also not negligible, race straw amounted to 2,118,610 tons in addition to its husks and brans which were about 423,722 tons and 211, 861 tons respectively in 2019. Cotton and Coffee residues were estimated at 900,000 tons and 146,353 tons respectively. Residues like sugarcane (740,000), cassava (588,000 tons), maize (480,000), Mango (133,000 tons), and natural rubber (65,000 tons) are also considerable.

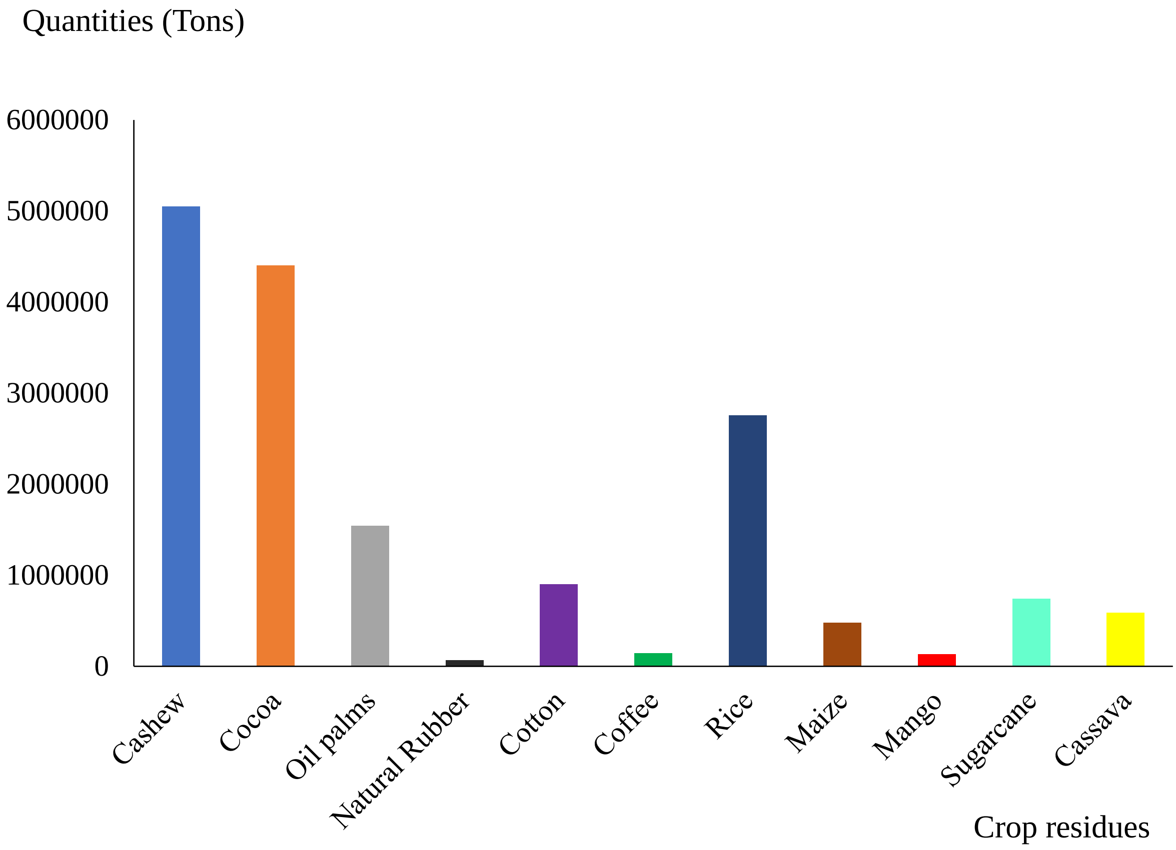


Figure 8: Côte d'Ivoire estimated quantities of crop residues (Tons) in 2019

By combining all the residues produced by the different crops, it turns out that in 2019 the total estimated crop residue is 16,801,306 tons. These wastes continue to increase. Cashew nut residues consisting of shells and apples were the most abundant, accounting for 30.05% of the aforementioned residues. That is relatively link to the increase of cashew farm and its productivity. Furthermore, despite its virtues in beverages, vitamin C, food, health, and energy, the cashew apple is almost not valued and only 1% is transformed. The remaining 99% of cashew apples are not used and are abandoned in the field after the removal of the raw nut (Guero et al., 2021). The following byproducts which are also significantly huge are from the cocoa farm. The combination of both cocoa pod husks and cocoa shells amounted to 4,403,760 tons (dry basis), an equivalent of 26.21%. This record is explained by the fact that a lot of investments have been injected into the cocoa sector in recent decades in order to maximize annual production and also to achieve a very good local processing rate of cocoa. In addition, rice residues (rice husks, rice straw) are also considerable and represent about 16.39%. This is due to the fact that rice is one of the favorite foods of Ivoirians and is consumed in almost all the regions of the country. Oil palm, cotton, sugarcane, cassava, and maize are 9.18%, 5.36%, 4.40%, 3.50%, and 2.86% respectively. These residues are low because they are partly used for direct combustion or animal feed (mainly cassava). Conversely, coffee, mango and natural rubber have very low residues and are rated 0.87%, 0.79%, and 0.39% respectively. These quantities of residues are explained by the fact that these crops are only specifically grown in certain regions. They also produce relatively less residue in their treatment. The diagram below shows the share of crop residues in 2019.

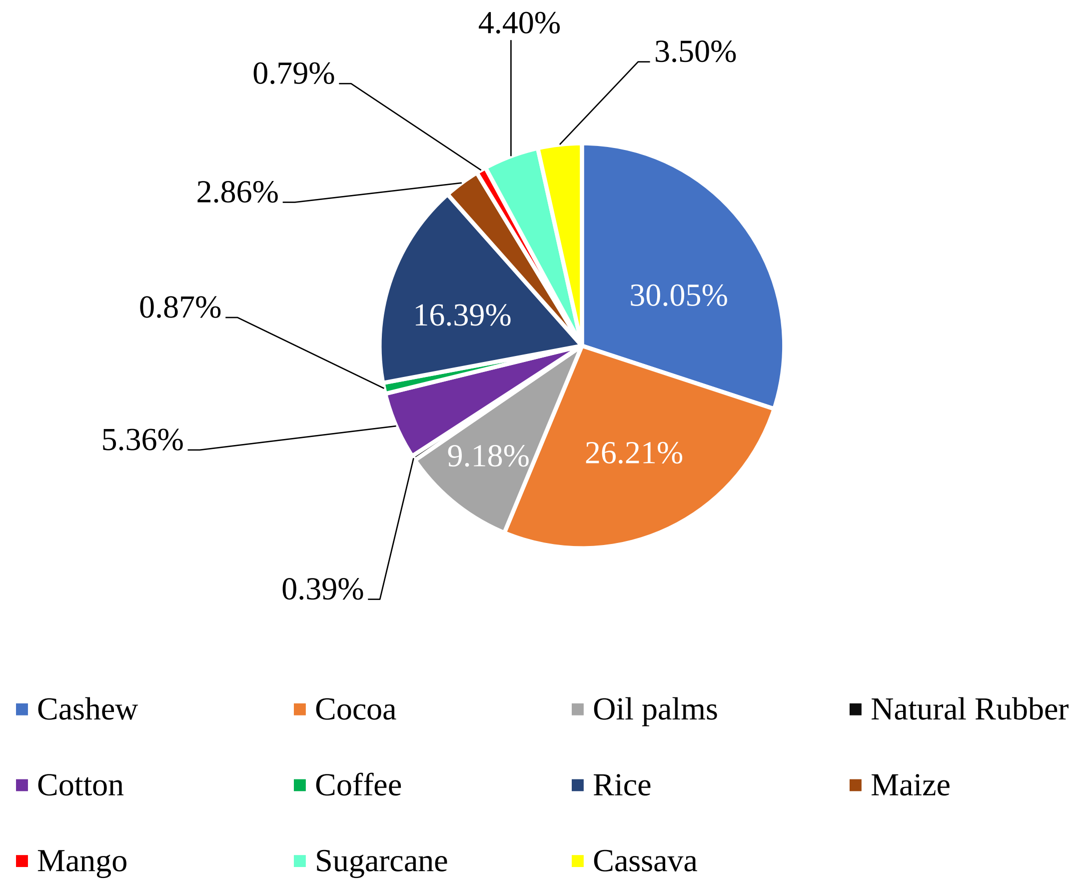


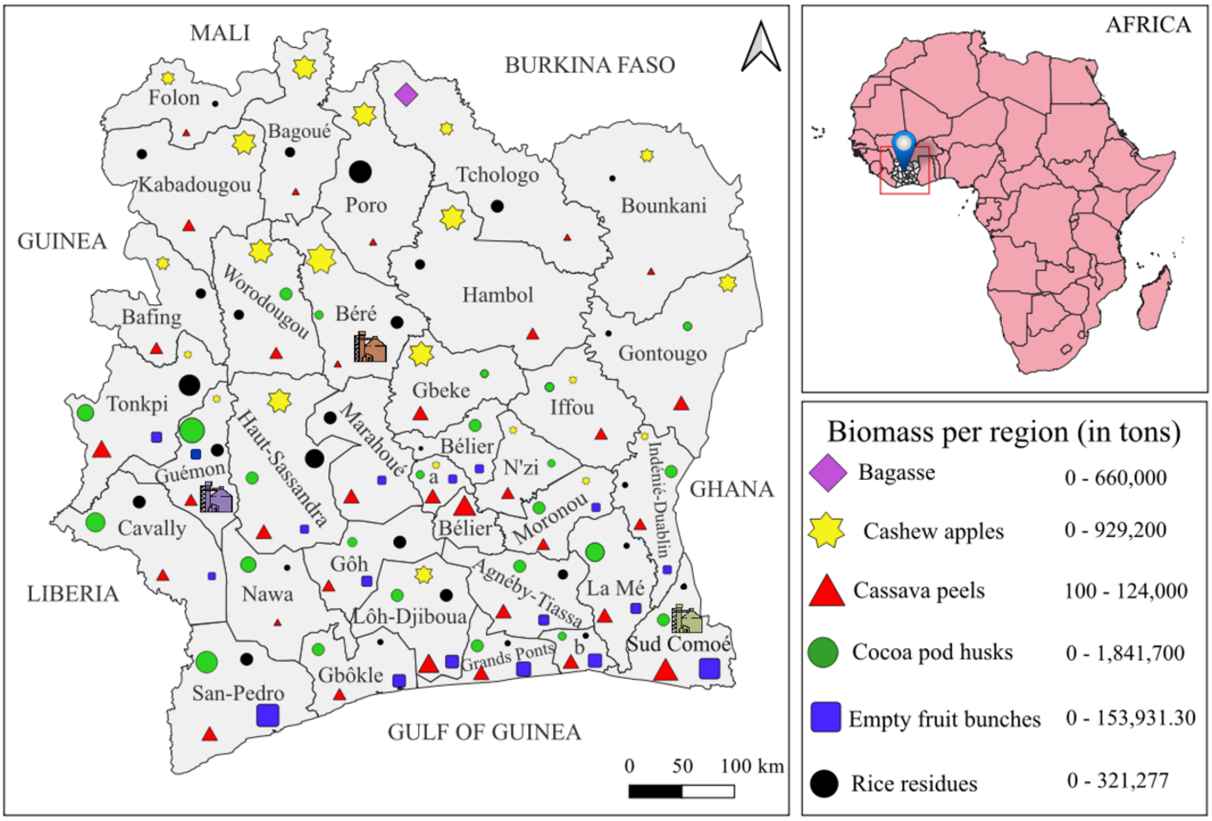
Figure 9: The share of various crop residues in Côte d'Ivoire in 2019

3.1.2. Location of the biomasses

In Côte d'Ivoire, crops are very diversified and distributed in different regions according to climate, rainfall, soil fertility, etc. Some regions can only plant a variety of species. For example, cocoa is much more popular in the southwest of Côte d'Ivoire. The region that produces a lot of dry beans is Guémon with 1,841,700 tons of waste, followed by San Pédro and Cavally with about 1,820,000 tons and 1,791,300 tons respectively. Cocoa residues are free of charge and used locally to produce charcoal or directly burned. Cashew nut waste is very abundant in northern regions than in other regions. There were a significant amount of cashew apples and shells in the regions of Béré, Gbeke, Hambol and Worodougou with the availability of 1,010,540 tons, 709,964 tons, 642,460 tons and 522,470 tons respectively in 2021.

Access to these residues is in most cases free of charge because they are neglected in remote fields or processing sites. On the contrary, cassava is cultivated in almost all regions of the country but predominates in the Sud Comoé region with a potential of about 123,970 tons, the Belier region 57,909 tons and Marahoué accounted for 51,377 tons. This waste is freely available and is sometimes used to feed animals such as sheep. However, much of it is released after processes and emits greenhouse gases during its decomposition. The oil palm increases in the southern part. The highest biomass potential of Palm Oil is recorded in the regions of San Pedro (278,542 tons), Sud Comoé (267,336 tons), Grands Ponts (89,991 tons), Marahoué (59,856 tons), Gbokle (57,548 tons), and Abidjan (42,066 tons). Except for empty fruit bunches which are free, a tiny fraction of the aging palm trees is often sold to the villagers at a low price to make small-scale commercial palm wine. Nevertheless, a large part is left to be used as green fertilizer, after decomposition in the fields. Concerning natural rubber, the biomass potential is mainly concentrated in the south of Côte d'Ivoire. San Pédro (103,376 tons) and Cavally (88,096 tons) in the Southwest, and Grands Ponts (117,849 tons), and Sud Comoé (118,405 tons) in the Southeast. Others biomass are as well spread, the cotton residues are allocated in the North, rice everywhere, maize in the North and center, mango in the North and sugarcane bagasse in the north and West (GIZ, 2020).

The use of QGIS has helped to map some areas that have biomass potential. In addition, Aboisso, Duékoué and Mankono are the areas where the hydrogen production plants are to be implemented and it is indicated on the map. Here, however, several biomasses have been discussed but only six of them are laid out due to the lack of detailed data for some residues.



a: Autonomous District of Yamoussoukro b: Autonomous District of Abidjan

Figure 10: Quantities of crop residues per region in Côte d'Ivoire in 2019

3.1.3. Energy potential

The eighteen types of crop residues used in the study present a lot of energy potential that varies from one residue to another (See Table 3 below). This energy potential can be used for electricity generation.

Table 3: Energy potential from various crop residues

Crop	Residues types	Residues available (Tons /year)	Energy potential (GJ/year)
Cocoa	Pod husks	4,360,000	67,492,800
	bean shells	43,760	655,960
Cashew	Shells	49,000	976,080
	Apples	5,000,000	76,200,000
Palms Oil	Empty Fruit Bunches	1,542,000	28,372,800
Rubber tree	Seeds	65,000	1,553,500
Cotton	Stalks	900,000	14,346,000
Coffee	Husks	128,000	1,634,560
	grounds	18,353	345,040
Rice	Straws	2,542,332	46,880,600
	Bran	211,861	3,690,620
Maize	Cobs	80,000	1,290,400
	Stalks	400,000	7,260,000
Mango	Peels	70,000	1,248,100
	Seeds	63,000	1,110,060
Sugarcane	Bagasse	660,000	10,626,000
	Molasses	80,000	1,120,000
Cassava	Peels	588,000	8,584,800
Total		**16,801,306**	**273,387,320**

The total energy potential of the biomass which is the amount of energy that can be generated when the biomass is completely combusted accounts for 273,387,320 gigajoules in the year 2019. Among all the agricultural residues presented here, cashew apple has the higher energy potential and accounts for 76,200,000 gigajoules. This energy potential can generate a lot of amount electricity if one desired electrical energy. Importantly, the energy potential of cocoa pod husks is also on the top level, amounted for 67,492,800 gigajoules. This energy potential of cocoa pod husks is doubly higher than 30,180,000 gigajoules found by Koua et al. (2022) in their study. This could be explained by the fact that the cocoa area has gained a lot of investment thus the increase of crop productivity. Rice straw accounting for 46,880,600 gigajoules is also higher than 18,820,000 gigajoules presented by (Koua et al., 2022).

The palm oil empty bunches which are hugely available in the southern part of the country show an energy potential of 28,372,800 gigajoules. The Ivorian government assessing this potential, planned an energy project to generate up to 46 MW of energy utilizing palm oil waste in Ayébo, Aboisso (Sud Comoé region). The dry cotton stalls, sugarcane bagasse, cassava, and maize stalks being highly combustible yield energy potential of 14,346,000 gigajoules, 10,626,000 gigajoules, 8,584,800 gigajoules and 7,260,000 gigajoules respectively.

These energy potentials are lower than cashew apples, cocoa pod husks because of their small amount in terms of residues. It can be seen on the Figure 11 below that coffee, mango, cashew shell and cocoa pods shell have the lowest energy potential due to the fact that these crop are exported to the international market thus their waste are processed abroad. The reason of their exportation is directly related to the lack of scalable local industries for crop transformation.

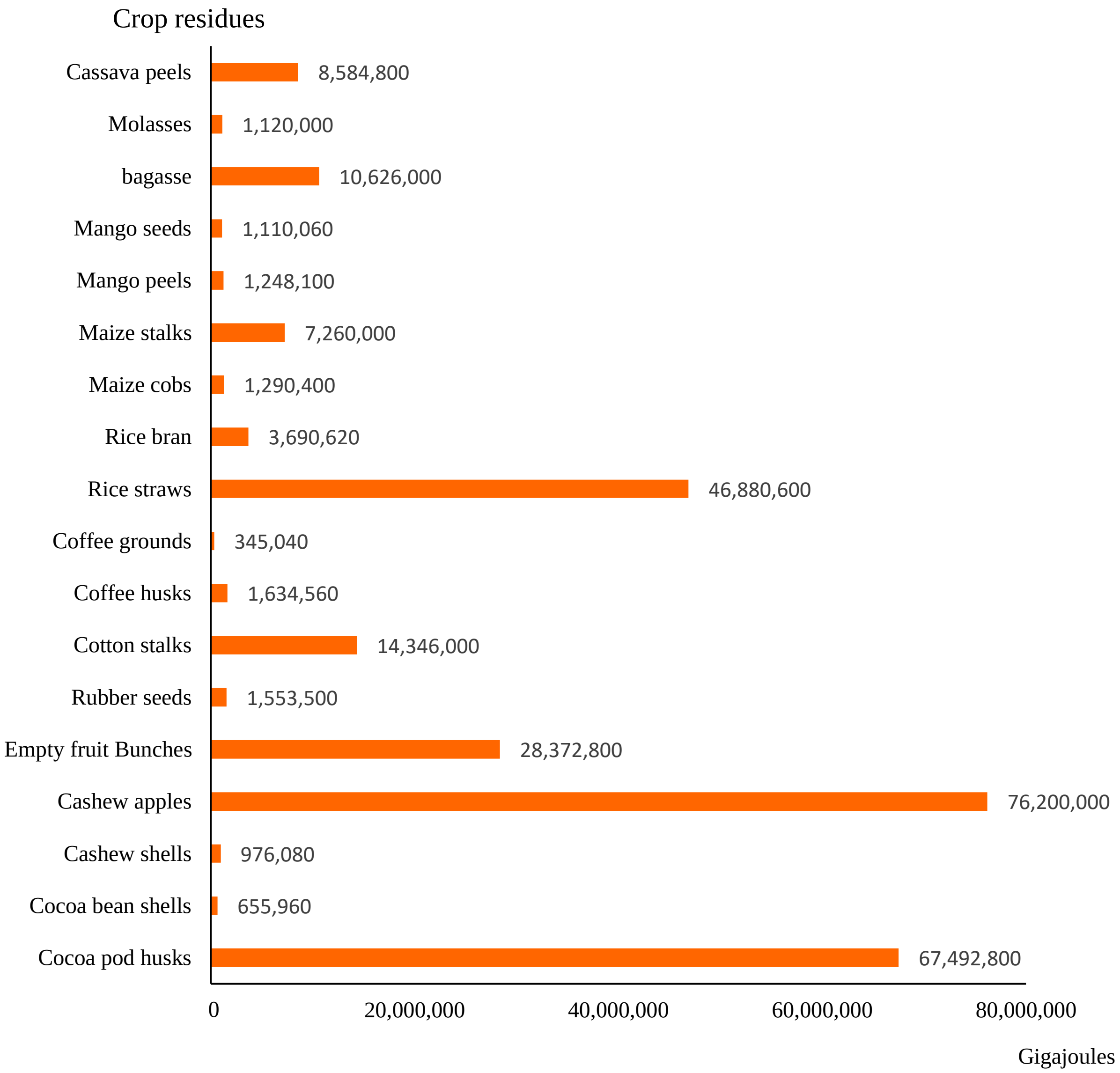


Figure 11: Energy potential from crop residues in 2019 in gigajoule

3.1.4. Hydrogen potential

The total potential of biomass-based hydrogen production is estimated at 1,296,424.84 tons. Looking at the different biomass sources, the cashew apple has the greatest hydrogen potential, amounting to 294,240.84 tons. This is mainly because of the abundance of underutilized cashew apples in Côte d'Ivoire, coupled with the increased cultivation of cashew farms in recent years. Following cashew apple, cocoa pod husks demonstrate a significant hydrogen potential of 281,858.59 tons. However, by comparing the hydrogen potential of their shells, namely the cashew nutshell and the cocoa bean shell, the hydrogen potential are substantially lower. This can be attributed to the country's predominant practice of exporting crop products rather than processing them locally. Rice straw also holds considerable promise in terms of hydrogen production, with a potential of 222,552.24 tons, which is slightly closer to that of cocoa pod husks and higher than palm oil empty fruit bunches, which amount to 187,179.19 tons. Furthermore, cotton stalks have a sizeable hydrogen potential of 96,566.52 tons. Notwithstanding, cassava peels, bagasse, and maize stalks contribute to the overall potential, offering 60,786.08 tons, 53,586.84 tons, and 32,997.99 tons, respectively, of hydrogen potential. Despite their small quantities, these biomass sources remain valuable and can be used effectively. On the other hand, certain biomasses such as molasses, mango peels and seeds, maize cobs, rice bran, coffee grounds and husks, and rubber seeds exhibit a much lower potential for hydrogen. This can be assigned to the fact that initially, the residues from these crops were limited in quantity, which consequently affects their hydrogen potential.

Considering a conversion efficiency of 70% for both gasification and dark fermentation (Holladay et al., 2009), the total technical hydrogen potential becomes 907,497.39 tons. This technical hydrogen potential is more or less realistic compared to the theoretical potential. Meanwhile, in real life, it could be reduced due to certain operating conditions, parameters and losses during the process. With regard to electricity generation, the conversion efficiency of the fuel cell is assumed to be 60%. Table 4 and Figure 12 show the theoretical and technical hydrogen potential of each crop residue. Blue color represents the ideal (theoretical) hydrogen potential while green color represents the technical hydrogen potential.

Table 4: Theoretical and technical Hydrogen potential from various crop residues

Residues types	Theoretical Hydrogen potential (Tons/year)	Technical Hydrogen potential (Tons/year)
Cocoa pod husks	281,858.59	197,301.01
Cocoa bean shells	3,718.17	2,602.72
Cashew shells	5,665.31	3,965.72
Cashew apples	294,240.84	205,968.59
Palm oil empty fruit Bunches	187,179.19	131,025.43
Rubber seeds	5,752.80	4,026.96
Cotton stalks	96,566.52	67,596.57
Coffee husks	7,451.14	5,215.80
Coffee grounds	2,262.16	1,583.51
Rice straws	222,552.24	155,786.56
Rice bran	18,599.30	13,019.51
Maize cobs	5,787.91	4,051.54
Maize stalks	32,997.99	23,098.59
Mango peels	6,105.48	4,273.83
Mango seeds	5,600	3,920
bagasse	53,586.84	37,510.79
Molasses	5,714.29	4,000
Cassava peels	60,786.08	42,550.26
Total	**1,296,424.84**	**907,497.39**

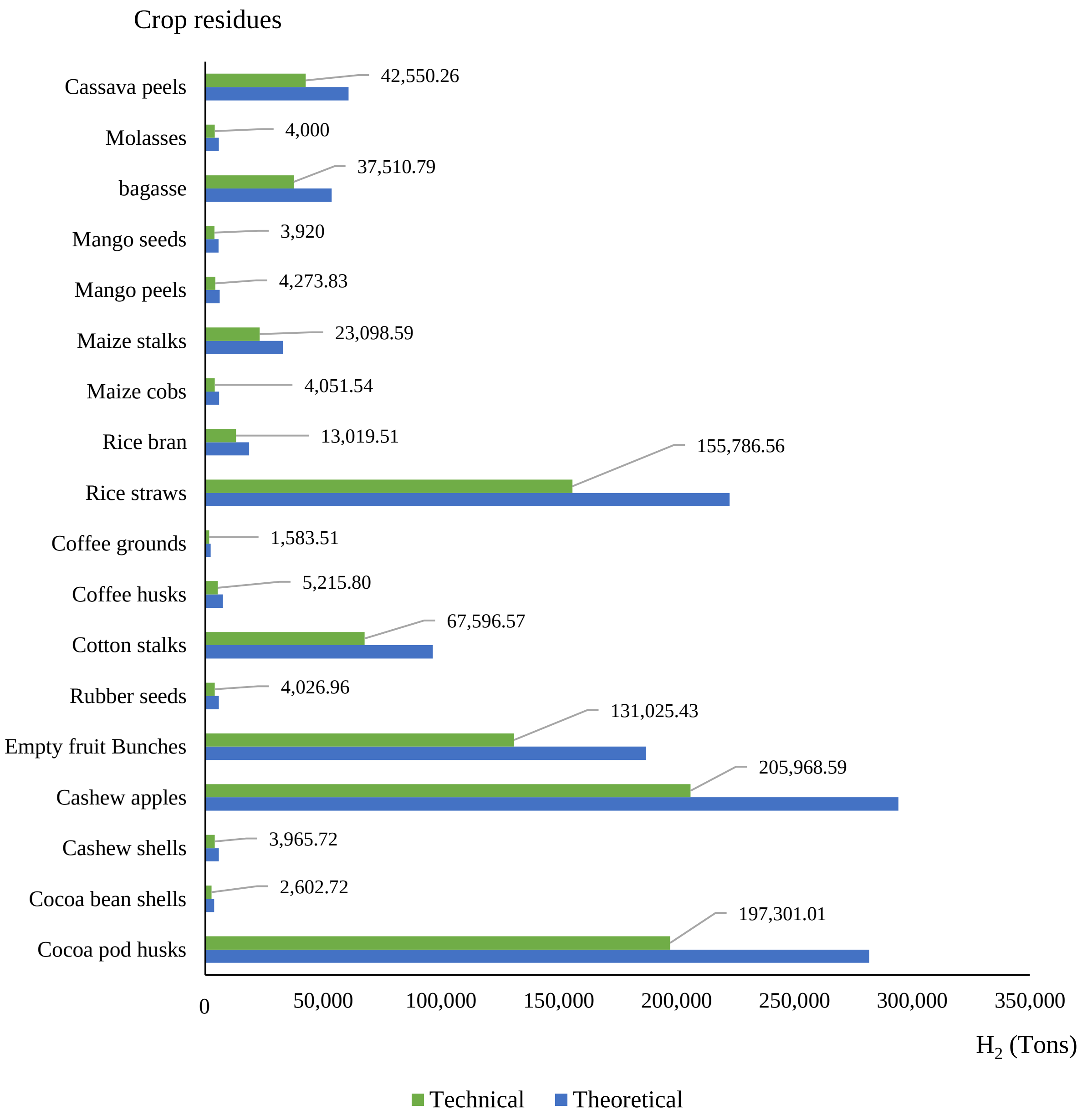


Figure 12: Technical and theoretical hydrogen potential from crop residues in 2019 (Tons)

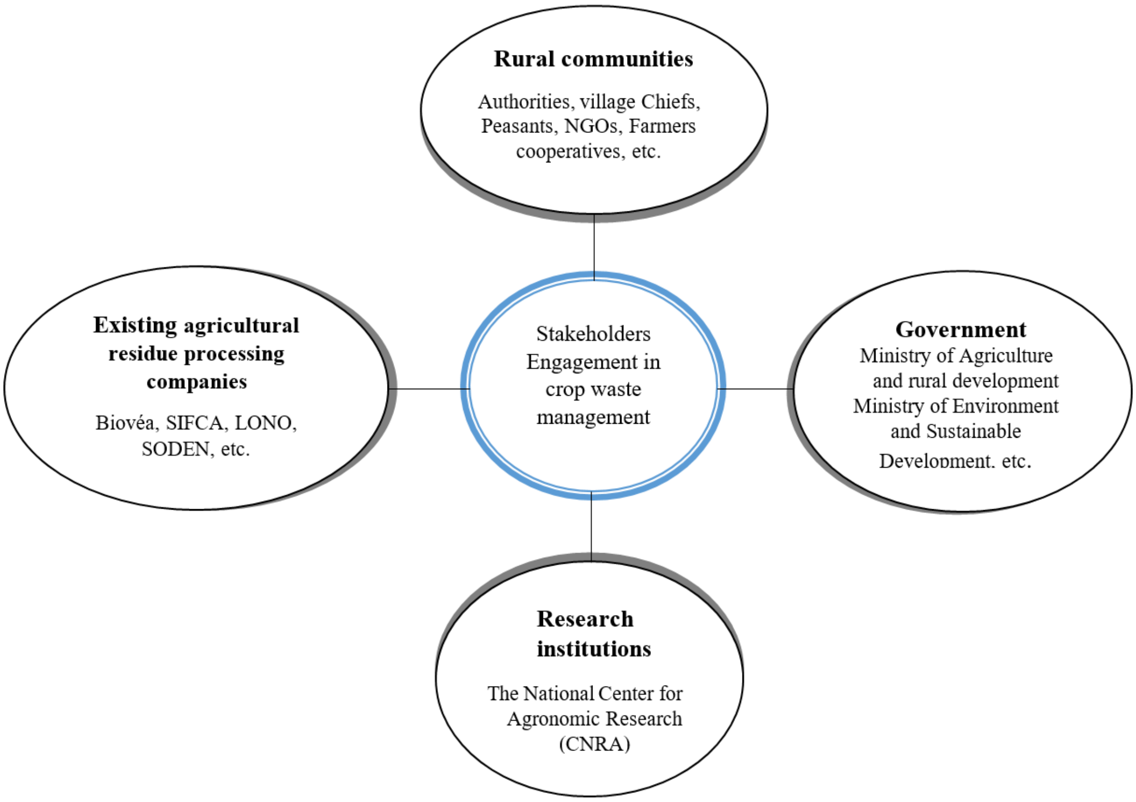
3.2. Discussion

3.2.1. Strategy for crop residues management

Currently, Côte d'Ivoire lacks an effective framework for managing crop leftovers. Since these untreated residues are frequently burned, dumped, or abandoned in plantations, this presents a long-term environmental concern. Although the majority of these crop residues are easily accessible and free of charge, the logistical costs associated with transporting and storing it might be substantial. Mostly because of the plantations' rural locations and challenging accessibility. Furthermore, it can be difficult to guarantee residue supply throughout the year. For instance, the peak cocoa harvest season lasts from October to March, while cashews are normally picked from late December to early February. Additionally, there are several barriers preventing the efficient waste management, including inadequate stakeholder participation, insufficient research on farm waste management, absence of appropriate residues disposal sites, and a scarcity of knowledge and labor. It is essential to create a comprehensive plan for collecting and storing residues to overcome these problems and enable the hydrogen producing sectors to operate effectively. Multiple actors and different stages should participate in this action.

Stage 1: Stakeholder Engagement

The participation of various stakeholders such as rural communities, crop residues processing industries, research institutions, the Ministry of Agriculture and Rural Development and the Ministry of Environment and Sustainable Development, and private sectors is essential. To effectively manage agricultural residues through an appropriate collection approach, all parties need to work together to emphasize the importance of adopting best practices. To guarantee stakeholders' meaningful engagement, communication channels must be established. Online platforms, surveys, forums, seminars, awareness campaigns, one-on-one meetings with farmers, radio and television advertisements, and leveraging the influence of social media for information dissemination are examples of these channels. However, delegates should personally meet peasants in distant places where they lack regular access to communication tools such as the internet and smartphones to promote awareness and provide required communication facilities. This inclusive and transparent approach will promote collective accountability and active participation of all stakeholders. It is also critical to encourage teamwork and build partnerships. Subsidies, including financial and technical support, should be made available to farmers and private organizations participating in residue management projects.



Stage 2: Education and Training

To overcome the lack of information amongst the vast majority of farmers, farmer education and training programs focused on proper crop waste handling and collecting procedures, as well as the numerous advantages of residue collection, are vital. These programs should attempt to provide information on appropriate residue separation and packing processes to assure the quality and viability of the collected residues. It is critical that trained persons (famers, group of people, etc.) can also train other new people. The creation of mobile software applications that incorporate local dialects and French is critical to improving accessibility and convenience. These programs would allow farmers to attend crop residues management courses on their smartphones at any time and from any location. Furthermore, to effectively reach a large audience, it is important to broadcast small television programs on waste management in both the French language and local dialects. These programs should be hosted by specialists in the field. Farmers should also be encouraged to learn how to use digital technologies such as drones, FarmLogs, ArcGIS, and QGIS. In reality, these can assist farmers in tracking and mapping agricultural waste generation, storage, and disposal sites.

Stage 3: Development of the system for collecting, storing and transporting crop residues

The strategic location of an appropriate number of collection points near agricultural areas in some regions of Côte d'Ivoire will allow farmers to easily access these facilities to deposit crop residues. To prevent hazardous effect, appropriate collection equipment, such as personal protection equipment must be provided. In addition collections machines such as balers and forage harvesters, are needed to efficiently gather and process crop residues. These machines are capable of cutting, shredding, and baling the residues into manageable sizes, facilitating easier storage and transport. The Construction of suitable storage facilities that cater to the different types of crop residues on the storage site is necessary. These storage facilities should be designed to maintain the quality of the residues. Additionally, adequate ventilation, moisture control mechanisms, and fire prevention measures must be taking into account during the construction. After collecting and gathering the residues a transportation system that effectively transports the crop residues from the collection point to the designated hydrogen plants must be established. It should be very well designed to minimize transportation time and costs. Equipment such as loaders, conveyors, or trailers should be employed to safely and efficiently load, unload, and transport the residues from the field to storage facilities or hydrogen production site.

3.2.2. Strategy for capacity building

The development of capacity in hydrogen will address the lack of expertise and manpower in Côte d'Ivoire. First, to achieve this, it is essential to promote awareness of the potential of hydrogen as an alternative energy carrier through seminars, workshops and public campaigns. The public, educational institutions, NGOs, and industries must be mobilized to understand the importance of hydrogen and its applications. The institutions to target are high schools, colleges, universities, and the companies like ivoire hydrogen. After this great awareness, Hydrogen Research and Development Centre must be established. This Centre should collaborate with universities such as Félix Houphouët-Boigny University in Abidjan, the University of Man and many other universities. The Yamoussoukro engineering school, which is quite implicated in scientific research and trains the country's elites, must be strongly involved. This will indeed encourage the development of hydrogen technologies. This Centre must also offer training programs, and internships. By bridging the gap between academia and practical applications, industry experts can offer real-world insights and advice to students and researchers. Moreover, to facilitate the development of hydrogen, the universities mentioned must integrate a specialized hydrogen track in their programs. This ensures that students receive comprehensive education and specific training on hydrogen technologies. The program should include courses on hydrogen production, storage, transportation, use safety, etc. In addition, partnerships should be established between Ivorian universities and reputable institutions abroad such as European, American, and Asian universities and industries that have expertise in hydrogen technologies. This collaboration will boost knowledge transfer and joint research projects. It will expose students and researchers to international best practices and cutting-edge advances in the field. More importantly, the government must provide scholarships or funding opportunities for deserving students to pursue graduate studies or research in hydrogen-related disciplines abroad. This investment in human capacity allows students to acquire in-depth knowledge and practical experience, which they can bring back to contribute to the development of the hydrogen sector in Côte d'Ivoire.

3.2.3. Scenarios based on hydrogen development in Côte d'Ivoire

The scenarios are hypothetical cases that help to understand the implementation aspect. Here, three different scenarios are explored, each considering the entire process from hydrogen production to its end use in Côte d'Ivoire. The transport, industrial, agricultural, and electricity generation sectors are specifically considered in these scenarios. The allocation of hydrogen is determined based on product consumption, be it energy or chemical fertilizer. Currently, as there are no hydrogen-powered vehicles in Côte d'Ivoire, the transport sector is assigned with 5 percent share of the total available hydrogen in each scenario. However, it is anticipated that this percentage will increase once hydrogen cars and buses become available in the country. Given the relatively smaller number of industries compared to developed countries, the industrial sector is assumed to use only 10 percent of the available hydrogen. On the other hand, the electricity generation sector receives half of the produced hydrogen in scenario A. This could be explained by the desire to increase the share of renewable energy in the electricity supply in Côte d'Ivoire. The agricultural sector heavily dependent on chemical fertilizers expected to gain 50 per cent of hydrogen for green fertilizer manufacturing in scenarios B and C. Additionally, considering the substantial hydrogen potential, the exportation aspect is also taken into consideration. In each scenario, up to 35 percent of the yielded hydrogen is to be exported to countries with high hydrogen demand. Such hydrogen exports could boost the country's economy and establish it as a prominent hydrogen hub in West Africa and Africa as a whole. It is important to note that these scenarios only consider the five most potent and readily available residues during a specific period of the year, not accounting for all potential residues.

3.2.3.1.Scenario A

In this first scenario, 1,542,000 tons of palm oil residues and 588,000 tons of cassava residues are collected from various farms and transported to Aboisso in Sud comoé region where the hydrogen plant is assumed to be located. Through the gasification process, 173,575.50 tons of hydrogen will be generated. Regarding the transport sector, the 5 percent give 8,678.78 tons of hydrogen that will be used in hydrogen station to power 1,092 buses and 4,133 cars. Despite this low percentage (5% of total hydrogen), the expected hydrogen cars and buses are considerable. On the other hand, the electricity sector receiving 50 percent (86,787.75 tons) of available hydrogen is supposed to supply 5,727,992 local and urban communities with 1,718.40 gigawatt-hour over a year. This means that non-electrified areas in the country will have access to electricity. Furthermore, the heat that can be generated from 10 percent of hydrogen to power industries is 2,082,906 gigajoules. Therefore, contributing to the decarbonization of industrial sectors in Côte d'Ivoire. Taking into account the pressing energy requirements of European nations and some African countries, which currently rely on Russian gas and are grappling with acute shortages stemming from the devastating conflict between Russia and Ukraine, there exists a palpable and urgent need for alternative sources of energy. Consequently, the exportation of 35 percent of the hydrogen abundance, encompassing an impressive 60,751.43 tons, would not only serve to ameliorate this energy crisis but concurrently contribute to the substantial growth of the gross domestic product (GDP). The actual process of hydrogen exportation can be effectively executed via the employment of various means, such as ships, pipelines, or extensive vehicular transport. A visual depiction of these diverse processes is provided in the Figure 13 below.

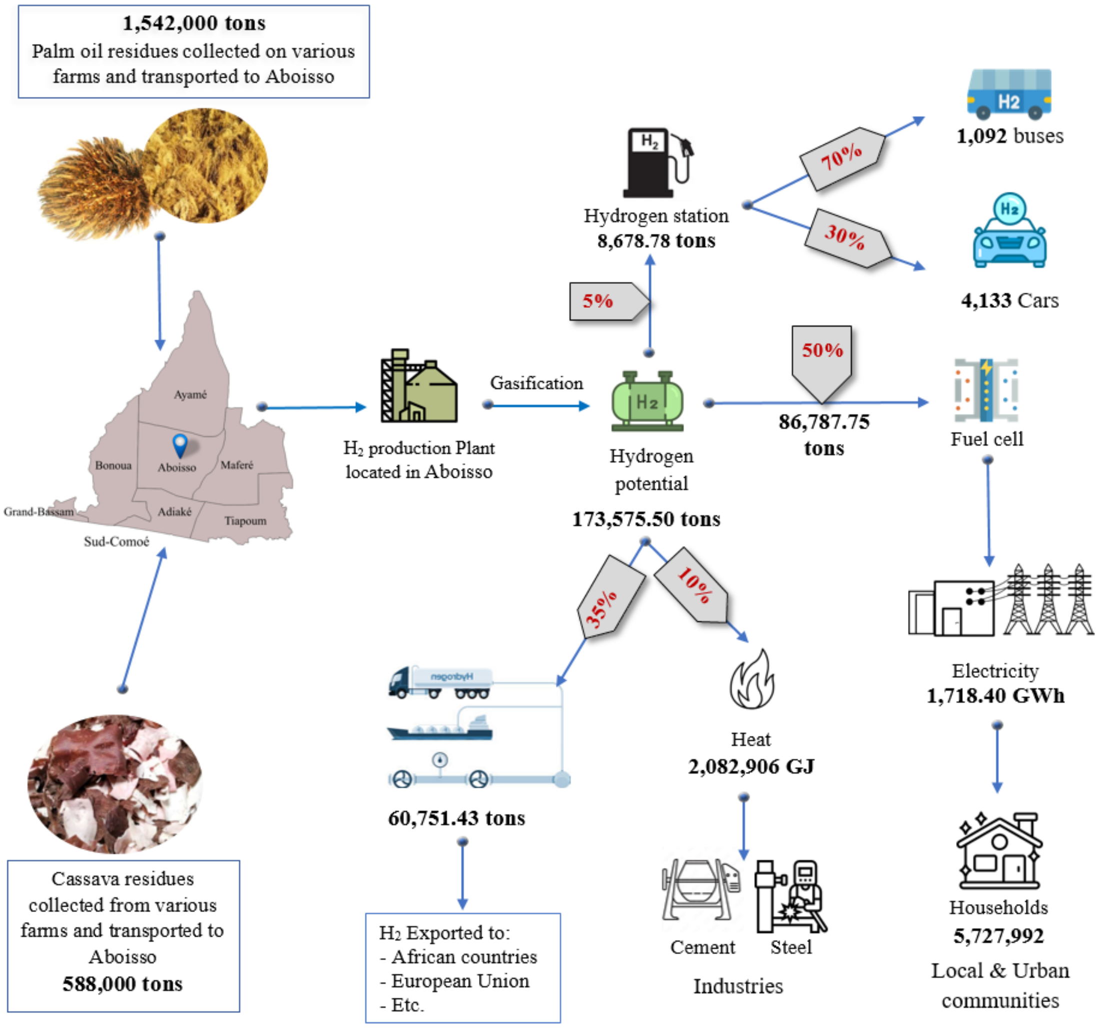


Figure 13: Schematic diagram of different steps of scenario A

3.2.3.2. Scenario B

For this scenario, a substantial quantity of 4,403,760 tons of cocoa residues and 2,754,193 tons of rice residues are procured from diverse agricultural farms and subsequently conveyed to Duékoué, a town situated within the Guémon region, which is the designated site for the hydrogen production. The application of the gasification process facilitates the generation of an impressive 368,709.81 tons of hydrogen which is twice as high as the first scenario. With a specific focus on the transportation sector, a mere 5 percent of this hydrogen abundance effectively energizes a fleet of 2,319 buses and 8,779 cars. On the flip side, in terms of fertilizer provision, a significant portion of the hydrogen resources, specifically 50 percent amounting to 184,354.91 tons, is allocated to the agricultural sector. This allocation can provide a remarkable 520,776.57 tons of green ammonia that has the potential to greatly benefit a large number of farms. Taking into account the consumption of fertilizers per unit of arable land (51.9 kg/hectare) in 2020, an estimation of 10,034,230.59 hectares can have access. Therefore, this could reduce Côte d'Ivoire's dependence on imported chemical fertilizers from Russia and Morocco etc. In addition, Côte d'Ivoire could become a fertilizer exporter nation in Africa. Heat, up to 4,424,517.72 gigajoules from 10 percent of hydrogen can be used in the industrial sector. Heat is an essential form of energy used in various industrial processes, such as manufacturing and refining. The availability of such an important heat source can provide numerous benefits to industries, including increased productivity, increased efficiency, and reduced reliance on conventional energy sources. The amount of hydrogen that could be exported is 129,048.43 tons to the international market. It is a significant quantity that can replace a large bulk of fossil energy. Hydrogen has gained attention as a clean and versatile energy carrier with various applications, including transportation, power generation, and industrial processes in European nations. The exportation of such a considerable quantity of hydrogen would enhance the energy transition. This particular scenario is the most promising.

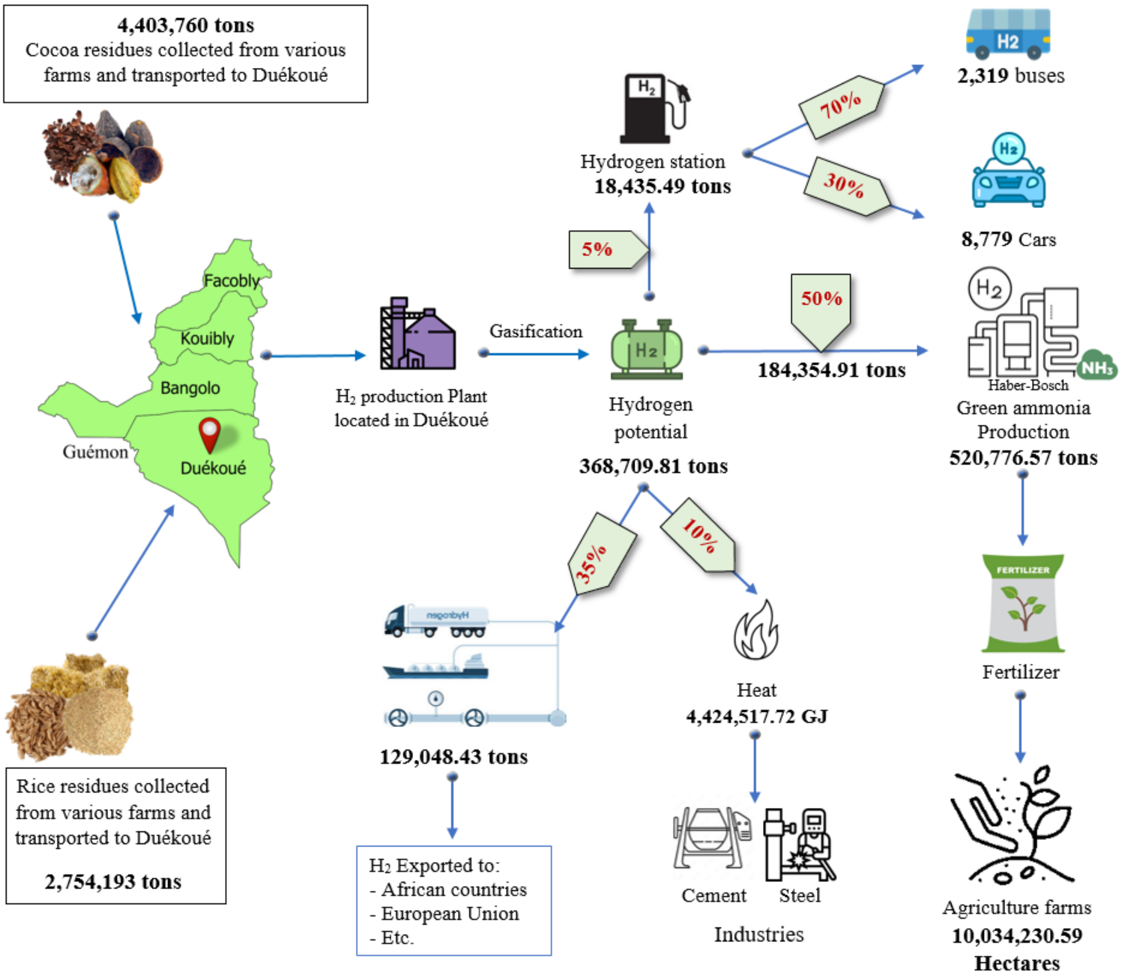


Figure 14: Schematic diagram of different steps of scenario B

3.2.3.3. Scenario C

Besides the two situations aforementioned, this scenario focuses on the use of wet biomass, particularly cashew apples. The suitable conversion method is the dark fermentation process. It is planned to establish a hydrogen factory near the farms in Mankono, located in the region of Béré, in the north of the country. Approximately 5,049,000 tons of cashew nut residues will be transported from agricultural fields and local industries to the plant, as cashew apples are subject to rapid decomposition. Technically, this process has the potential to produce 209,934.31 tons of hydrogen. Such an amount of hydrogen (50 percent) could provide 296,517.39 tons of green ammonia fertilizer and supply 5,713,244.45 hectares of arable land. Thereby, adding it to the second scenario will increase the fertilizer supply to 817,293.95 tons per year supplying a considerable arable land of 15,747,475.04 hectares. Fertilization improves plant nutrition, promotes plant growth, improves crop quality, and ultimately maintains and even enhances soil fertility. Ammonia is extremely effective in providing nitrogen to the soil to improve crop yields. Additionally, 1,321 buses and 4,998 cars could benefit from 10,496.72 tons of hydrogen. In terms of heat supply, approximately 2,519,211.72 gigajoules could be obtained from the 10 percent hydrogen dedicated to the industrial sector. Moreover, under this scenario, a maximum of 73,477.01 tons of hydrogen can be exported to the international market. It is important to note that while these scenarios hold great opportunities, their implementation would require careful planning, coordination, and investment in infrastructure and technology. Considerations should include hydrogen, storage, safety measures, and market demand. Furthermore, environmental considerations and sustainability practices should be incorporated for long-term sustainability and positive impact.

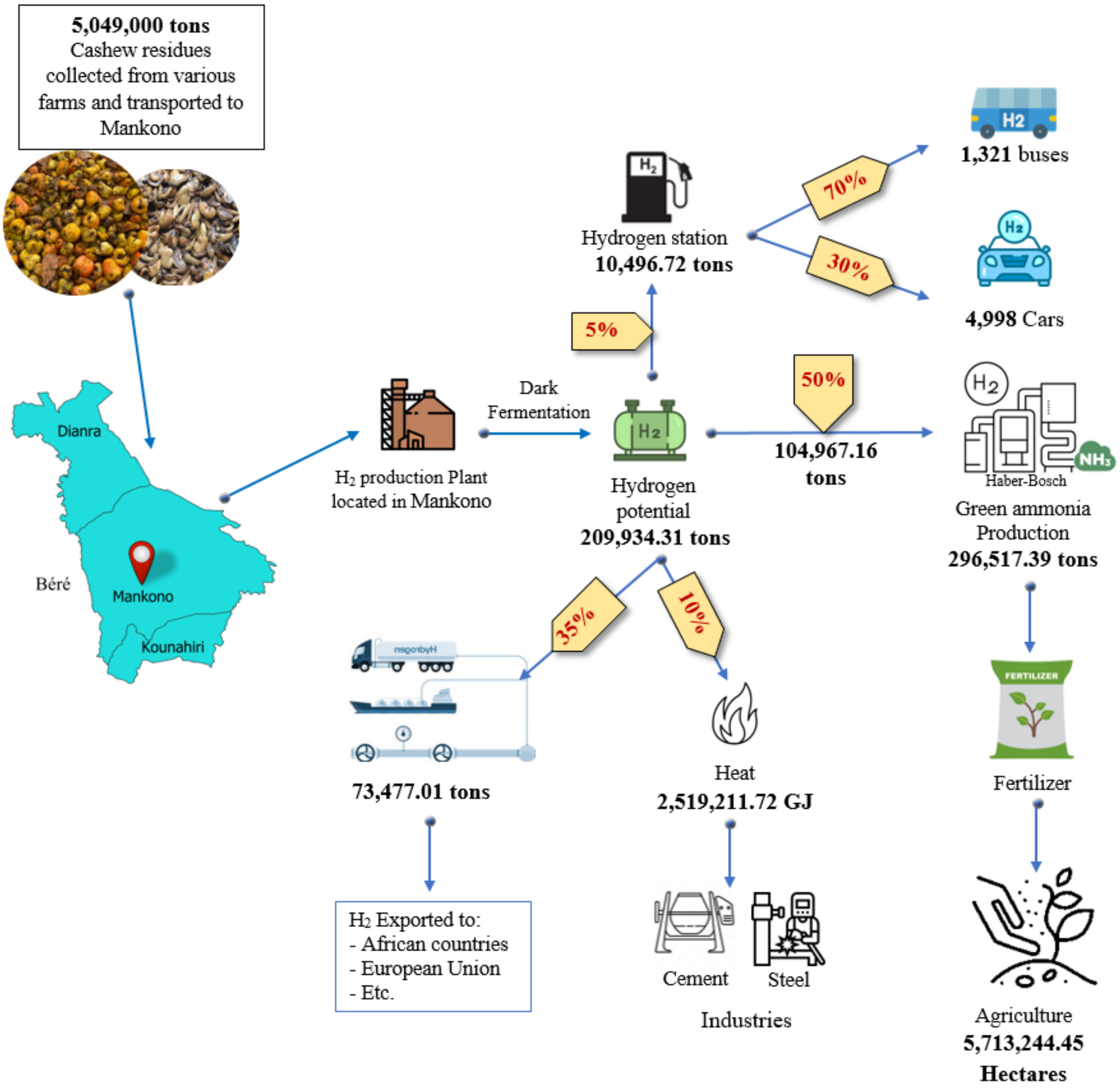


Figure 15: Schematic diagram of different steps of scenario C

3.2.4. Impact of the scenarios

The three scenarios have a positive impact on the environment, the economy and society. In Côte d'Ivoire most of the vehicles are older than 10 years therefore, enhancing greenhouse gas emissions and increasing air pollution because of the incomplete burnt fuel (Doumbia et al., 2018). Assuming the amount of hydrogen to be equivalence of gasoline (1kg H_2 equal to 2.8kg Gasoline) for small vehicles and diesel (1kg H_2 equal to 2.79 kg Diesel) for buses (Milojević, 2016), an overall 194,110.50 tons of CO_2, emission could be reduced yearly. Specifically, the scenarios (A, B, C) are able to reduce 44,794.47 tons of CO_2, 95,133.56 tons of CO_2 and 54,182.46 tons of CO_2 respectively. As a result, that will decarbonize the transport sector up to 12%. Hence, resulting in climate change mitigation, the improvement of air quality, public health enhancement and environmental benefits. On the other hand, the emission of CO_2 in the electricity sector will be greatly reduced. The first scenario which provide 50 percent of total hydrogen produced will have a CO_2 reduction of 945,120 tons per year. Thus, contributing 57% of decarbonization. This will not only reduce dependence on fossil fuels, but also boost the integration of renewable energies to 42.92%. As a result, this will increase and exceeds the government's target of 42% renewable energy by 2030. In addition, increasing the use of hydrogen in the electricity sector will increase income while decreasing poverty and improving education, can promote sustainable development. The diagram below shows the share of electricity generation by source.

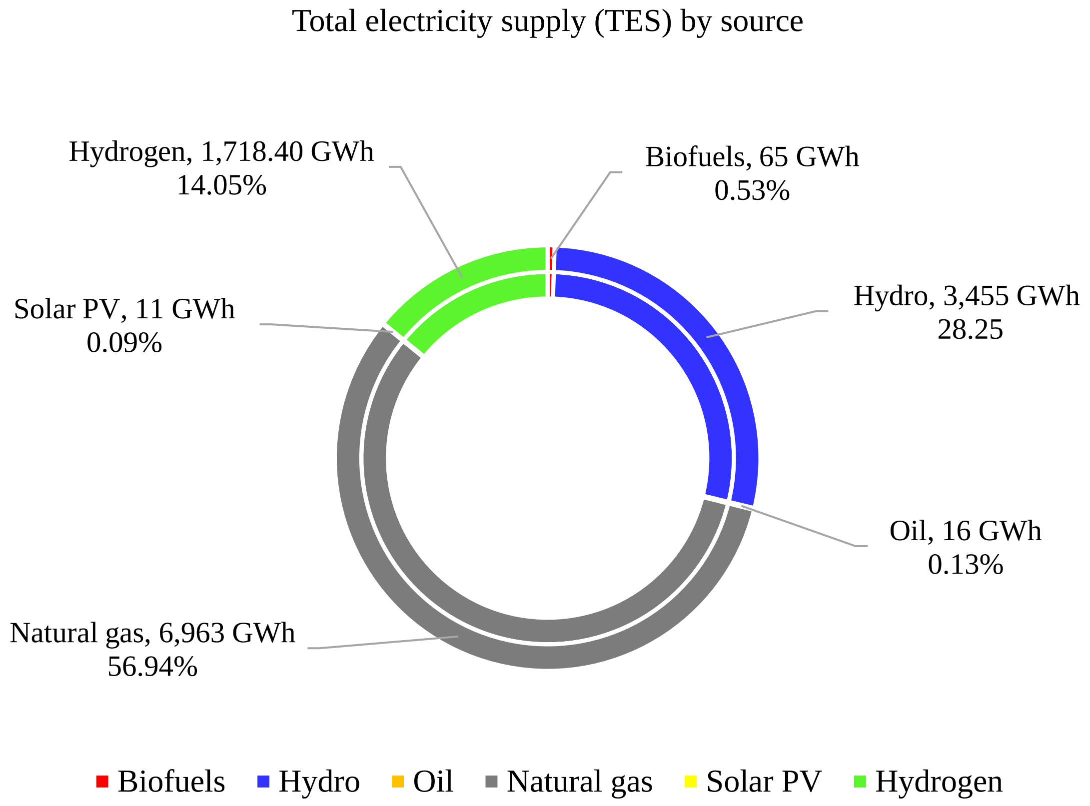


Figure 16: Total electricity supply by source including the scenarios

The industrial sectors which represents a hard-to-debate sector is positively impacted in the three scenarios. Supplying heat from hydrogen will replace fossil energy, and natural gas and indeed mitigate up to 505,491.58 tons of CO_2 emissions specifically, 116,642.74 tons, 247,772.99 tons, and 141,075.86 tons, for scenarios A, B and C respectively. This CO_2 reduction will lead to 31% of decarbonization. Considering that Côte d'Ivoire currently emits around 14.5 million tons of CO_2, the implementation of this project would result in a substantial annual reduction of 11.34% in carbon dioxide emissions. This highlights the significant impact that these measures can have on CO_2 mitigation and the promotion of sustainable practices. On the economical aspect, the production cost of renewable hydrogen in Africa is cheaper as compared to Europe. Kalinci et al. (2012) investigated three different gasifiers for hydrogen production, namely, downdraft gasifier, circulating fluidized bed gasifier and plasma gasifier. Their study reported production costs per unit mass of 1.16 $/kg, 3.33 $/kg and 2.45 $/kg respectively. Considering circulating fluidized bed gasifier cost, the production cost of scenario A and B could be estimated at 578,006,415 US Dollars and 1,227,803,667 US Dollars respectively. This means that hydrogen can be produced entirely in Côte d'Ivoire, if a lot of efforts are being made. Additionally, exporting hydrogen will trigger the country's economy. More importantly, according to the Ivorian Ministry of the Economy and Finance, in 2021 the imported fertilizer cost was 107 million Euros for 357,179 tons. Comparing with the green fertilizer production in the scenarios, up to 817,293.95 tons of fertilizers could be generated. While considering a local selling price (22.33 US Dollars per kilograms of fertilizer), up to 18,250,173.9 US Dollars can be earned per year. This will not only stimulate the economy, but also make the country independent of imported fertilizers and increase crop productivity. All these scenarios will provide many employment opportunities to young generation and cope with unemployment. The diagram shows the carbon that could be reduced in each sector.

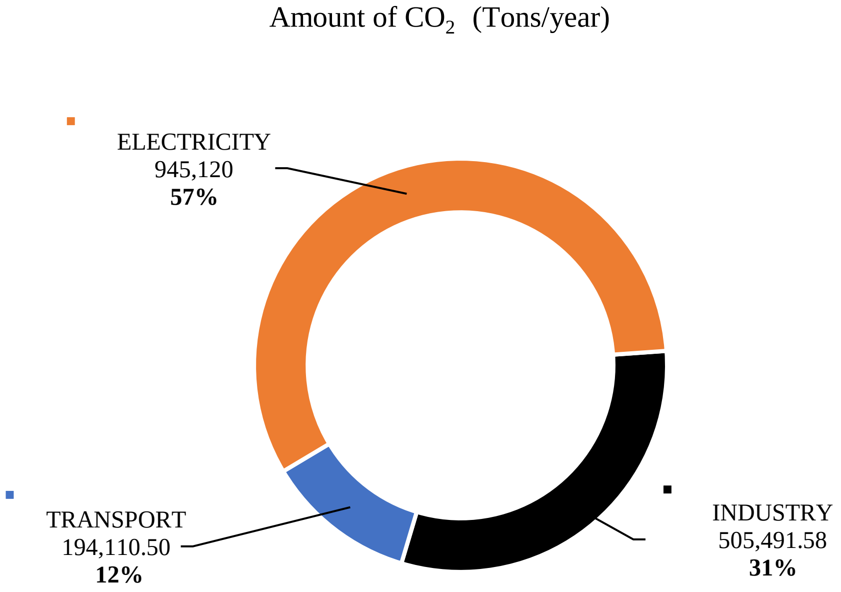


Figure 17: Carbone dioxide (CO_2) reduction from the scenarios

CONCLUSION AND PERSPECTIVES

In this work, strategies for hydrogen development in Côte d'Ivoire are illustrated. The study focused primarily on assessing the potential of biomass and the amount of energy and hydrogen that can be produced. Scenarios have been developed to highlight the strategies needed to build hydrogen industries, as well as sectors that would have a high demand for hydrogen. The approach used in this study was entirely theoretical. The results revealed that Côte d'Ivoire generated in 2019, up to 16,801,306 tons of crop residues from 11 types of crops. These residues are diverse and dominated by the cashew sector in the northern regions with Béré (929,200 tons) and Gbeke (652,800 tons). Following by cocoa in the West and Southwest regions. Guémon and San Pedro regions have the highest cocoa residues at 1,841,700 tons and 1,820,000 tons respectively. This considerable amount of biomass has an energy potential of 273,387,320 GJ and theoretical hydrogen potential of 1,296,424.84 tons and could technically produce up to 907,497.39 tons of hydrogen per year. To achieve this, the study emphasized on the adoption of crop waste management strategy by involving stakeholders and training farmers. Followed by a strategy for capacity building in order to have a highly skilled workforce. The three proposed scenarios demonstrated a significant impact. The Ivorian industries can be supplied with 9,026,635 gigajoule of heat. Under these scenarios, up to 17,910 cars and 4,732 buses could run on hydrogen. The agricultural sector could receive up to 817,293.95 tons of green ammonia, which can be used on 15,747,475.04 hectares of arable land. In addition, the electricity sector could be positively impacted by supplying an electricity to approximately 5,727,992 households with an annual production of 1,718.40 gigawatt-hour. Thus, up to 1,644,722.08 tons of CO_2 could be reduced, shared as follows: 12% in transport, 31% in industry, and 57% in the electricity sector. Added to this, there is the possibility of exporting 263,276.87 tons of hydrogen to other countries.

This research has highlighted the benefits of valorizing crop residues and demonstrated the significant impact of hydrogen in various sectors. According to the finding of this study, it can be seen that there are potential crop residues that can be converted to hydrogen, which is a promising solution. However, the lack of public awareness of the use of residues, the lack of funding for the management of crop residues, the lack of government policies and regulations, etc. are a major challenge. It is therefore imperative to conduct in-depth experimental studies to make these results more accessible and applicable. It is also necessary to develop political and financial strategy to trigger the development of hydrogen in Côte d'Ivoire.

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APPENDIX 1: CARBON DIOXIDE EMISSION MITIGATION

- ELECTRICITY SECTOR

CO_2 EMISSION = Electricity consumption* × *Emission factor

Emission factor for natural gas	0.55 kgCO_2/kWh
Electricity consumption	1,718,400,000 kWh/year
Emissions reduction in electricity sector	945,120,000 kgCO_2/year
Emissions reduction in electricity sector	945,120 tonsCO_2/year

- TRANSPORT SECTOR

Assumptions:

On average a car in Côte d'Ivoire drives 100 km/day so 36,500 km/year**.**	On average a bus in Côte d'Ivoire drives 150 km/day therefore 54,750 km/year.
Since 1kgH_2 in a car can travel 96.56 km, a car will consume 378 kgH_2/ year**.**	Since 1kgH_2 in a bus can travel 16.4 km therefore will consume 3,338.4 kgH_2/year.

To find the CO_2 emission reduction, the H_2 consumed by a car and a bus is assumed to be gasoline and diesel respectively:

If 1 kgH_2 = 2.8 kg Gasoline then 378 kgH_2/year =1,058.4 kg Gasoline.	If 1 kgH_2 = 2.79 kg Diesel then 3,338.4 kgH_2/year = 9,314.136 kg Diesel.
1.5 kg Gasoline = 2 L Gasoline	1 kg Diesel = 1.16 L Diesel
1,058.4 kg Gasoline = 1,411.20 L/year	9,314.136 kg Diesel = 10,804.40 L/year

CO_2 EMISSION = Fuel consumed × Number of vehicles × Emission factor

	Scenario A	Scenario B	Scenario C	
Number of cars	4,133	8,779	4,998	
Number of buses	1,092	2,319	1,321	
Emission factor for gasoline	2.36	2.36	2.36	$kgCO_2/L$
Emission factor for diesel	2.63	2.63	2.63	$kgCO_2/L$
Annual amount of gasoline consumed by a car	1,411.20	1,411.20	1,411.20	Liter
Annual amount of diesel consumed by a bus	10,804.40	10,804.40	10,804.40	Liter
Annual amount of gasoline consumed by cars	5,832,490	12,388,924.80	7,053,177.60	Liter
Annual amount of diesel consumed by buses	11,798,402.35	25,055,398.41	14,272,609.44	Liter
Emissions reduction for cars	13,764,675.46	29,237,862.53	16,645,499.14	$kgCO_2$/year
Emissions reduction for buses	31,029,798.19	65,895,697.81	37,536,962.83	$kgCO_2$/year
Emissions reduction for cars	13,764.68	29,237.86	16,645.50	$tonsCO_2$/year
Emissions reduction for buses	31,029.80	65,895.70	37,536.96	$tonsCO_2$/year

Total emission reduction in each scenario	44,794.47	95,133.56	54,182.46	tonsCO_2/year

- INDUSTRIAL SECTOR

CO_2 EMISSION = Heat consumption × Emission factor

	Scenario A	Scenario B	Scenario C	
Emission factor for natural gas	56	56	56	kgCO_2/kWh
Heat consumption	2,082,906	4,424,517.72	2,519,211.72	kWh
Emissions reduction from heat generation	116,642,736	247,772,992.32	141,075,856.32	kgCO_2/year
Emissions reduction from heat generation	116,642.74	247,772.99	141,075.86	tonsCO_2/year