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ASSESSMENT OF BIOMASS POTENTIAL FOR BIOENERGY PRODUCTION IN MALI: ENHANCING ENERGY SECURITY

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by:

Djènèba FANE

<u>Exam Committee members:</u>

Chair: Amivi Kafui TETE-BENISSAN, Professor, Université de Lomé - Togo

Examiner/judge: Pali KPELOU, Associate Professor, Université de Lomé - Togo

Main Supervisor: Komi AGBOKA, Associate Professor, Université de Lomé - Togo

Co-Supervisor: Satyanarayana NARRA, Professor, University of Rostock - Germany

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

Bundesministerium für Forschung, Technologie und Raumfahrt

Dedication

This thesis is dedicated to my parents, sisters and brother for their constant guidance and encouragement over my span of studies.

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Declaration

I, Djènèba Fané hereby declare that this master’s thesis is my own work and has been written independently, with all sources used duly acknowledged.

Abstract

Despite Mali's abundant biomass resources, its potential for bioenergy production remains untapped, contributing to persistent energy insecurity, heavy reliance on traditional biomass and imported fossil fuels. This study assesses and quantifies available livestock waste, cereal crops residues and municipal solid waste, for biomethane, energy and biohydrogen production, with the aim of enhancing national energy security. Secondary data from the three principal biomass types across nine main regions of Mali, especially Kayes, Koulikoro, Sikasso, Ségou, Mopti, Tombouctou, Gao, Kidal and Bamako were processed and analyzed based on data collected from 2013 to 2018 to estimate the potential for the years 2020, 2025, 2030, 2035, 2040, and 2045. Subsequently, bioenergy potentials were quantified using Buswell's equation for anaerobic digestion and the general biomass gasification equation for thermal conversion.

The results showed that the central region, Mopti, has the greatest potential for biomethane, energy and hydrogen production (1134402.9 kt, 2018428376.53 GWh and 226276698.38 Mmol respectively in 2045) through anaerobic digestion, whereas it was Kayes which showed the highest cereal crops potential for hydrogen production through gasification (67.68 Mmol, 291.18 Mmol, 1345.02 Mmol, 6410.05 Mmol, 30999.19 Mmol and 151019.89 Mmol for the years 2020, 2025, 2030, 2035, 2040 and 2045 respectively). Overall, the results highlighted the significant and region-specific potential of biomass resources to support decentralized renewable energy solutions in Mali, particularly through anaerobic digestion and gasification technologies.

These findings contribute to the field by providing a data driven foundation for policy development, investment planning, and the promotion of sustainable energy practices tailored to local biomass availability.

Key words: Waste-to-energy; Mali; anaerobic digestion; gasification; biomass potential.

Résumé

Malgré les ressources abondantes du Mali en biomasse, son potentiel de production bioénergétique reste inexploité, ce qui contribue à une insécurité énergétique persistante et à une forte dépendance à l'égard de la biomasse traditionnelle et des combustibles fossiles importés. Cette étude évalue et quantifie les déchets d'élevage, les résidus de cultures céréalières et les déchets solides municipaux disponibles pour la production de biométhane, d'énergie et de biohydrogène, dans le but de renforcer la sécurité énergétique nationale. Les données secondaires provenant des trois principaux types de biomasse dans neuf régions principales du Mali, en particulier Kayes, Koulikoro, Sikasso, Ségou, Mopti, Tombouctou, Gao, Kidal et Bamako, ont été traitées et analysées sur la base des données collectées entre 2013 et 2018 afin d'estimer le potentiel pour les années 2020, 2025, 2030, 2035 et 2040 et 2045. Par la suite, les potentiels bioénergétiques ont été quantifiés à l'aide de l'équation de Buswell pour la digestion anaérobie et de l'équation générale de gazéification de la biomasse pour la conversion thermique.

Les résultats ont montré que la région centrale, Mopti, présente le plus grand potentiel en termes de production de biométhane, d'énergie et d'hydrogène (1134402,9 kt, 2018428376,53 GWh et 226276698, 38 Mmol respectivement, en 2045) à travers la digestion anaérobie, tandis que c'est Kayes qui présente le plus grand potentiel de production d'hydrogène à partir de céréales par gazéification (67,68 Mmol, 291,18 Mmol, 1345,02 Mmol, 6410,05 Mmol, 30999,19 Mmol and 151019,89 Mmol pour les années 2020, 2025, 2030, 2035, 2040 and 2045 respectivement). Dans l'ensemble, les résultats ont mis en évidence le potentiel important et spécifique à chaque région des ressources biomasse pour soutenir des solutions décentralisées d'énergie renouvelable au Mali, en particulier grâce aux technologies de digestion anaérobie et de gazéification.

Ces résultats contribuent à l'avancement de la recherche dans ce domaine en fournissant une base factuelle pour l'élaboration de politiques, la planification des investissements et la promotion de pratiques énergétiques durables adaptées à la disponibilité locale de la biomasse.

Mots clés: Valorisation énergétique des déchets; Mali; digestion anaérobique; gazéification; potentiel de biomasse.

Acronyms and Abbreviations

MSW: Municipal Solid Waste

AD: Anaerobic Digestion

Mtoe: Million tonnes of oil equivalent

GHG: Greenhouse Gases

CO_2: Carbon dioxide

CH_4: Methane

CO: Carbon monoxide

H_2O: Water

H_2: Hydrogen

MPa: Mega Pascal

RGPH: Recensement Général de la Population et de l'Habitat

CAGR: Compound Annual Growth Rate

MJ: Megajoules

m^3: Cubic meter

kWh: Kilowatts-hour

GWh: Gigawatts-hour

EWh: Exawatt-hour

Gmol: Gigamoles

Mmol: Megamoles

kmol: Kilomoles

Mtoe: Million tonnes of oil equivalent

ktoe: Kilotonne of oil equivalent

GDP: Gross Domestic Product

VFA: Volatile fatty acid

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Introduction

Mali faces persistent challenges in meeting its growing energy demand. Traditional biomass, mainly firewood and charcoal, which constitute the majority of household energy consumption, are a vital source of energy in the country. This dependence worsens health problems associated with indoor air pollution in addition to rapid deforestation and land degradation. Electricity access remains limited in rural areas (Figure 2) despite efforts to expand solar energy and hydropower.

In addition, Mali is susceptible to the effects of climate change, which threatens water availability and agricultural productivity. Although the country's GHG keeps increasing due to growth of the population, expansion of agriculture and traditional biomass use.

In the light of this, biomass is an important yet underutilized renewable energy source in Mali. However, the country produces a lot of municipal solid waste, livestock manure, and agricultural residues, which might be converted into energy to diversify the energy mix, reduce reliance on imported fossil fuels and increase energy availability.

1. Background

- **Current energy situation in Mali**

In recent decades, fossil fuels have accounted for approximately 80% of the world's energy demand [1]. However, their widespread use poses two significant challenges. Firstly, burning fossil fuels contributes to environmental degradation and releases greenhouse gases (GHGs), which are the primary drivers of climate change [2]. Secondly, they are finite resources, meaning they will eventually be depleted [3]. In Mali, an emerging economy, the demand for energy is increasing as its population grows and its economy expands. The country's energy supply is largely dependent on traditional biomass, such as firewood and charcoal, which accounts for approximately 78% of its total energy consumption [4]. Another study from [5] showed that in 2014, the total primary energy supply was 5.1 million tonnes of oil equivalent (Mtoe) in which 69% (about 3.6 Mtoe) was from firewood and 7% from charcoal. They further stated that 1.02 Mtoe (20%) was accounted for petroleum products (gasoline and diesel) mainly used for the transport sector. Taking the same total of energy supply, only 3.8% was considered as the share of electricity including imports.

- **Greenhouse gas emissions in Mali**

Since the 1990s, Mali has experienced significant economic and demographic development in a context of global warming. Although Mali is a country with low greenhouse gas emissions, it remains vulnerable to the adverse effects of climate change and faces increasing pressure on its natural resources. Mali's economy is based primarily on the agro-pastoral sector (which employs almost 80% of the population and accounts for more than 40% in GDP). However, following the increase in the scale of production, it is accompanied by environmental degradation [6].

The same author further stated that, the latest estimates have shown that Mali is responsible for about 0.06% of global greenhouse gas (GHG) emissions; and Mali's energy supply in 2007 to 2012 rise from 3,543 to 4,755 ktoe, an increase of 34.21% over the three years. For the same period, greenhouse gas emissions have increased slightly from 3433.662 to 4513.955 tons.

The agricultural sector contributes approximately 71% of the country's total greenhouse gas (GHG) emissions, mainly through rice production and livestock farming. This generally high percentage is largely explained by low emissions from energy production (12% of natural emissions), which relies heavily on the use of hydropower. Of these emissions, crop production accounts for 31% of total agricultural emissions and livestock production for 69%. Organic soil cultivation is one of the main contributors to GHG emissions, with savanna burning accounting for 21% of agricultural emissions. In the livestock subsector, enteric fermentation is a major source of emissions (39% of agricultural emissions), closely followed by manure left on pastures (28% of agricultural emissions) [7].

Biomass combustion remains the main source of greenhouse gas emissions in the energy sector. The residential is the most polluting sector, consuming almost all solid biomass. It is followed by the transport sector, which mainly uses petrol and diesel. Carbon dioxide is by far the most dominant greenhouse gas emitted from energy production and consumption in Mali [6].

- **Biomass resources in Mali**

Biomass originates from plants and includes agricultural, forestry waste, sewage, municipal solid waste (MSW) and energy crops. It has been traditionally used to generate heat through direct combustion of firewood, charcoal, agricultural residue, and dung [1]. Mali is one of the Sub-Saharan countries with the highest dependence on traditional biomass use [8]. By 2020, biomass accounted for around 64% of the total energy supply. This was followed by oil at 33%, hydro at 3%, and solar, coal and other sources which were practically insignificant. Mali is primarily considered as an agricultural country and heavily reliant on this activity for its socio-economic development. Thereby, there is considerable amount of crop residues and livestock waste produced, which has not yet been quantified in detail. Furthermore, municipal solid waste is poorly treated in the country. Disposing of waste at uncontrolled open landfill sites is the most common practice. However, waste-to-energy technologies are favoured in waste management hierarchies because they are more socio-economically and environmentally beneficial. Therefore, MSW could also be a potential source resource for the country [3], [9].

2. Problem statement

Mali is confronted with ongoing challenges in achieving energy security as a significant part of the population still does not have access to electricity as seen in (**Error! Reference source not found.**). Moreover, the country's heavy reliance on imported fossil fuels and traditional biomass contributes to deforestation, greenhouse gas emissions, and public health risks from indoor air pollution. Although the country has abundant biomass resources from livestock waste, crop residues, and MSW, their potential for producing bioenergy remains largely unquantified and underutilized. Existing studies often focus on individual biomass resources or specific regions, leaving a critical gap in comprehensive, long-term assessments covering all major regions of Mali. Without accurate data on the sustainable availability of these resources and their energy conversion potential, policymakers and investors lack the necessary evidence to plan and implement effective renewable energy strategies. The present research addresses this gap by assessing some of Mali's biomass potential and estimating its capacity to generate biomethane, biohydrogen and energy from 2020 to 2045, with the aim of enhancing national energy security.

3. Research questions

This study is driven by the following questions:

- What is the potential of livestock waste, cereal crops, and MSW in the nine main regions of Mali for the years 2020, 2025, 2030, 2035, 2040, and 2045?
- What is the biomethane, energy and biohydrogen potential from livestock and MSW.
- What is the biohydrogen potential from cereal crops residues.

3. Research hypotheses

This research is based on the following hypotheses:

- There is no significant potential of livestock waste, cereal crops, and MSW in Mali.
- There is a no significant biomethane, energy and biohydrogen potential sufficient to enhance the country's energy security.
- There is a significant potential of livestock waste, cereal crops, and MSW in Mali to produce biomethane, energy and biohydrogen that can enhance the country's energy security.

4. Objectives

Main objective

The main objective of this study is to assess Mali's biomethane, energy and biohydrogen potential from livestock waste, cereal crops residues, and MSW to enhance its energy security.

Specific objectives

- To estimate the potential of livestock waste, cereal crops residues, and MSW in the nine main areas of Mali for the years 2020, 2025, 2030, 2035, 2040, and 2045.
- To calculate the biomethane, energy and biohydrogen potential from livestock waste and MSW through anaerobic digestion.
- To calculate the biohydrogen potential from cereal crops through gasification.

5. Structure of the thesis

This thesis is organized into three main chapters:

- **Chapter one**: Literature review

This chapter reviews existing studies on livestock waste, cereal crops and MSW, as well as hydrogen conversion technologies such as anaerobic digestion, pyrolysis, gasification, hydrothermal, dark fermentation, photo-fermentation, and bio-photolysis.

- **Chapter two**: Materials and methods

This chapter describes the data sources, analytical methods, and calculation procedures used to estimate the potential of the three biomasses used in Mali from 2020 to 2045. It also details the approaches of quantifying biomethane, energy and biohydrogen generation through anaerobic digestion and gasification, in line with study's specific objectives.

- **Chapter three**: Results and discussion

The last chapter in this work presents and interprets the results of the biomass potential assessment. It discussed the quantity of the available biomass and their corresponding biomethane, energy and biohydrogen potential.

Chapter 1: Literature review

This chapter provides an overview of the key literature on biomass resources and bioenergy conversion technologies. It further explores the main biomass sources available in Mali, such as crop residues, livestock waste and MSW, highlighting their characteristics and potential for energy production. The chapter also reviews the fundamental processes of anaerobic digestion, as well as various thermochemical and biological methods of generating biohydrogen and electricity from biomass. Finally, it discusses the evolving dimensions and importance of energy security in achieving sustainable energy development.

1.1 Major biomass types

1.1.1 Crop residues

Crop residues are known as a key biomass resource to feed tomorrow's sustainable bioeconomy [10]. They are distributed resources with variations in their spatial and temporal availability, as well as in their characteristics. Gross residues and surplus residues are different categories of crop residues. The gross residues are used by farmers for different purposes, and the surplus residue depends on it and the area covered by cultivation [11].

The major type of crop produced in Mali are cereals and the main grown for subsistence are millet, sorghum, rice, and maize (corn), which represent almost 75% of total crop production for food in the country. Considering the production of cowpea, groundnut, and sweet potatoes, it increases the share to around 82%. There are also fruit crops like mango, banana, and orange which contribute significantly to food production. According to the Malian government, cotton and sugarcane are considered as the two main cash crops since sugarcane has a high production potential and cotton a key crop for socio-economic development [3].

1.1.2 Livestock

Livestock is a large and growing sector at an accelerated rate due to increased demand for animal products from a rapidly growing and affluent human population. The contribution of different livestock systems to the supply of these products varies widely. Most meat and milk come from mixed crops-livestock production systems and industrial [12].

Grazing systems contribute relatively little to the global food supply, despite occupying a large proportion of land and playing a key social role, particularly in very extensive conditions. The importance of grazing systems as users of natural resources, a source of livelihoods, and engines of economic growth has attracted significant attention in the last decade. The livestock sector is the largest land-use system on earth. It contributes 40% of global agricultural gross domestic product and provides income for over 1.3 billion people as well as nourishment for at least 800 million food-insecure individuals. However, it uses vast areas of rangeland, one-third of the world's freshwater, and one-third of global cropland for feed [13]. Livestock systems emit about 8 to18% of GHGs and use 25 to 32% of global fresh water [12].

In the process, livestock can contribute valuable nutrients to crops but can also be responsible for nutrient pollution and soil degradation. They can provide both protein and micronutrients essential to human nutrition and contribute to obesity. The role played by livestock farming varies depending on location and circumstances, as this sector presents many dualities [13].

The waste generated by livestock is a mixture of solid and liquid materials, including animal-by-products derived from cattle, poultry, pigs, rabbits, sheep, and goats. The livestock waste is either transported to treatment facilities or directly applied to agricultural fields as fertilizer. For the treatment facilities, the waste undergoes anaerobic or aerobic digestion, resulting in biogas and digestate. The biogas produced can be used to generate thermal energy and electricity, while the residual by-product is separated into solid and liquid components. These components can be used in a variety of ways: the liquid is used as fertilizer, while the solids are frequently made into compost or animal bedding [14].

1.1.3 Municipal solid waste

The municipal biomass is classified into three major categories such as municipal solid waste, municipal sewage, and urban wood biomass. It contains significant quantities of carbohydrates, which have considerable potential to be applied as an energy source [15].

The same author further designated MSW as a solid waste released from people's daily life and work generated in households, commercial establishments, institutions, and businesses in urban areas. Items like used paper, discarded cans and bottles, food scraps, yard trimmings, industrial process wastes, agricultural wastes, mining waste are common constituents of MSW. Conventionally, MSW is divided into different categories based on the material. These include food residue, wood waste, paper, textiles, plastics, and rubber. In terms of its chemical and biological properties, MSW can be divided into organic matter such as paper, wood, textiles, and leather, which is considered the main feedstock for waste-to-energy processes using different energy conversion technologies (incineration, digestion, pyrolysis and bio-technologies), and inorganic matter consisting of metals, glass, concrete, masonry and so on.

Inefficiency in municipal corporations' collection and transportation capacity results in significant MSW accumulation. Furthermore, the open, unsanitary and indiscriminate dumping of MSW in landfills poses an additional threat, contributing distinctly to GHG emissions, primarily methane (CH_4). Additionally, negligible segregation of collected MSW, leads to leachate generation, degrading the surrounding soil and water resources and impacting the health of nearby residents [16].

1.2 Bioenergy conversion technologies

Various bioenergy technologies can be used to convert biomass into different forms of useful energy. These methods are usually categorized as thermochemical, biochemical, or biological, depending on whether heat-driven processes or microorganisms are used. The subsequent sections outline the main processes for converting biomass into energy carriers such as biogas, hydrogen, and bio-oil, emphasizing both thermochemical and biological approaches.

1.2.1 Anaerobic digestion

Anaerobic digestion is a biological process that involves biochemical reactions by converting organic matter into a CH_4-rich gas phase in an oxygen-free environment [17]. It is one of the useful techniques that produces biogas by reducing waste. Hydrolysis, known as the first step of the anaerobic digestion process, is where complex organic materials (protein, lipids…) and carbohydrate polymers (starch and cellulose) are hydrolyzed to create monomers (long fatty acids, sugars and amino acids) [18]. During acidogenesis the second phase, hydrolysis products are converted into intermediate volatile fatty acids (VFAs) such as acetic propionic and butyric acids along with minor amounts of ethanol, and lactic acid by acidogenic microorganisms. Now comes the third stage, acetogenesis where acetic acid, hydrogen, and CO_2 are produced from VFAs. The process ends with the methanogenesis phase, whereby the methanogens utilize H_2 as an electron donor to produce CH_4 [17]. The process flow of anaerobic digestion is shown in (Figure 1).

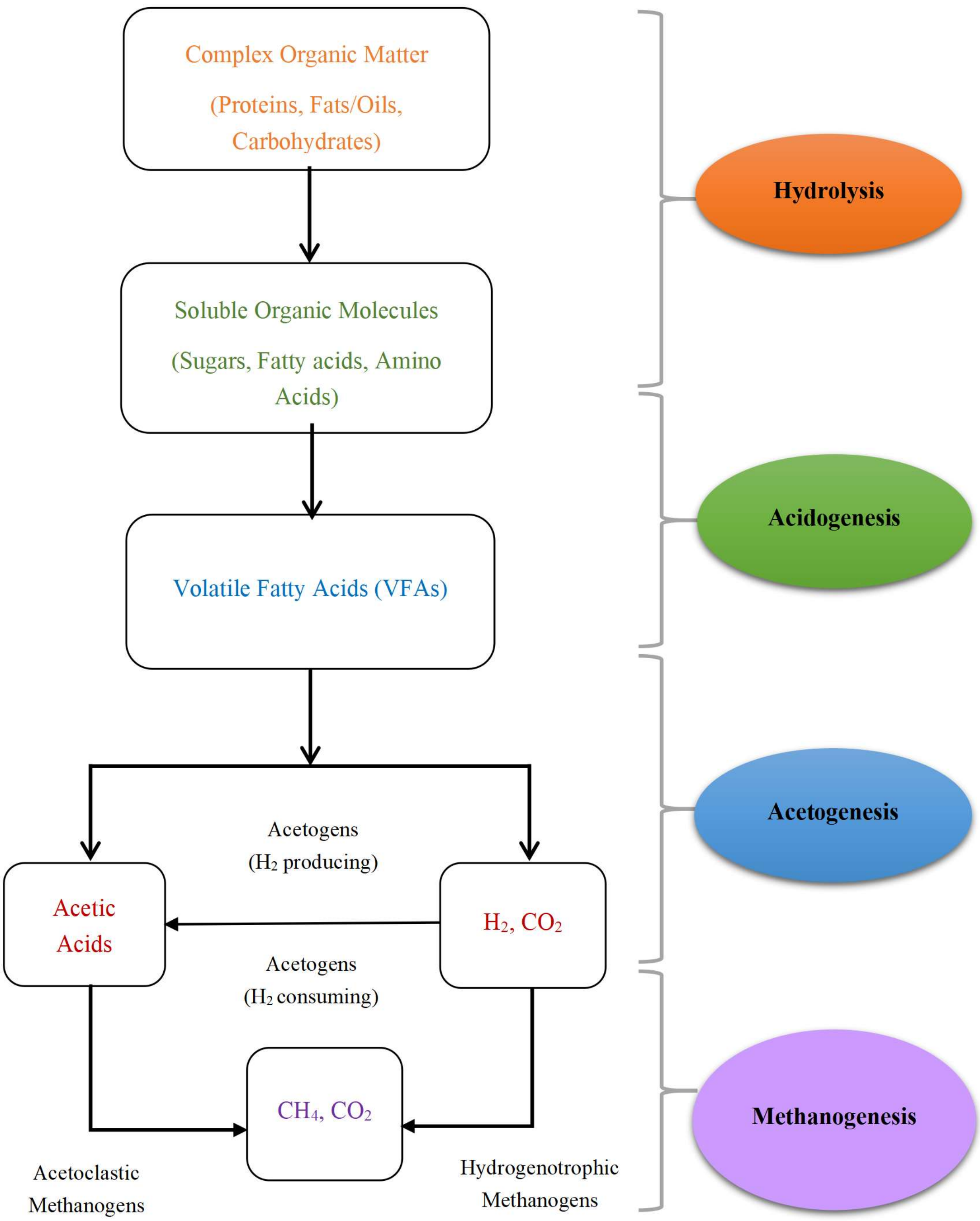


Figure 1: Process flow diagram of anaerobic digestion

1.2.2 Biohydrogen production methods

Biohydrogen production is a process of producing hydrogen from biomass that offers a promising pathway toward achieving sustainable and eco-friendly energy systems. It can be done either from thermochemical methods (gasification, pyrolysis and hydrothermal) or biological methods (dark fermentation, photo fermentation and bio-photolysis) [19].

1.2.2.1 Thermochemical methods

1.2.2.1.1 Gasification

Biomass gasification, a significant bioenergy production technology, is a pathway for transforming woody materials into thermal energy, electrical power and diverse vehicular fuels. Partial oxidation is involved in its process to enhance the generation of syngas and obtain maximum hydrogen quantity. The distribution of products relies on factors like the chemical makeup of biomass and the gasifying agent used. The resulting gas from the primary components are H_2, CO_2, CO, H_2O, N_2 and CH_4. Gasification process of biomass may occur with or without the presence of a catalyst and fluctuate within temperatures from 500 to 1000°C and pressures around 0.98 to 2.94 atmospheres [20].

1.2.2.1.2 Pyrolysis

Pyrolysis is known as a precursor to the multiple thermochemical processes converting low-energy-density biomass into high-energy-density biomass in an oxygen-depleted atmospheres [21]. As one of the promising methods for generating renewable energy and reducing environmental pollution, biomass pyrolysis uses organic materials generated from agricultural, forestry, and industrial activities as waste. Some of the advantages of this process include utilizing waste materials, reducing the competition between food and energy production and decreasing the cost of feedstocks. The main products from pyrolysis are char, bio-oil, and syngas, transformable into valuable energy resources [22]. The temperature of this process ranges from 300 to 600°C depending on the types: fast pyrolysis is more effective because of the higher temperatures and faster heating rates compared to slow pyrolysis which has lower temperature [21].

1.2.2.1.3 Hydrothermal

Hydrothermal process is an emerging technology using hot compressed water to convert various biomass feedstocks like recalcitrant organic compounds in biowastes into desired solid, liquid, and gaseous products. Based on operating conditions, hydrothermal treatment of biomass is classified into hydrothermal carbonization (HTC), hydrothermal liquefaction (HTL), and hydrothermal gasification (HTG). HTC occurs at low temperatures (130 to 250°C) and self-generated pressures (1 to 5 MPa) obtaining solid products: hydro-char used as solid fuels and carbonaceous materials [23]. HTL technology utilizes subcritical water which has higher ionic products and lower dielectric constant, to break down organic pollutants such as polyhydroxyalkanoates, triclosan, polychlorinated biphenyls, pesticides and polyfluoroalkyl substances efficiently [24]. HTL works under a moderate temperature (250 to 374°C) and pressure (4 to 22MPa) ranges. The bioproducts from this process, bio-oil, serve as potential chemical buildings blocks. HTG is a process where gaseous products are formed such as H_2, CO_2, CO, and CH_4 above 374°C and 22 MPa [23].

1.2.2.1.4 Steam methane reforming

Steam methane reforming (SMR) is currently the most widely used method to produce hydrogen [25]. Compared to the other industries such as energy and transport, it is the main chemical reaction for the large-scale production of hydrogen and synthesis gas in the chemical industry [26]. During the reaction, methane reacts with steam to produce hydrogen, carbon dioxide and carbon monoxide. Today, almost all hydrogen in oil refineries is produced by SMR and accounts for over 48% of global H_2 production [25]. A high operating temperature of 700 to 900°C is necessary for the process, which is significantly endothermic, to ensure consistent conversion of methane to hydrogen. Additionally, low pressures are also favorable for SMR since the reaction involves an increase in the number of molecules [27].

1.2.2.2 Biological methods

1.2.2.2.1 Photo-fermentation

Photo-fermentation is known as a biological process through which organic substrates from wastewater or biowaste are converted into hydrogen gas using particularly purple non-sulfur as bacteria (PNSB). These types of bacteria are made to utilize light energy to drive hydrogen production. It is a process that combines metabolic and photosynthetic pathways [28]. Due to its utilization of solar energy and diverse carbon sources, photo-fermentation is viable and has the advantage of continuous operation, ensuring a consistent and uninterrupted hydrogen gas supply [19].

1.2.2.2.2 Dark fermentation

Dark fermentation process involves the production of hydrogen through the degradation of complex organic substrates (carbohydrates mainly). Demonstrated to have a high production rate, it provides the advantage of using various types of organic waste such as agricultural waste, and food waste. Moreover, effluents from dairy, paper industries and other carbohydrate-rich wastewaters can be also used as feedstocks [29]. Dark fermentation is a versatile and efficient process for hydrogen production because of its operation in the absence of light [19].

1.2.2.2.3 Bio-photolysis

Bio-photolysis is a mechanism in biohydrogen production that occurs in two forms: direct and indirect [30]. Direct photolysis derives its energy from sunlight using specialized microorganisms or photocatalysts to directly convert water into hydrogen gas. Unlike indirect photolysis primarily in cyanobacteria, which generates organic compounds that are then transformed into hydrogen gas through chemical or biological processes by involving photolysis of biomass [19].

1.3 Electricity production methods from biomass

There are variety ways to produce electricity from biomass. Options for the prime mover include steam turbine, internal combustion engine and gas turbine [31].

1.3.1 Steam turbine

The central component of a thermal power plant is a steam turbine, which converts the thermal energy of the steam into mechanical energy. This mechanical power is then converted into electricity in a generator [32]. In a biomass power plant, biomass is burned in a boiler to produce pressurized steam. This steam is then expanded through a turbine to generate electricity. A fully condensing turbine is used for power production only, while it is a condensing-extraction also called back-pressure which is used for electricity and heat production [31].

1.3.2 Internal combustion engines

Internal combustion engines are machines that convert heat produced by combustion into mechanical work [33]. It is a small scale alternative for generating electricity from producer gas or biogas [31]. A producer gas is a combustible gas that is generated from biomass gasification in a reactor known as a gasifier. Feedstock used in a gasifier are generally wastes from agricultural and forestry biomass. Additionally, a product of gasification, raw producer gas, can be used directly as fuel for burners for heating purposes, or as fuel for internal combustion engines [34].

1.3.4 Gas turbines

The gas turbine is a continuous-flow engine that produces a steady flame during combustion. This favorable feature enables the use of various fuels and ensures clean combustion in the gas turbine [35]. It is composed of three parts: a compressor, a combustion chamber and a turbine. The process involves gas being compressed in the compressor, fired in the combustor, and then expanding inside the turbine. This causes the turbine to spin rapidly, transforming some of chemical energy in the gas or liquid fuel into mechanical work and producing electrical power. Additionally, gas turbines have a compact structure that is much smaller than that of steam turbines. However the fuels used in gas turbines are generally combustible gases and oils [36].

1.4 Energy security

The term 'energy security' is defined differently in different contexts [37]. In the 1870s and 1980s, [38] defined it as a stable supply of cheap oil in the face of potential embargoes and price manipulation by exporters. However, in 2006 [39] defined the term as encompassing a broader range of issues beyond oil supplies. Furthermore, [40] stated the concept of energy security now involves other energy policy issues, such as mitigating climate change and providing equitable access to modern energy. The notion of energy security has been introduced by the Asia Pacific Energy Research Centre and published in many other articles. Notably, it has been related to the four "As": availability, accessibility, affordability, and acceptability [41] Another definition of energy security was demonstrated in the study by [42]. They referred to this as the low vulnerability of vital energy systems involving energy resources, infrastructure, and uses linked together by energy flows.

Public economic decisions can affect energy security, affordability, reliability and sustainability, and have a strong influence on the electricity sector. Therefore, it is important to analyze applicable indicators in the electricity sector to ensure a clear understanding of the wider energy landscape. This is important for achieving economic growth and social development objectives [43].

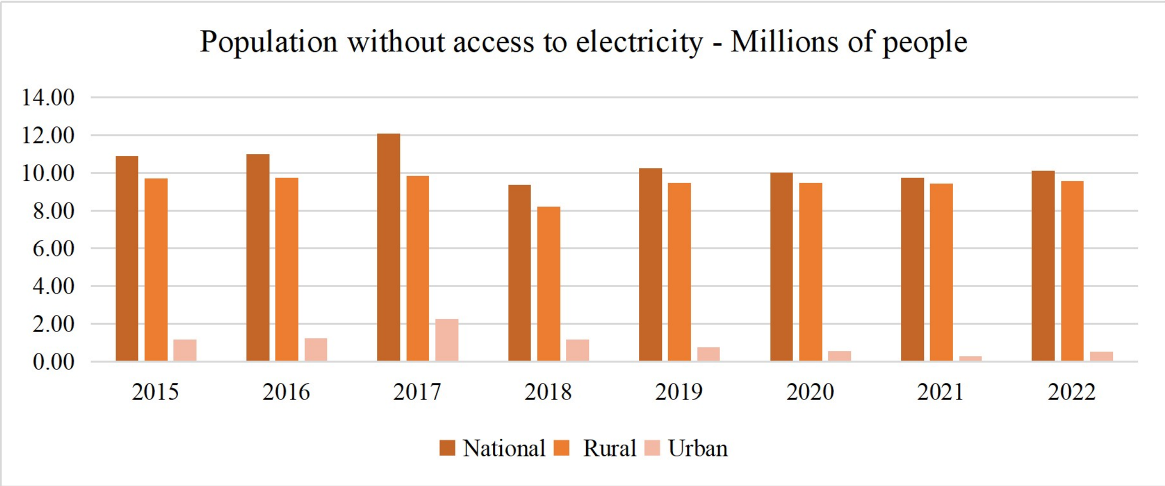


Figure 2: Mali's population without access to electricity [44]

<u>Chapter 2:</u> Materials and methods

2.1. Study area

Mali, one of the landlocked countries located in the sub-Saharan West Africa and having a high dependence on traditional biomass use, is divided into three separate climatic zones: in the south a tropical savanna, a hot semi-arid region in the center and a hot desert in the north [3]. The country has a size of 1,241,238 square kilometers with a population of 20,250,833 habitants according to [45]. This work focuses on cereal crops, livestock waste and MSW potential assessment in Bamako, the capital city located in the southern part, and the eight main regions of the country according to the country's division before 2016 [46]. However, due to unavailable data, Taoudénit and Ménaka were out of the selected regions. The ones considered are: Kayes and Koulikoro in the west, Sikasso and Ségou in the south, Mopti in the center, Tombouctou in the north, and Gao and Kidal in the northeast [47] as seen in (Figure 3) from [48].

Figure 3: Map of the study site

2.2. Methods

Figure 4 summarizes the flowchart of the methodology's major steps. By combining the potential of livestock waste and MSW, biomethane, biohydrogen and energy were produced. Only cereal crops were used to produce biohydrogen in each specific region over the years considered.

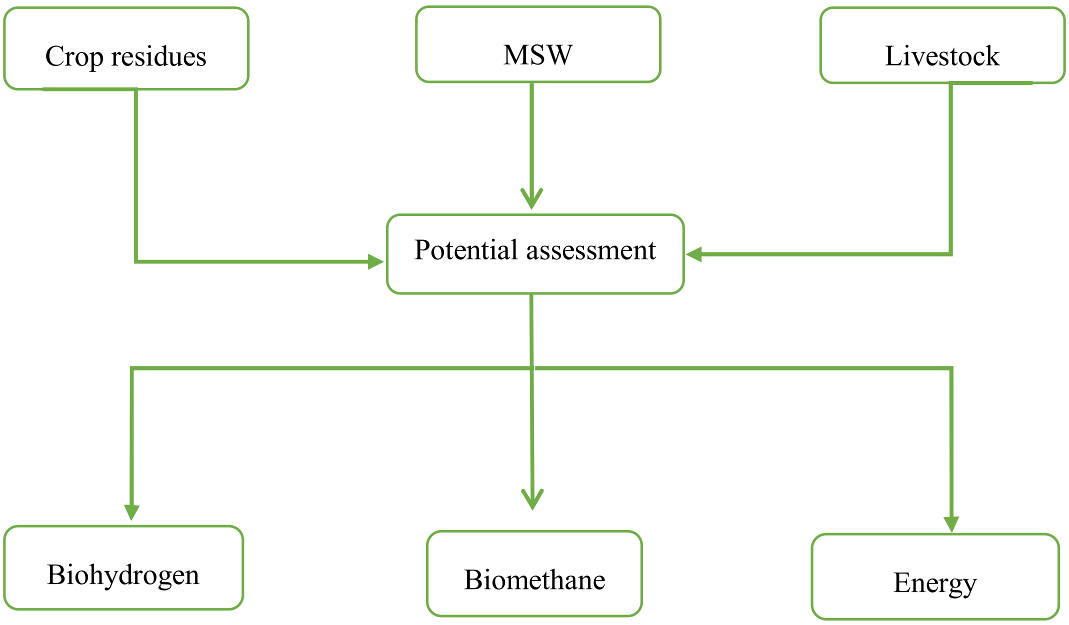


Figure 4: Flowchart of the methodology

2.2.1. Data Collection

The data needed to calculate Mali's livestock waste, cereal crop residues, and MSW potential were secondary data collected from articles and the Statistical Yearbook of the Rural Development Sector published by the Finance and Economy's Ministry.

2.2.2. Data processing and analyzing

The data collected of the various feedstocks were classified by region and year. Data from 2013 to 2018 was used to estimate biomass potential from 2020 to 2045 in each region. The results were processed in Microsoft Excel and presented using tables and figures in Origin Pro for interpretation.

2.3. Biomass resources assessment

2.3.1. Livestock waste

The livestock used in this study includes cattle, sheep, goats, horses, donkeys, camels, pigs and poultry. Biomass potential, which according to [3] is the share of biomass waste that could be collected and is disposed of or burned is calculated using (Equation 1) for determining the livestock waste potential in each region of the country.

$$\mathrm{LWP} = \mathrm{N_a} * \mathrm{Y_m} * \mathrm{C_c} * \mathrm{D_y} \qquad \textit{(Equation 1)}$$

Where LWP is the livestock waste potential; N_a is the number of head of animals in the region; Y_m is the daily manure yield of the animal; C_c is the collection coefficient or availability factor for the animal and D_y, the number of days in a year.

- **Calculations**

The following stages were considered for the calculation of livestock waste potential (LWP) for the years 2020, 2025, 2030, 2035, 2040 and 2045:

- **Stage one:**

The number of animals for each region from 2013 to 2018 expect 2015 (data not available) were obtained from the Statistical Yearbook of Mali. Then ((Equation *2)*, (Equation *3)* and (Equation *4*)) were used to calculate the Compound Annual Growth Rate (CAGR) and the trend values of the number of animals (N_a) for the years 2019, 2020, 2021, 2022 and 2023. CAGR is commonly applied to estimate the average yearly rate of growth [49], [50] of a variable over time, assuming a continuous exponential growth. The same equations were considered to estimate Na for 2025, 2030, 2035, 2040 and 2045.

$$Y_n = (a * b)^n \qquad \textit{(Equation 2)}$$

$$R = \left(\frac{V_f}{V_i}\right)^{1/n} - 1 \qquad \textit{(Equation 3)}$$

Where Y_n is the annual number of animals that must be calculated, a is the intercept value of Y when n = 0, b = (1+ R); R being the compound annual growth rate to be determined.

$$V_f = V_i * (1 + R)^n \qquad (Equation\ 4)$$

Where V_f is the final number of animals to be estimated for a specific year, V_i is the initial number of animals for the year based on, and n is the number of years between V_i and V_f.

- **Stage two:**

Regarding the collection coefficient or availability factor and the manure yield of the animal, data were collected from literature. The average of the minimum and maximum values obtained were taken as seen in (Table 1 and Table 2).

- **Stage three:**

The values obtained from stage one and two were multiply by 365 (number of days in a year) to get the livestock waste potential in each region for the years 2025, 2030, 2035, 2040 and 2045.

Table 1: Collection coefficient of livestock waste

Animal	Collection coefficient	References
Cattle	0.2 - 0.6	[3], [51], [52]
Sheep	0.2 - 0.33	[3], [51], [53], [54]
Goats	0.2 - 0.33	[3], [51], [53], [54]
Horses	0.5	[3], [54]
Donkeys	0.46 - 0.5	[3], [51], [53], [54]
Camels	0.5	[3], [54]
Pigs	0.5	[3], [51]
Poultry	0.5 - 0.99	[3], [54]

Table 2: Manure yield of animals in kg/(day*head)

Animal	Manure yield	References
Cattle	10 - 23	[3], [54], [55]
Sheep	1.2 - 2	[3], [51], [54]
Goats	1.5 - 2	[3], [51], [54]
Horses	10 - 16	[3], [54], [55]
Donkeys	10 - 15	[3], [54]
Camels	15 - 22.5	[3], [54], [56]
Pigs	3.12 - 3.6	[3], [51], [52]
Poultry	0.01 - 0.12	[3], [52], [55]

2.3.2. Cereal crops residues

In this work, only cereal crops were used as crop residues due to the lack of data for fruit and vegetable crops. The main cereal crops considered are millet, sorghum, rice, maize (corn), wheat, and fonio. Moreover, the regions Bamako and Kidal were not part of this assessment due to unavailable data of their annual cereal crops produced.

- **Theoretical cereal residues potential**

Cereal crop residues' theoretical potential was obtained by multiplying the annual production by the residue to product ratio as shown in (Equation 5).

$$\mathrm{Th} = \mathrm{AP} * \mathrm{RPR} \qquad \textit{(Equation 5)}$$

Where Th is the theoretical potential in ton/year; AP is the annual production of a specific crop in ton/year; RPR is the residue to product ratio of the crop.

The residue to product ratio (RPR) was found from literature. The annual production of each crop was collected from the Statistical Yearbook of the country for the years 2013, 2014, 2016, 2017 and 2018. As for livestock, (Equation 2 and (Equation *3*) were used to estimate the average annual growth rate and production from 2019 to 2025. The same method was applied for the estimations of the years 2030, 2035, 2040 and 2045.

- **Technical cereal residues potential**

To determine the technical potential of cereal crops residues, the theoretical potential is multiplied by the surplus residue fraction. (Equation 6) below shows it:

$$\mathrm{TP} = \mathrm{Th} * \mathrm{SRF} \qquad \textit{(Equation 6)}$$

Where TP is the technical crop residue potential in ton/year and SRF, the surplus residue fraction. For the surplus residue fraction (SRF), a value of 25% was assumed to represent the portion of residues retained in the field for soil conservation according to [57].

Table 3: Residue to Product Ratio for each crop

Crop	**Crop residue**	**RPR**	**References**
Millet	Millet straws	2	[3], [58]
	Millet stalks	2	[58]
Sorghum	Sorghum straws	1.9	[59]
	Sorghum stalks	2.25	[60]
Rice	Rice straws	0.75	[3]
	Rice husks	0.21	[3], [60]
Maize	Maize stalks	1.2	[3], [60]
	Maize husks	0.21	[60]
	Maize cobs	0.65	[3], [60]
Wheat	Wheat straws	1.55	[59]
	Wheat husks	0.8	[58]
Fonio	Fonio straws	1.55	[61]

- **Usable crops potential**

The usable crop refers to the quantity of waste which can be used for bioenergy production after extracting the percentage of surplus residue fraction from technical potential. It is calculated by using (Equation 7) below.

$$\mathrm{UCP} = \mathrm{Th} - \mathrm{TP} = 75\%\mathrm{Th} \qquad \textit{(Equation 7)}$$

Where UCP is the usable crop potential, Th is the theoretical potential and TP is the technical potential.

2.3.3. Municipal solid waste potential

- **Annual MSW generation**

The annual MSW generation for each region was calculated by using (Equation 8) [57]. For its estimation, based was made on the urban population as the waste generated per capita in this area is far high compared to the rural areas. Moreover, in the rural areas, waste collection strategies remain unknown [3].

$$\mathrm{AMSW} = \mathrm{UP} * MSW_g * D \qquad \textit{(Equation 8)}$$

Where AMSW is the annual MSW generation, UP is the urban population for each region, MSW_g is the MSW generated in each region, and D is the number of days in a year (365).

The following stages were adopted for the calculations:

- **Stage one**:

The share of urban population for each region was obtained with data from the fourth General Census of Population and Housing in 2009 (RGPH-2009) in the country, which is the most recent and published by the Ministry of Economic and Finance, and the National Institute of Statistics each ten years. The estimations from 2020 to 2045 have been made by calculating the CAGR using the available data of RGPH which was for the years 1976, 1987, 1998 and 2009 in each region.

- **Stage two**:

For the daily generation of MSW, a value of 0.65 kg / (person*day) was used for the whole country [3].

- **Theoretical MSW potential**

The theoretical MSW potential was determined using (Equation 9) below.

$$TMSW = AMSW * OFMSW \qquad \textit{(Equation 9)}$$

Where TMSW is the theoretical MSW and OFMSW, the organic fraction of municipal solid waste in Mali. It was found a value of 51% in the literatures [62], [63] for the OFMSW.

- **Technical MSW potential**

The technical MSW potential was calculated using ((Equation *10*) below [3].

$$T_eMSW = TMSW * CR \qquad \textit{(Equation 10)}$$

Where T_eMSW is technical MSW potential and CR is the collection rate, which refers to the ratio of total waste collected to total waste generated according to [64]. Regarding the collection rate of MSW, an average value of 60.5% for the year 2025 has been determined from [64].

2.3.4. Total biomass potential

The total biomass potential for each region was calculated by summing up the total of livestock waste, cereal crops residues and MSW potential in each region for the respective years. (Equation 11) shows that.

$$TBP = LWP + UCP + T_eMSW \qquad \textit{(Equation 11)}$$

2.3.5. Bioenergy potential estimation

In this study, anaerobic digestion was used to evaluate the biomethane, biohydrogen and energy potential from the combination of livestock waste and MSW potential as they have high moisture content. Conversely, cereal crops were used in the evaluation of biohydrogen potential through gasification across all regions of the country due to their low moisture content.

2.3.5.1. Biogas potential from MSW and livestock through anaerobic digestion

- **Buswell's equation**

Buswell's equation (Equation 12) from empirical formula $C_xH_yO_zN_vS_u$ [57], [65] was used to calculate the theoretical biogas composition, methane and energy yield of the various feedstock used which are OFMSW and livestock (cattle, sheep, goats, horses, camels, pigs, and poultry) manure. However, donkey was not considered in the calculation due to unavailable data of its elemental analysis as seen in Table 4.

$$C_xH_yO_zN_vS_u + \frac{4x - y - 2z + 3v + 2u}{4} H_2 \rightarrow \frac{4x - y - 2z - 3v - 2u}{8} CH_4 + \frac{4x - y + 2z + 3v + 2u}{8} CO_2 + vNH_3 + uH_2S$$

(Equation 12)

Table 4: Ultimate and proximate analysis of livestock manure and OFMSW (on a dry basis (%))

Feedstock	**Ultimate analysis**					**Moisture content (%)**	**Dry matter (%)**	**References**
	C	**H**	**O**	**N**	**S**			
OFMSW	47.03	6.75	32.7	2.58	0.52	60	40	[57], [66]
Cattle	44.65	5.85	38.18	2.05	0.09	77.00 ± 0.73	23	[67], [68]
Sheep	40.60	5.10	30.70	2.10	0.60	38.71 ± 3.50	61.29	[67], [68]
Goats	42.24	5.10	27.50	2.34	0.76	37.7 ± 0.3	62.3	[69], [70]
Horses	43.00	5.70	49.50	1.00	0.80	67.6	32.4	[67], [71]
Camels	35.33	1.29	60.61	2.77	0	38.00	62	[72]
Pigs	54.30	7.50	31.50	5.10	1.70	73.10 ± 3.00	26.9	[67], [68], [73]
Poultry	38.10	5.60	30.90	3.50	0.60	49.59 ± 5.00	50.41	[67], [68]

- **Theoretical methane, energy and hydrogen yield**

To determine the theoretical methane, energy and hydrogen from MSW and livestock, five main phases were followed:

a) Theoretical biogas composition

This outlines the calculation of methane and carbon dioxide percentages for each feedstock, based on (Equation 12 and (Equation *13*). The following steps detail the procedure employed:

- **Step one**: Empirical MSW formula

To get the empirical formula of OFMSW, the elemental values of its ultimate analysis shown in Table 4 were divided by the corresponding atomic mass.

- **Step two**: CH_4 and CO_2 coefficient from OFMSW

The empirical formula gotten in step one was used in theoretical Buswell's equation to determine the coefficients of both methane and carbon dioxide.

- **Step three**: CH_4 and CO_2 percentage from OFMSW

The percentage of methane was obtained by dividing its coefficient with the sum of CH_4 and CO_2 coefficients as indicated in (Equation 13).

$$\%(\mathrm{CH_4}) = \frac{n(\mathrm{CH_4})}{n(\mathrm{CH_4})+n(\mathrm{CO_2})} \times 100 \qquad \textit{(Equation 13)}$$

b) Kilograms of carbon converted to biogas

This stage details the steps followed to determine the amount of carbon that can be converted into biogas from OFMSW.

- **Step one**: Conversion from kt to kg

The initial municipal solid waste potential calculated earlier in kt was converted into kg by multiplying it by 10^6.

- **Step two**: Moisture content and dry matter

Using the proximate analysis displayed in Table 4, the theoretical moisture content and dry matter were determined by multiplying their respective percentages by the converted municipal solid waste potential in step one.

- **Step three:** Percentage of carbon from Buswell's equation

To obtain the carbon percentage, the elemental value for each element from the ultimate analysis was multiplied by their respective atomic mass. The value for carbon was then divided by the sum of the value for all the elements. This was lastly divided by one hundred to get the carbon percentage from Buswell's equation.

- **Step four:** Carbon content from OFMSW

The carbon content from OFMSW was determined by multiplying the theoretical dry matter potential by the percentage of carbon from Buswell's equation obtained in step three.

- **Step five**: Weight of carbon converted to biogas

Assuming 70% as biodegraded carbon percentage [57], the weight of carbon converted into biogas in kg was finally obtained by multiplying the percentage assumed by the carbon content from OFMSW.

c) Theoretical methane yield in kg

This section explains the process on how the theoretical methane was calculated using the weight of carbon that has been converted into biogas.

- **Step one**: Weight of methane carbon

This was determined by multiplying the weight of carbon converted into biogas by the percentage of methane earlier calculated using (Equation 13).

- **Step two**: Weight of methane in kg

Assuming 1 mol of CH_4 equals to 16g of CH_4 [57], [74], the weight of carbon was calculated by multiplying 16 with the weight of methane carbon. The obtained value was then divided by the atomic mass of carbon to get the weight of methane in kg.

d) Energy value from methane in MWh

To calculate the energy value of OFMSW from the weight of methane in kg, the following steps were followed:

- **Step one**: Conversion of CH_4 from kg to g then cubic meter

The weight of CH_4 calculated in kg was converted into grams by multiplying its previous value by 10^3. According to [57], [74] 1 mol CH_4 equals to 22.4 L (liters) at standard temperature and pressure, therefore 16 g of CH_4 is equivalent to 22.4L. The amount of CH_4 in grams was then converted to cubic meter by multiplying the obtained amount by 22.4 and 10^-3 and divided all by 16.

- **Step two**: Energy value in GWh

Assuming that 1 m^3 provides 36 MJ (megajoules) of energy and considering that 1 kWh is equivalent to 3.6 MJ [75], this corresponds to 10 kWh per cubic meter, or 10^-5 GWh. The energy value in GWh was then calculated by multiplying the CH_4 volume in cubic meter by 10^-5.

e) Theoretical hydrogen potential in Mmol through steam methane reforming (SMR)

This phase explains how hydrogen was obtained from the calculated methane value in grams using the steam reforming process.

- **Step one**: Stoichiometry of SMR

((Equation *14*) was used to get the amount of hydrogen produced in moles stoichiometrically since 1 mol of CH_4 (in grams) gives 3 mol of hydrogen.

$$CH_4 + H_2O \rightarrow CO + 3H_2; \ \triangle H°298K = 206\ kJ/mol \qquad \text{(Equation 14)}$$

- **Step two:** Conversion of hydrogen from mol to Mmol

The amount of hydrogen obtained in step one was converted from mol to megamoles (Mmol) by multiplying it by 10^-6.

These five phases were also applied for the calculation of theoretical methane, energy, and hydrogen produced for the other livestock.

- **Technical methane, hydrogen, and energy potential**

The steps below detail the calculation steps of technical potential by using the conversion efficiencies for each region of the country.

- **From MSW to technical methane potential**

It was determined a range value of 75% to 90% for the technical conversion efficiency of methane from the theoretical potential based on [75]. The calculation was carried out by multiplying the average efficiency with the theoretical methane previously obtained.

- **From livestock to technical methane potential**

The conversion efficiency of animal manures to methane was considered to range between 65% and 76% as reported in the literature [76]. This efficiency was then multiplied by the theoretical methane potential.

- **From methane to technical energy produced**

According to [74], 35% efficiency for methane-based energy produced was evaluated and multiplied by the theoretical energy potential to get the technical energy produced annually.

- **From methane to technical hydrogen potential**

For hydrogen, the conversion efficiency was determined as 75% [56], [77]. This value was then multiplied by the theoretical hydrogen potential earlier calculated to obtain the corresponding hydrogen potential technically.

2.3.5.2. Hydrogen potential from cereal crop residues through gasification

The theoretical hydrogen potential from the air gasification process was computed using the general equation for biomass gasification which is shown in (Equation 15) below [78].

$$nC_xH_yO_z + mH_2O(g) + wO_2 \rightarrow x_1CO + x_2H_2 + x_3CO_2 + x_4CH_4 + x_5H_2O + x_6O_2$$

(Equation 15)

If we assume that the fractions of CO_2, O_2, and H_2O (vapor form) produced during gasification mainly result from the combustion needed to supply the energy required for the gasification process and to compensate for energy losses associated with the reactor's efficiency, and that CH_4 production is negligible, the reaction for hydrogen production from biomass can be simplified to (Equation 16) below [79], [80].

$$nC_xH_yO_z + mH_2O \rightarrow x_1CO + x_2H_2 \qquad \textit{(Equation 16)}$$

From (Equation 16) the atomic values x, y and z were determined by dividing the mass percent for each element in (*Table 5*) by their respective molecular mass.

➢ **Theoretical hydrogen potential**

The theoretical hydrogen potential in mol for each crop was calculated using the stoichiometry in (Equation 16). The value obtained in mol was then converted into Mmol.

➢ **Technical hydrogen potential**

The energy efficiency for hydrogen yield through gasification ranges between 40% and 70% [81]. To obtain technical hydrogen potential, this efficiency was multiplied by the theoretical value gotten.

Table 5: Carbon, hydrogen and oxygen content of cereal crops (wt%)

Cereal residue	**C**	**H**	**O**	**LHV (MJ/kg)**	**References**
Millet straw	46.5	4.9	39.38	13	[76], [77], [78]
Millet stalk	44.4	6	43.8	15.51	[76], [79]
Sorghum straw	40	5.2	40.7	17.6	[80]
Sorghum stalk	43.11	5.97	50.58	15.7	[81], [82]
Rice straw	38.24	5.2	28.27	12.65	[80]
Rice husk	34.99	4.58	34.18	12.84	[80]
Maize stalk	43.73	5.55	41.35	18.5	[83], [84]
Maize husk	43.79	6	43.15	15.56	[75], [84]
Maize cob	50.2	5.9	43.5	17.34	[80]
Wheat straw	42.45	5.27	32.76	13.96	[80]
Wheat husk	40.78	6.29	43.55	12.9	[76], [85]

Chapter 3: Results and discussion

3.1. Results

3.1.1. Biomass resource potential

3.1.1.1 Livestock waste potential

- **Western and southern regions for livestock group 1**

Figure 5 below presents the projected potential of livestock waste group 1 (cattle, sheep, goats, and horses) in western and southern regions of Mali (Bamako, Kayes, Koulikoro, Sikasso, and Ségou) for the 2020, 2025, 2030, 2035, 2040, and 2045 represented in metric tons. The results reveal that cattle consistently have the highest sustainable potential across all regions, with strong and steady growth projected, especially in Sikasso with 4728499.81t, 5481360.33t, 6354089.51t, 7365772.57t, 8538533.4t, and 9898018.42t respectively. Sheep and goats show moderate increase in sustainable potential, whereas horses displayed lowest and nearly constant potential across the regions annually.

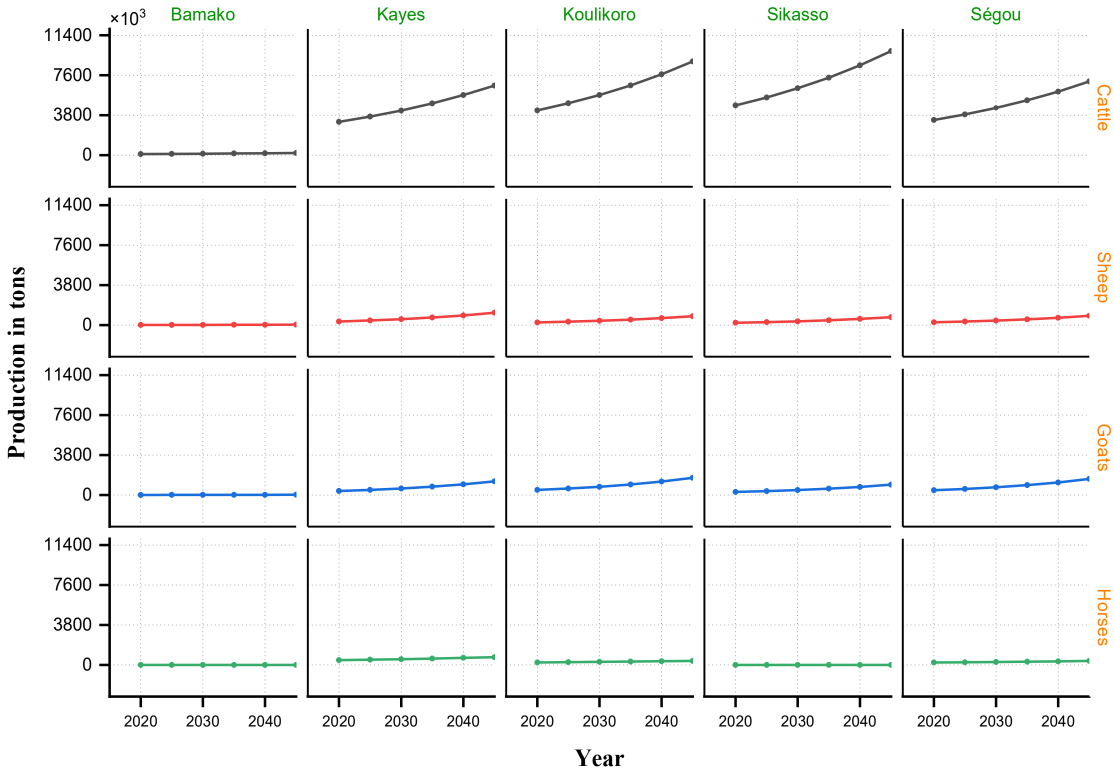


Figure 5: Cattle, sheep, goats, and horses' potential in western and southern Mali

- **Western and southern regions for livestock group 2**

Figure 6 shows the projected potential of livestock waste group 2 (donkeys, camels, pigs, and poultry) in western and southern regions of Mali. It indicates lower and more stable sustainable potential compared to group 1 livestock. However, poultry shows the highest potential in Bamako, with 207942.84t, 379332.83t, 691985.33t, 1262331.28t, 2302765.98t, and 4200744.48t for the years 2020, 2025, 2030, 2035, 2040, and 2045 respectively. This growth is mainly due to the rising urban demand and commercialization in the area. While camels and pigs provide a minimal and consistent contribution.

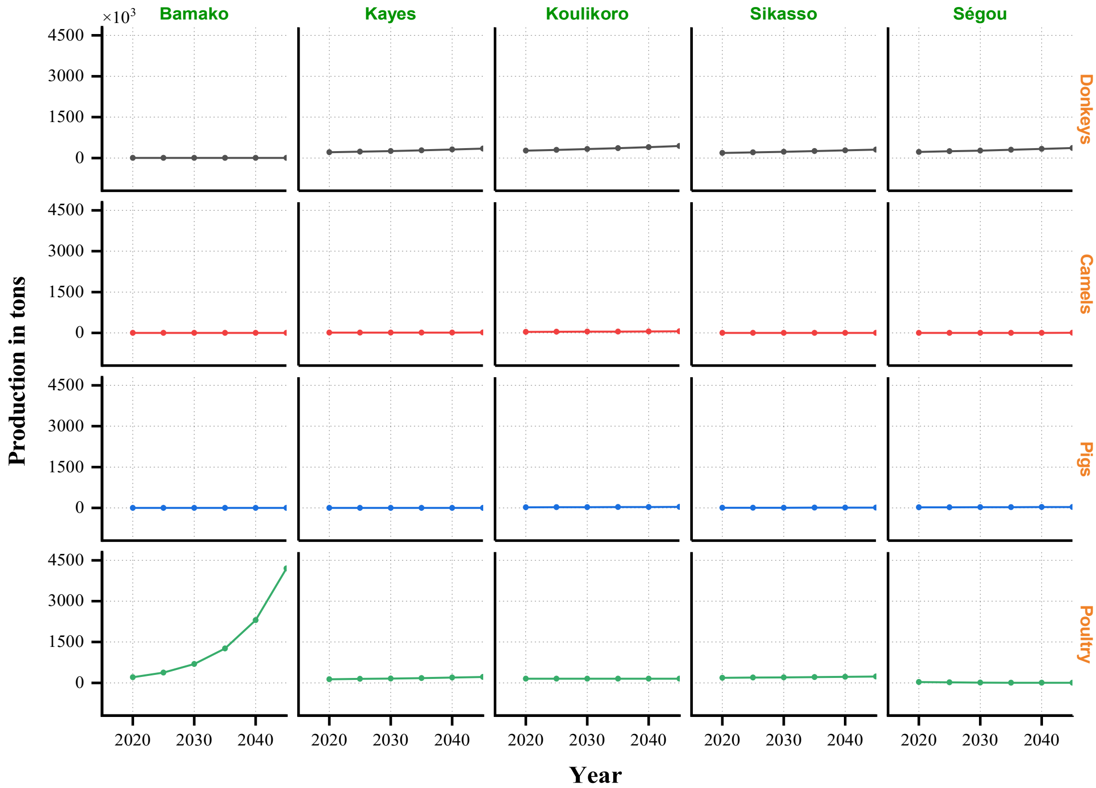


Figure 6: Donkeys, camels, pigs and poultry's potential in western and southern Mali

- **Central and northern regions for livestock group 1**

Figure 7 illustrates the projected potential of cattle, sheep, goats, and horses for the years 2020, 2025, 2030, 2035, 2040, and 2045 in central and northern Mali (Mopti, Tombouctou, Gao, and Kidal). It showed cattle as the livestock which has the strongest growth in Mopti, the central region of the country, where the production was: 8306467.22t, 9629437.34t, 11163116.76t, 12941065.14t, 15002187.15t, and 17391583.8 t respectively.

Although sheep and goats demonstrated stable increases over time with similar production levels across the regions, whereas horses had the lowest potential across all the regions annually.

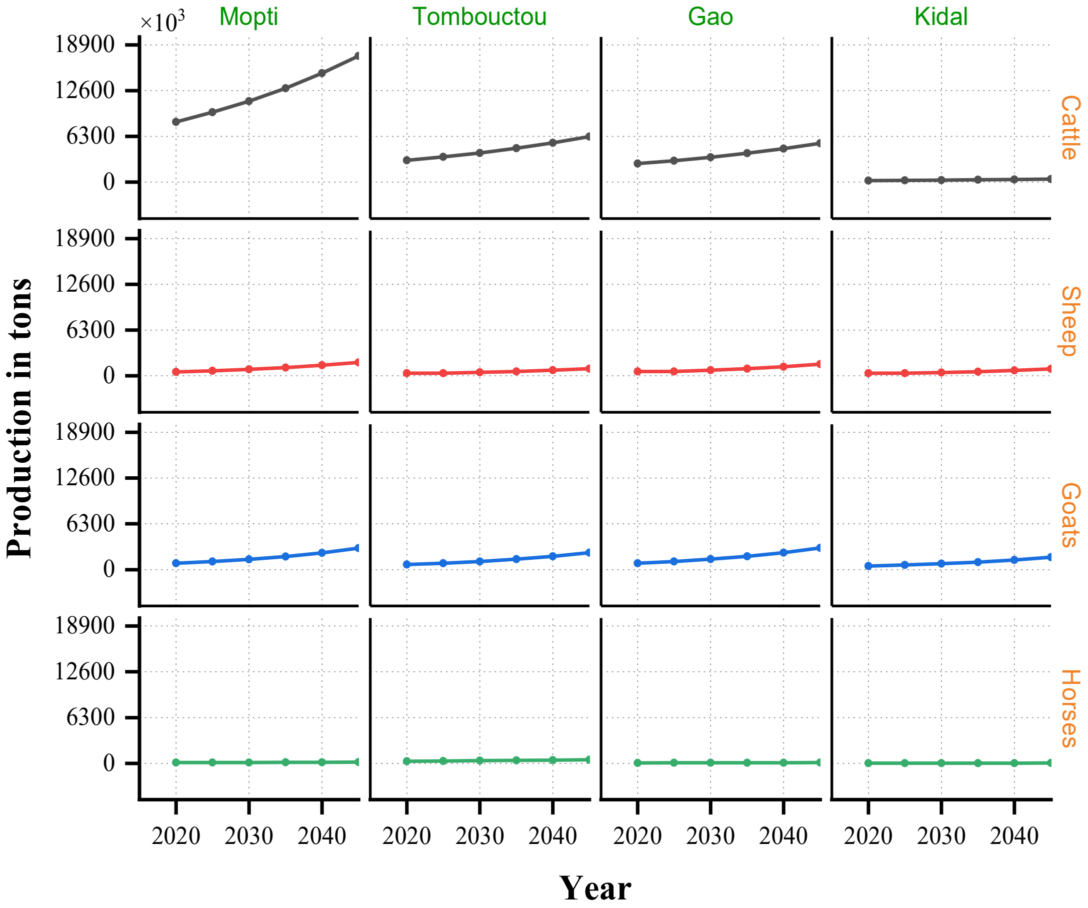


Figure 7: Cattle, sheep, goats and horses' potential in central and northern Mali

- **Central and northern regions for livestock group 2**

The graphic shown below in (Figure 8) presents the projected potential for donkeys, camels, pigs, and poultry in central and northern Mali. Camels appeared to have the highest sustainable production trends, mainly in Kidal with a potential of 2012279.28t, 2200435.91t. 2406186.1t, 2631174.81t, 2877200.94t, 3146231.57t for the years 2020, 2025, 2030, 2035, 2040, and 2045 respectively. However, pigs' waste showed the lowest across all regions.

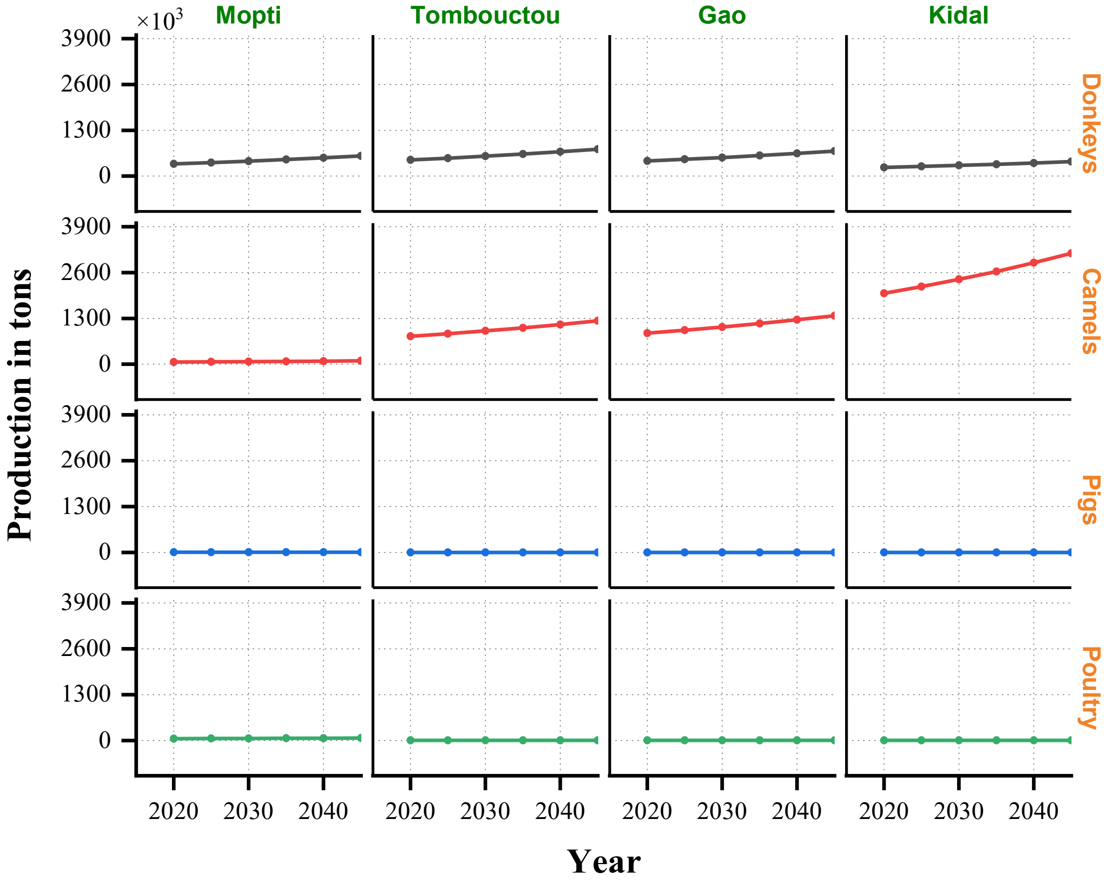


Figure 8: Donkeys, camels, pigs and poultry's potential in central and northern Mali

3.1.1.2. Cereal crops usable potential

- **Western and southern regions**

The usable potential of the cereal crop's residues in the western and southern regions of the country are illustrated below in (Figure 9 and Figure 10) for the years 2020, 2025, 2030, 2035, 2040, and 2045. Sorghum revealed significant potential in Kayes, and these were: 2654.94 kt, 13047.96 kt, 64125.53 kt, 315151.37 kt, 1548843.14 kt, and 7611945.54 kt respectively.

However, it was maize which showed the highest potential in Koulikoro. Its results for the years 2020, 2025, 2030, 2035, 2040, and 2045 were: 2204. 52 kt, 7687.48 kt, 26807.37 kt, 93481.3 kt, 325983.25 kt, and 1136752.2 kt respectively. In contrast, wheat and fonio residues had the lowest potential across all the regions.

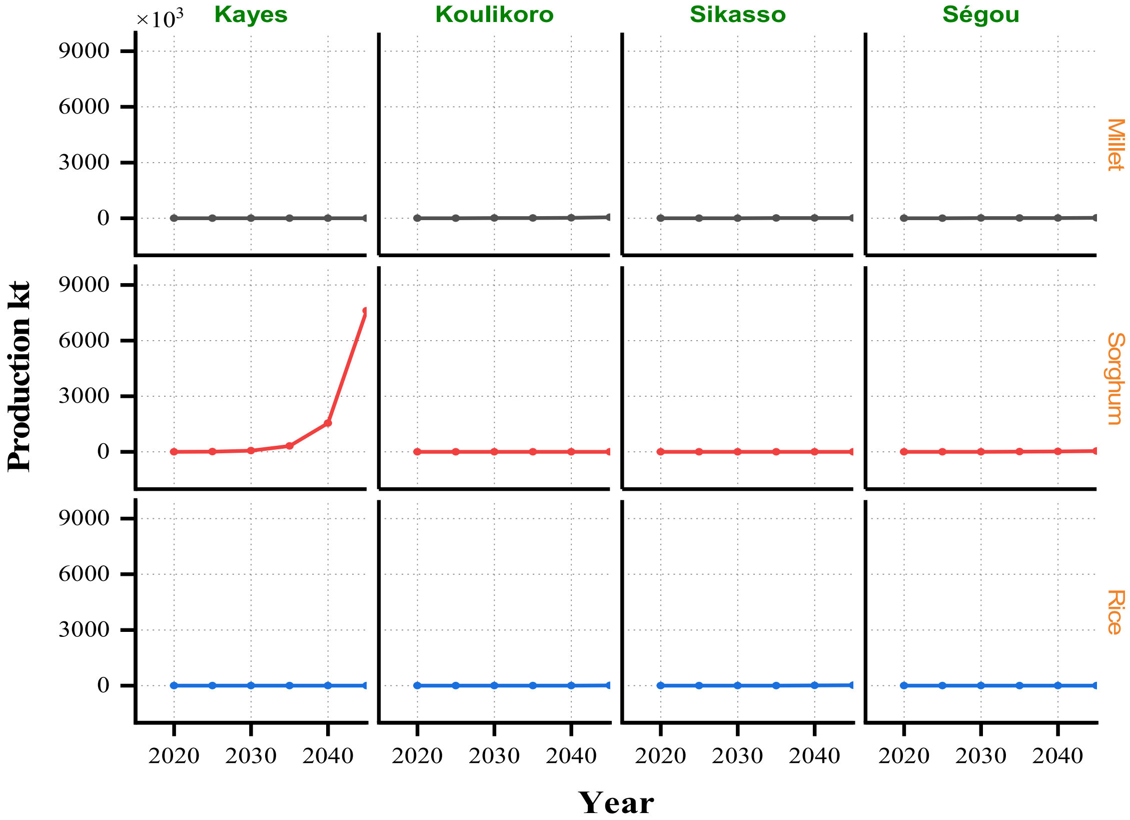


Figure 9: Millet, sorghum and rice's potential in western and southern Mali

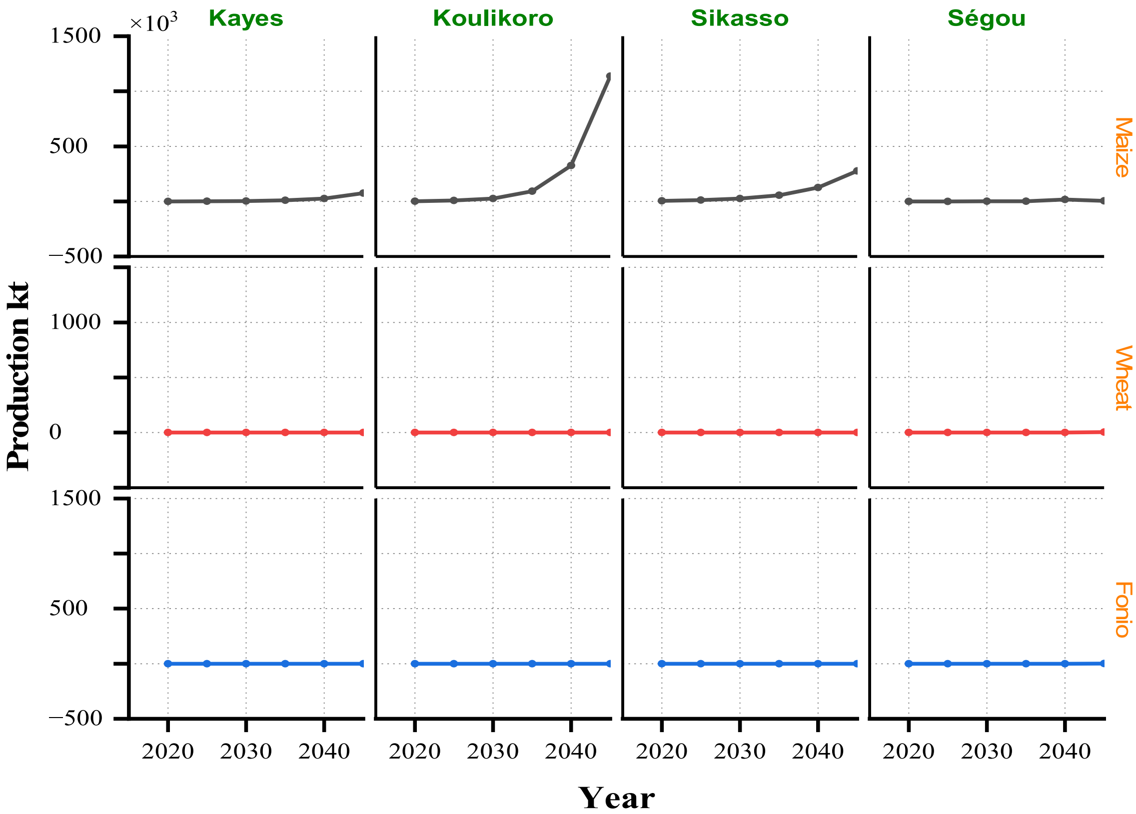


Figure 10: Maize, wheat and fonio's potential in western and southern Mali

- ### **Central and northern regions for cereal group 1**

Figure 11 and Figure 12 represent cereal crops residues potential in the central and northern Mali. The results showed that rice and wheat residues have the highest potential in the northern part, especially in Gao. Although the potential for the years 2020, 2025, 2030, 2035, 2040, and 2045 were: 413.28 kt, 2028.34 kt, 9954.78 kt, 48856.52 kt, 239780.32 kt, and 1176805.1 kt for rice residues and 1.36 kt, 3.05 kt, 6.84 kt, 15.32 kt, 34.31 kt, and 76.85 kt for wheat residues.

Nevertheless, maize and fonio showed the lowest potential across all the regions.

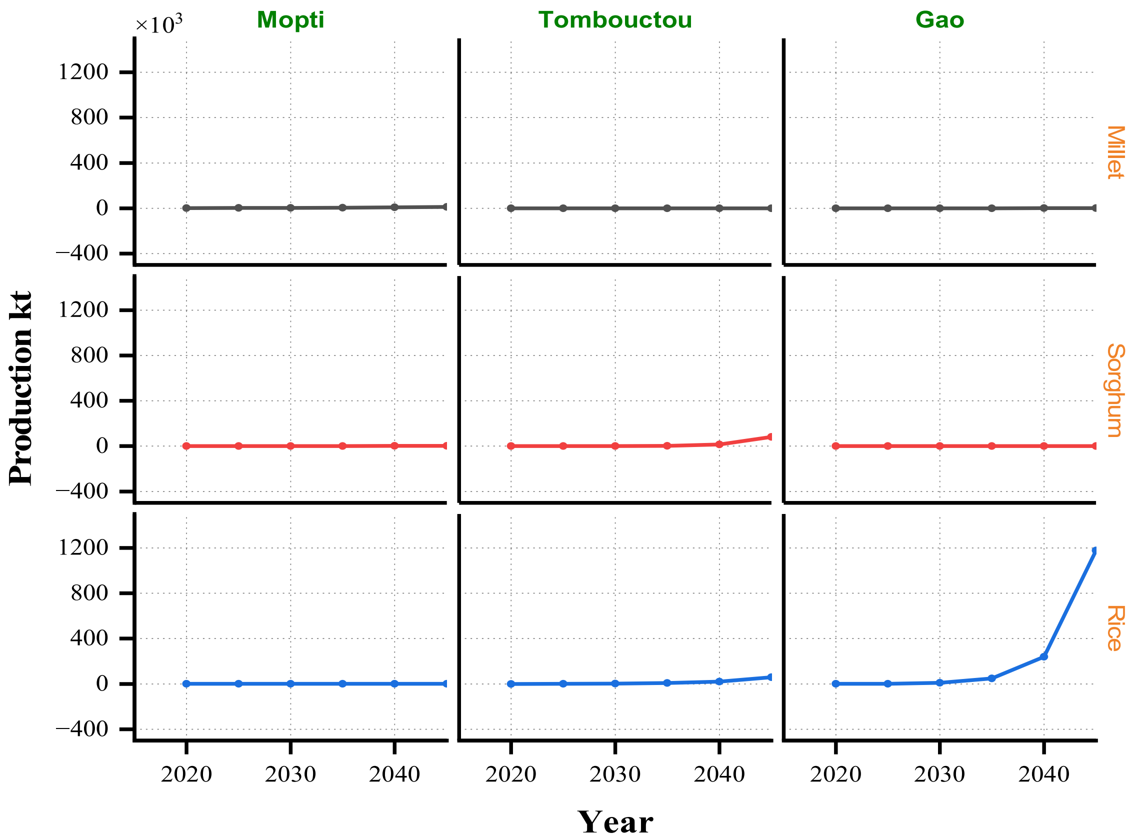


Figure 11: Millet, sorghum, and rice's potential in central and northern Mali

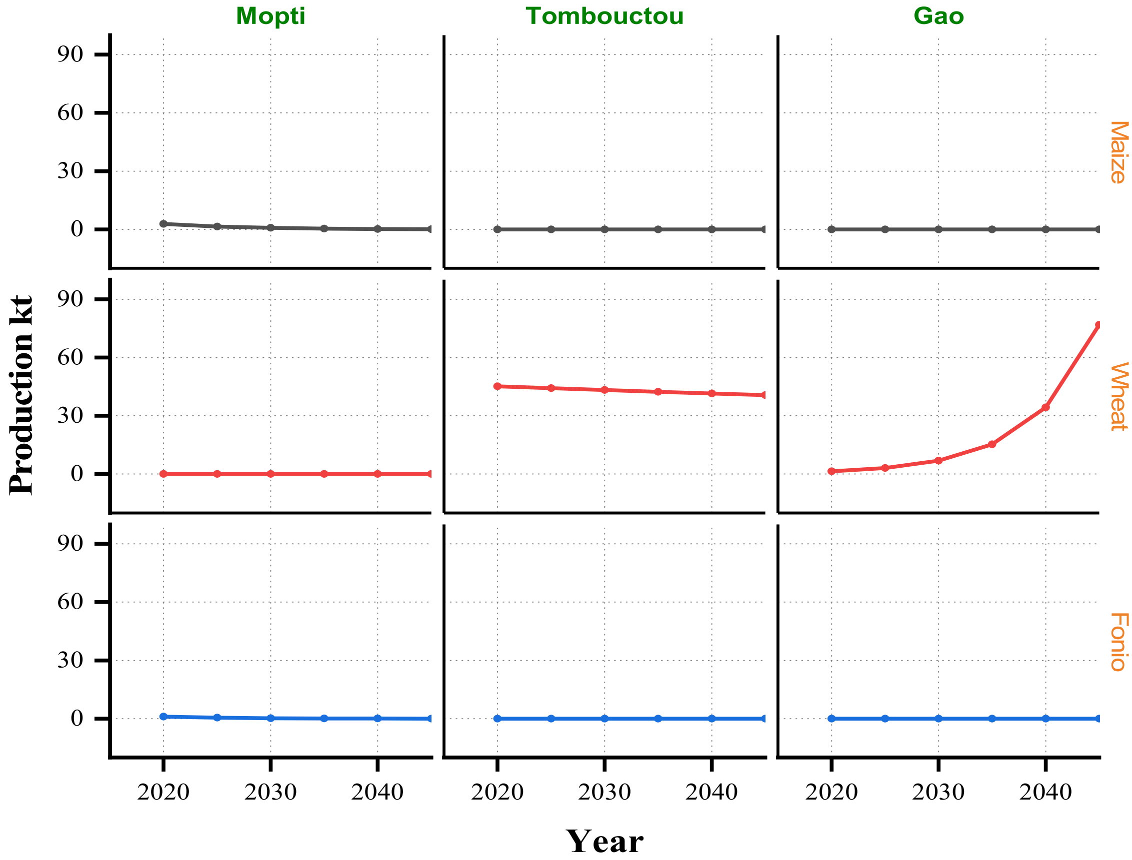


Figure 12: Maize, wheat and fonio's potential in central and northern Mali

3.1.1.3. Municipal solid waste sustainable potential

The graph illustrated in (Figure 13) represents the municipal solid waste potential for the years 2020, 2025, 2030, 2035, 2040, and 2045 in Mali. There is a consistent increase in MSW potential across all the regions annually. This is mainly shown in Koulikoro where we have the highest potential and which was: 120.09 kt, 176.16 kt, 258.40 kt, 379.04 kt, 555.99 kt, and 815.56 kt respectively. However, regions of the northern part (Tombouctou Gao and Kidal) show the lowest production over time. This is mainly due to a low urban population in those areas.

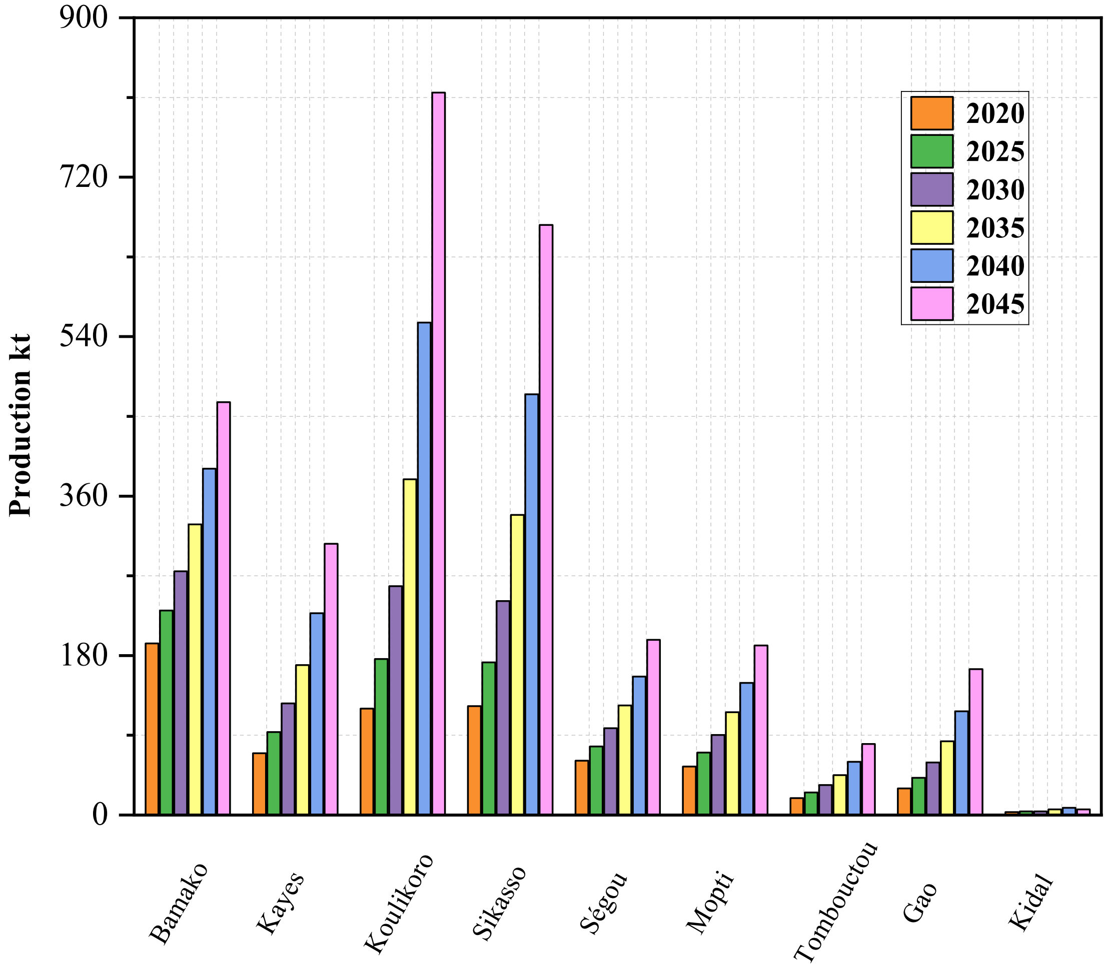


Figure 13: MSW potential for each region from 2020 to 2045

3.1.1.4. Total livestock waste, cereal crop residues and MSW potential for the whole country from 2013 to 2018

The total livestock, cereal crops residues, and MSW potential in Mali is represented in (Figure 14) for the years 2013, 2014, 2015, 2016, 2017 and 2018. The results revealed a significant mostly dominated by livestock. The potential obtained are: 47022.52 kt, 52480.85 kt, 51761.39 kt, 56833.44 kt, 57603.62 kt and 64049.16 kt respectively.

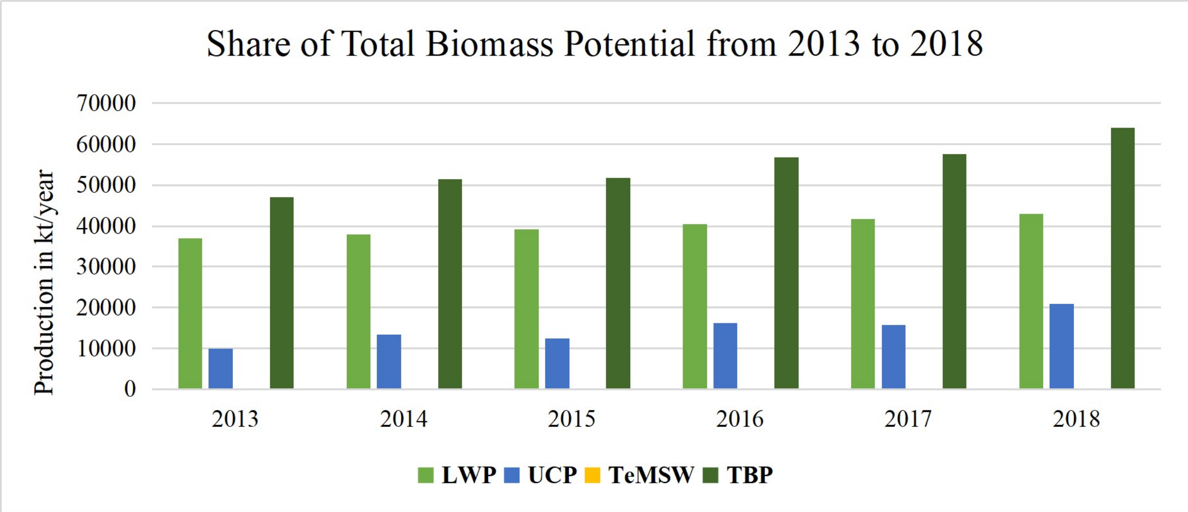


Figure 14: Total biomass potential in Mali from 2013 to 2018

3.1.1.5 Total livestock waste, cereal crop residues and MSW potential for the whole country from 2020 to 2045

Figure 15 shows the total livestock, cereal crops residues, and MSW potential in Mali for the years 2020, 2025, 2030, 2035, 2040, and 2045. Overall, the total biomass potential in Mali grows consistently over time and the results showed as total potential: 70330.34 kt, 110122.14 kt, 228055.91 kt, 661703.57 kt, 2495768.59 kt, and 10685985.41 kt respectively. Although, the growth is mainly driven by livestock. Although MSW have the lowest production potential in total.

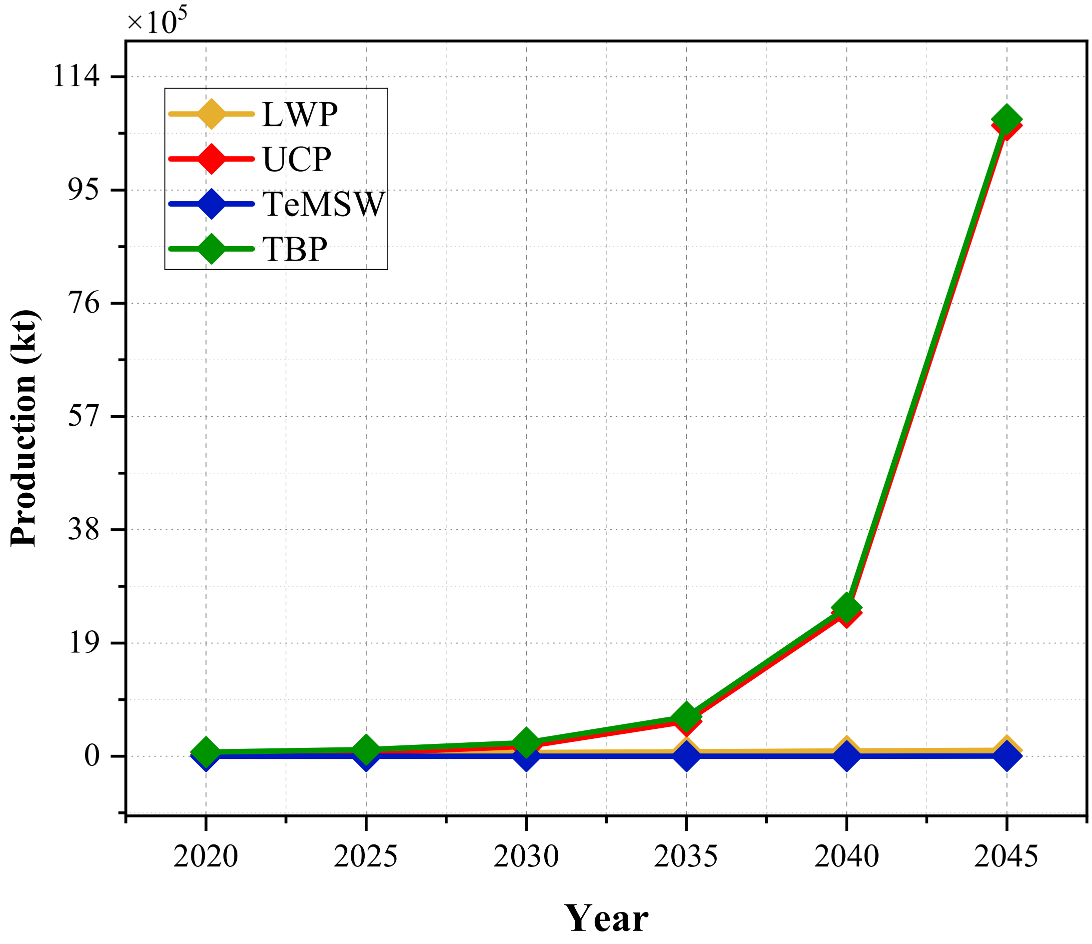


Figure 15: Total biomass potential in Mali from 2020 to 2045

3.1.2. Bioenergy potential

3.1.2.1 Methane, energy and hydrogen potential for the years 2013, 2014, 2015, 2016, 2017 and 2018

Figure 16, Figure 17, Figure 18 and Figure 19 shows the theoretical and technical potentials of methane, energy and hydrogen respectively for the years 2013, 2014, 2015, 2016, 2017 and 2018. Among the nine regions, Mopti, Tombouctou and Gao demonstrated significant potential over time which is mainly driven by the high cereal produced and livestock available in those areas compared to the other regions. The theoretical potentials are consistently higher than technical ones due to the conversion efficiency.

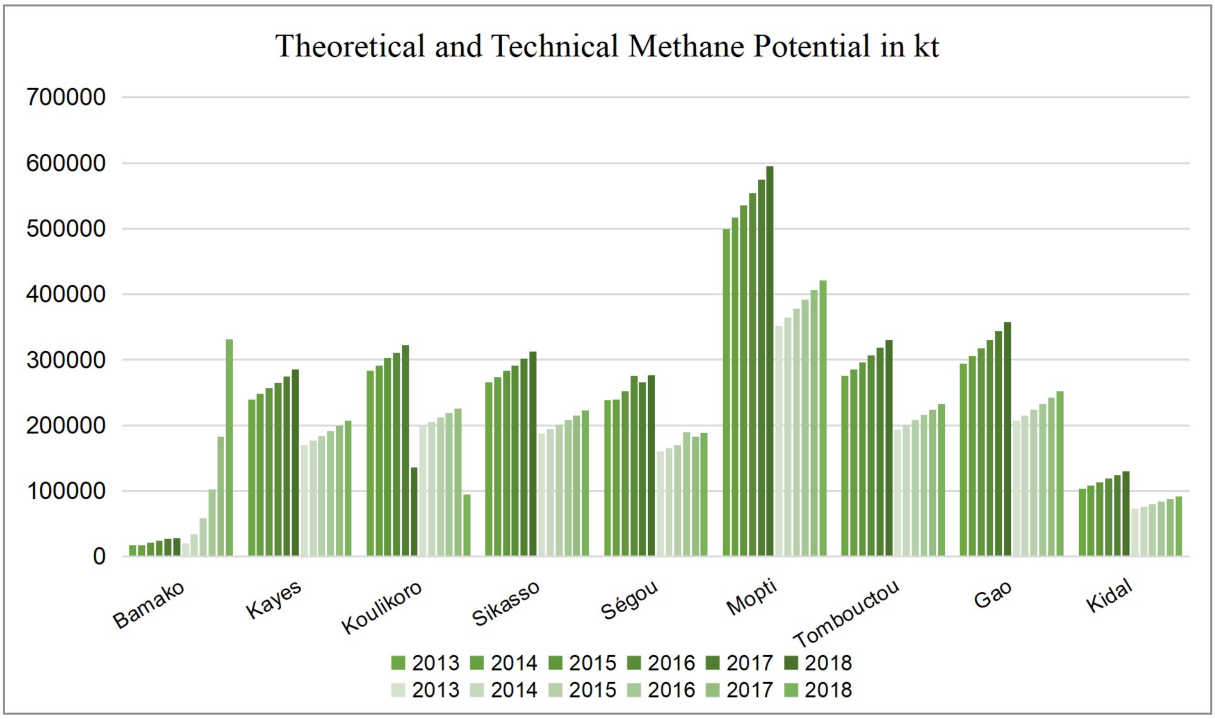


Figure 16: Theoretical and technical methane potential from livestock manure and MSW

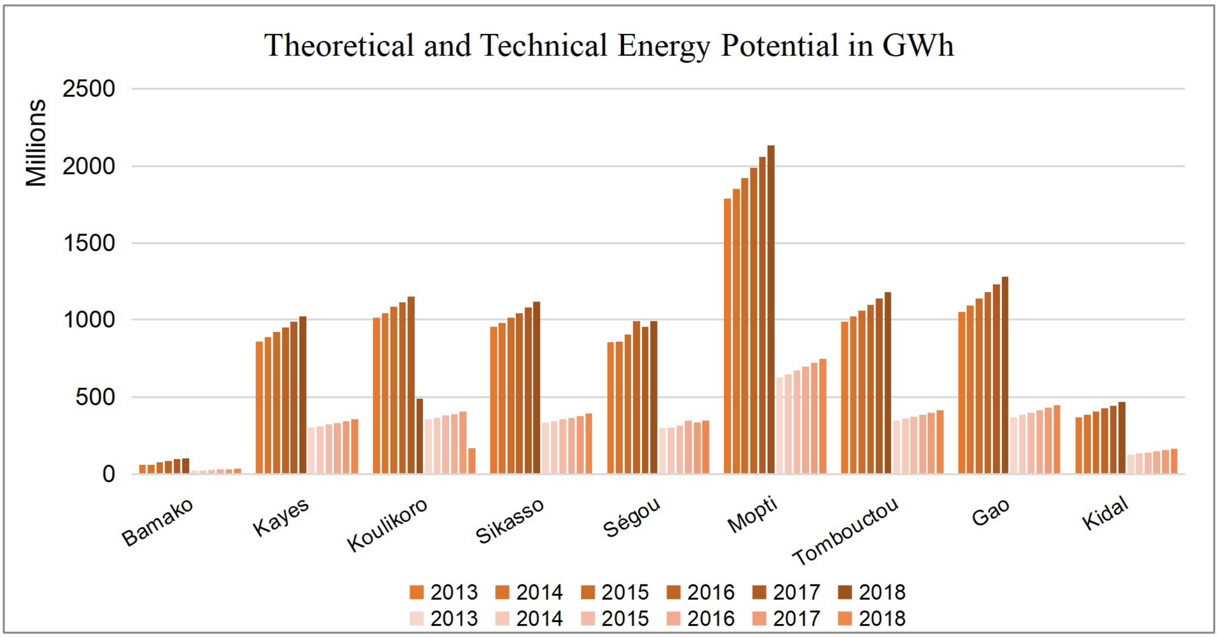


Figure 17: Theoretical and Technical energy potential from livestock manure and MSW

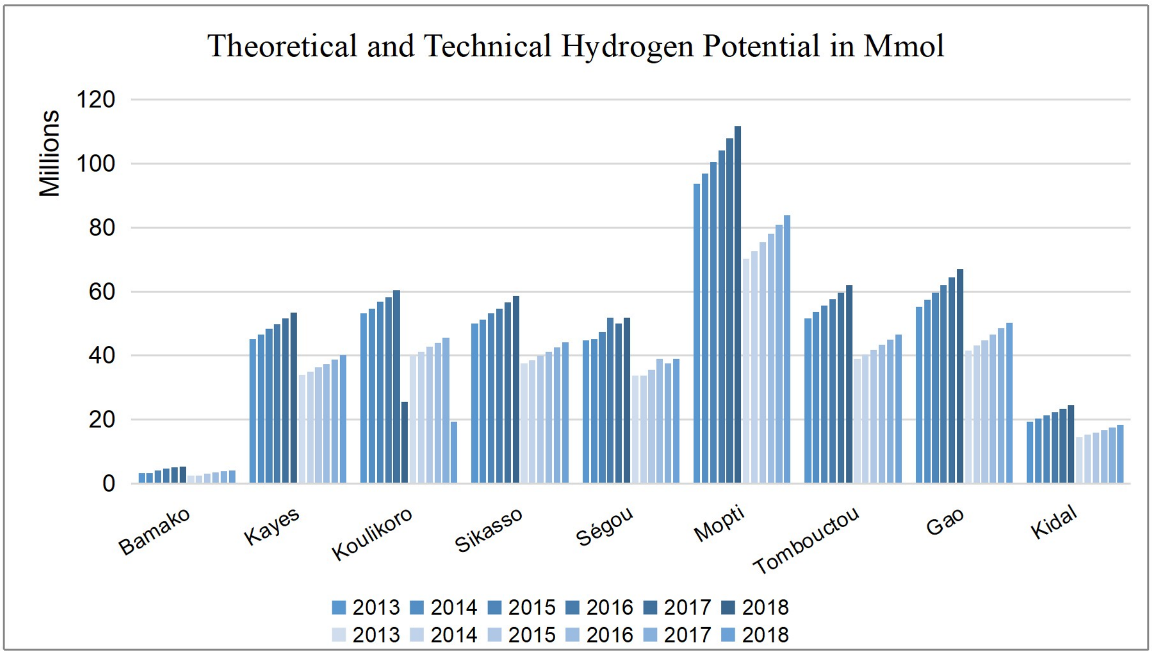


Figure 18: Theoretical and Technical hydrogen potential from livestock manure and MSW

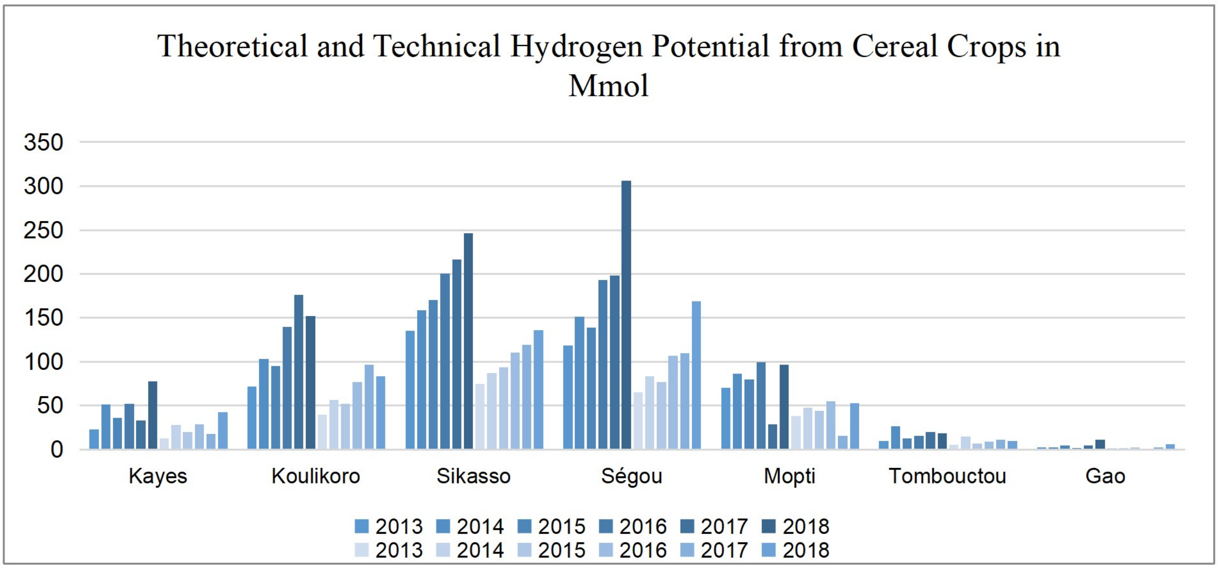


Figure 19: Theoretical and technical hydrogen potential from cereal crops

3.1.2.2 Theoretical methane, energy and hydrogen potential from livestock waste and MSW for the years 2020, 2025, 2030, 2035, 2040 and 2045

The results below show the theoretical methane, energy and hydrogen potential produced from livestock waste and MSW for the years 2020, 2025, 2030, 2035, 2040, and 2045 through anaerobic digestion as seen in (Figure 21, Figure 22 and Figure 22) respectively. Consistent production potential was observed in the central and northern parts of the country, especially in Mopti, Tombouctou, and Gao as compared in the western and southern regions like Kayes, Koulikoro, Bamako, Sikasso, and Ségou. However, for the same years, Mopti which showed the highest potential were: 639407.03 kt, 765383.28 kt, 918326.72 kt, 1104447.57 kt, 1331482.4 kt, 1609078.74 kt respectively.

Similarly, the highest energy production was observed in Mopti with a potential of 2291634801 GWh, 2743133666 GWh, 3291282947 GWh 3958340081 GWh, and 4772032937 GWh for 2020, 2025, 2030, 2035, 2040, and 2045 respectively.

On the other hand, the highest theoretical hydrogen production potential were: 119888818.4 Mmol, 143509364.5 Mmol, 172186259.1 Mmol, 207083918.8 Mmol, 249652950.8 Mmol, and 301702264.5 Mmol in region of Mopti for the considered years respectively.

In contrast, Bamako had the lowest production potential for theoretical methane, electricity, and hydrogen mainly due to the lack of livestock in this area compared to the other regions. The results obtained were: 30663.26 kt, 51116.06 kt, 87450.43 kt, 152554.57 kt, 269885.6 kt, and 482175.39 kt for methane; 109897107.5 GWh, 183199975.3 GWh, 313422330.2 GWh, 546755574 GWh, 967269996.8 GWh, and 1728116593 GWh for energy and 5749360.4 Mmol, 9584262.1 Mmol, 16396955.05 Mmol, 28603981.62 Mmol, 50603550.34 Mmol, and 90407885.37 Mmol for hydrogen.

3.1.2.3 Technical methane, energy and hydrogen potential from livestock waste and MSW for the years 2020, 2025, 2030, 2035, 2040 and 2045

The technical methane, energy, and hydrogen production potential in each region for the years 2020, 2025, 2030, 2035, 2040, and 2045 are represented below, in (Figure 21, Figure 22 and Figure 22) respectively. These results are similar to the theoretical potential obtained above where the highest were in the central and northern parts mainly in Mopti, Tombouctou, and Gao. However, the technical potential is lower than theoretical one due to the conversion efficiency. The production potential for methane in Mopti were: 450782.64 kt, 539596.09 kt, 647421.46 kt, 778636.98 kt, 938696.95 kt, and 1134402.9 kt for the year 2020, 2025, 2030, 2035, 2040, and 2045 respectively.

The technical electricity obtained in Mopti were: 802072180.2 GWh, 960096783 GWh, 1151949032 GWh, 1385419028 GWh, 1670211527.89 GWh, and 2018428376.53 GWh for the considered years. And its technical hydrogen potential was: 89916613.8 Mmol, 107632023.36 Mmol, 129139694.33 Mmol, 155312939.14 Mmol, 187239713.1 Mmol, and 226276698.38 Mmol for the respective years.

Unlike, Bamako showed the lowest potential for the technical methane, energy and hydrogen production when compared to the other regions, its results for the years 2020, 2025, 2030, 2035, 2040, and 2045 were: 21620 kt, 36039.7 kt, 61655.9 kt, 107555.06 kt, 190274.22 kt, and 339939.46 kt for methane; 38463987.6 GWh, 64119991.37 GWh, 109697815.6 GWh, 191364450.9 GWh, 338544498.9 GWh, and 604840807.5 GWh for energy and 4312020.3 Mmol, 7188196.58 Mmol, 12297716.3 Mmol, 21452986.21 Mmol, 37952662.75 Mmol, and 67805914.03 Mmol for hydrogen.

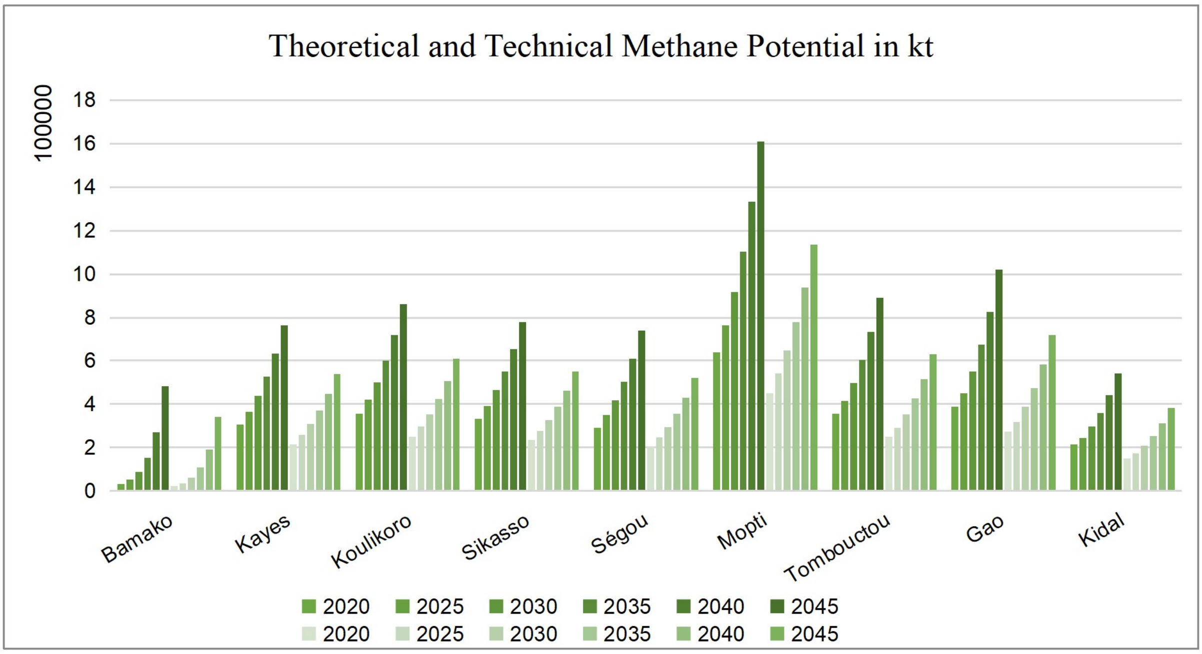
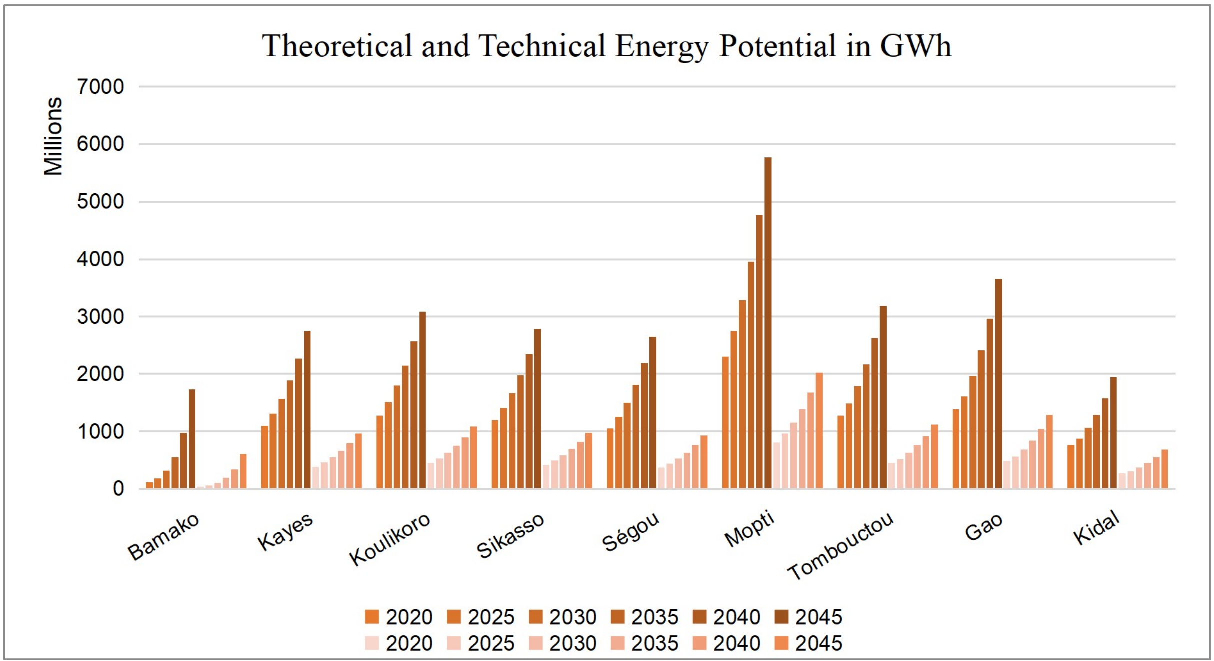


Figure 20: Theoretical and technical methane yield in Mali from 2020 to 2045

Figure 21: Theoretical and technical energy potential in Mali from 2020 to 2045



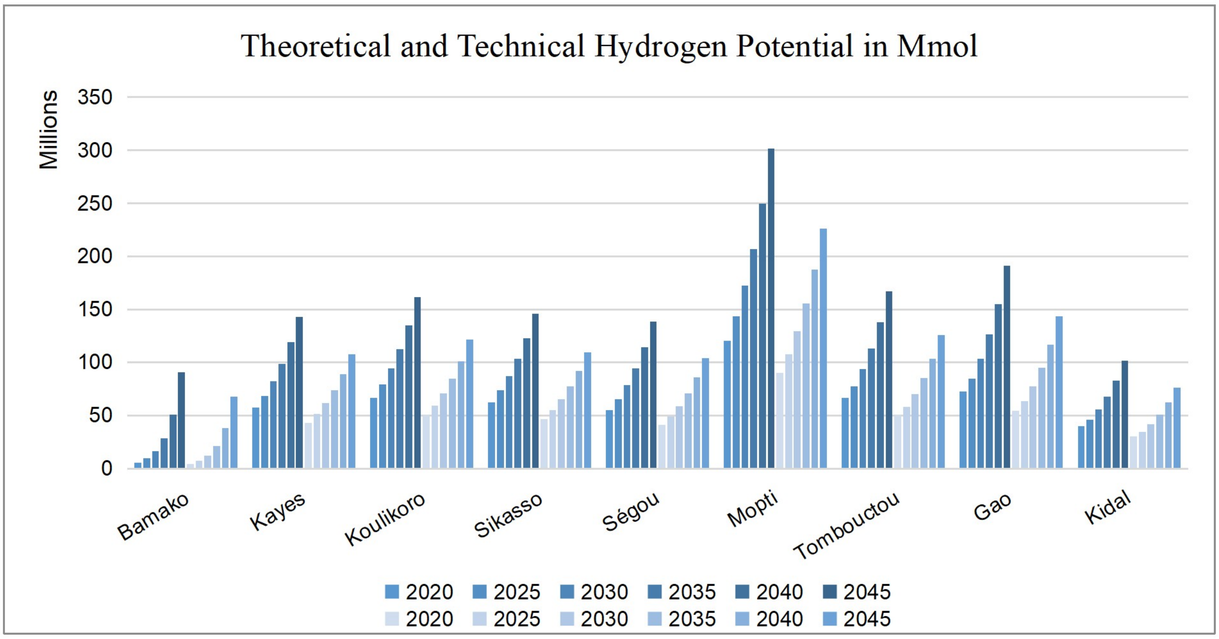


Figure 22: Theoretical and technical hydrogen potential in Mali from 2020 to 2045

3.1.2.4 Theoretical and technical hydrogen potential from cereal crops through gasification

The theoretical and technical production potential of cereal crops residues for the years 2020, 2025, 2030, 2035, 2040, and 2045 are illustrated in (Figure 23) below. The results showed that cereal crops' production potential is less than what obtained from the combination of OFMSW and livestock mainly due to the quantity of cereal crops considered and the unavailability data of some regions such as Bamako and Kidal. It demonstrated the highest production in Kayes over time for the years 2020, 2025, 2030, 2035, 2040, and 2045 with 123.05 Mmol, 529.42 Mmol, 2445.5 Mmol, 11654.63 Mmol, 56362.16 Mmol, and 274581.61 Mmol respectively as the theoretical potential which is greater than the technical potential.

The technical potential obtained in Kayes was: 67.68 Mmol, 291.18 Mmol, 1345.02 Mmol, 6410.05 Mmol, 30999.19 Mmol, and 151019.89 Mmol for the respective years.

On the contrary, Mopti showed the lowest potential over time. Although its technical potential obtained was: 64.31 Mmol, 89.74 Mmol, 127.34 Mmol, 183.43 Mmol, 267.95 Mmol, and 396.54 Mmol for the years 2020, 2025, 2030, 2035, 2040, and 2045.

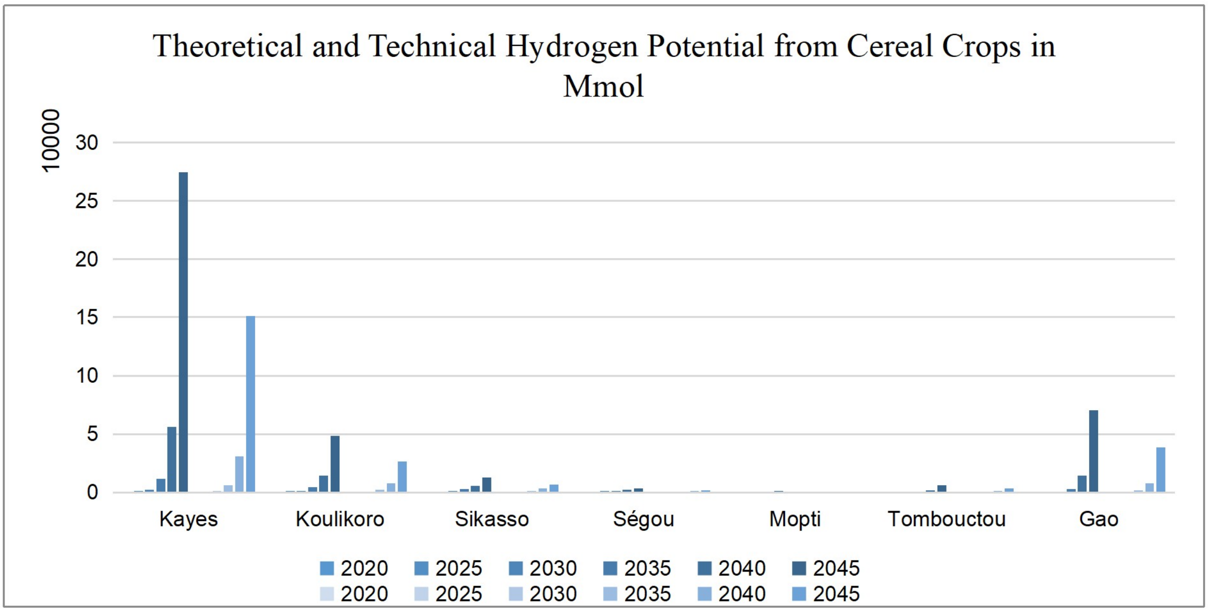


Figure 23: Theoretical and technical hydrogen potential in Mali from 2020 to 2045

3.1.2.5 Hydrogen production potential in Mali in 2045

Figure 24 presents the map of Mali with the technical hydrogen potential for the year 2045 alongside the best conversion technology in the studied regions. Anaerobic digestion is represented by the green shades and gasification by the blue shades. According to the results obtained from the previous technical production for both technologies, Mopti and Tombouctou showed very high hydrogen potential in 2045 through anaerobic digestion compared to gasification. This was followed by Ségou, Kidal, and Bamako.

Conversely, Kayes and Gao had highest hydrogen potential in 2045 through gasification. Thereafter, Koulikoro and Sikasso appeared to have lower potential through gasification but still considerable.

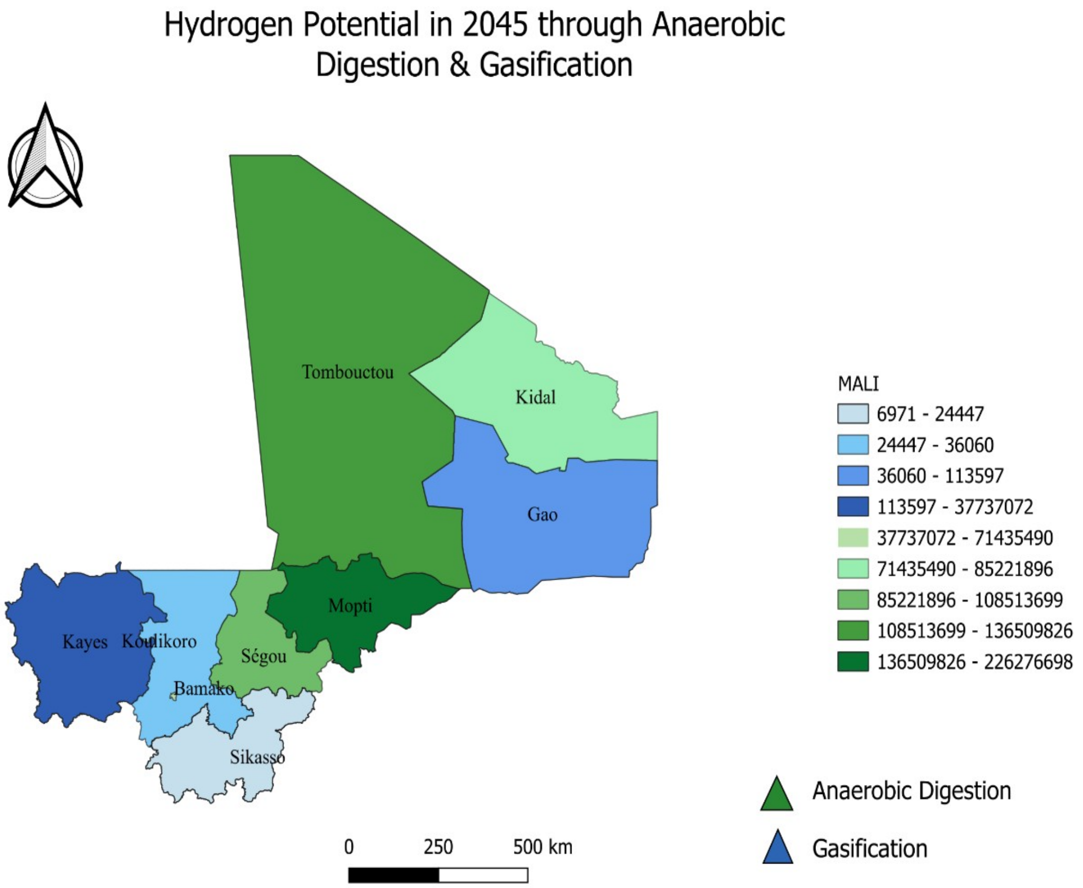


Figure 24: Hydrogen Potential in 2045 through AD and gasification in Mmol

3.2. Discussion

In this study, biomass potential of livestock waste, cereal crops residues and MSW were assessed for the years 2020, 2025, 2030, 2035, 2040, and 2045. It additionally estimated the bioenergy outputs in the form of biomethane, energy and biohydrogen through anaerobic digestion for livestock and MSW and gasification for cereal crops residues. The findings give a thorough evaluation of Mali's bioresource potential and its implications for energy security.

Mali faces the challenges of rising energy demand and dependence on traditional biomass and imported fossil fuels. This research aimed to quantify livestock manure, cereal crops residues, and MSW availability across nine regions, evaluate the potential methane, energy and hydrogen through anaerobic digestion and gasification, and determine how these resources could contribute to enhancing national energy security.

The results indicate that Mali's biomass resources increase significantly over time, mostly due to livestock expansion, rising cereal production and MSW generated. Although, livestock was found to be the largest contributor to total biomass potential, especially in regions with high cattle raising such as Mopti and Sikasso (17391.58 kt and 9898.02kt as potential in 2045 respectively). However, cereal residues also made significant contributions, with sorghum in Kayes and maize in Koulikoro which stood out as major sources of biohydrogen through gasification (7611945.54 kt and 1136752 kt in 2045 respectively). On the other hand, the potential of fonio and wheat residues was consistently low across all regions. In terms of MSW, the northern regions (Tombouctou, Gao, and Kidal) showed the lowest production potential, while Koulikoro showed the highest with 815.56 kt in 2045, which reflected the higher urbanization in this area.

The central region, Mopti, consistently showed the greatest potential for methane, energy and hydrogen (1134402.9 kt, 2018428376.53 GWh, 226276698. 38 Mmol in 2045 respectively) through anerobic digestion, whereas it was Kayes which showed the highest potential for hydrogen production through gasification (67.68 Mmol in 2045). These results highlight the strategic significance of those feedstocks for the deployment of bioenergy in the future.

The results align with earlier research that highlighted Mali's dependence on agriculture and livestock as the primary sources of biomass [4], [5], as well as with [65] and [86] which considered biomass conversion pathways into methane and hydrogen through anaerobic digestion and gasification.

This study, however, expands on earlier studies by presenting a long-term estimate (2020 to 2045) and considering several biomass categories at once, providing a more thorough assessment as considered by [57]. Although previous studies have observed that MSW is underutilized, this analysis measured its growth potential, supporting recommendations for improved waste management systems.

- Implications for policy and energy security.

The findings demonstrate how biomass could help lessen Mali's dependency on imported fossil fuels and reduce deforestation brought on by the usage of charcoal and firewood. The four "As" of energy security (Availability, Accessibility, Affordability, and Acceptability), could be addressed by extensively utilizing crop residues, livestock manure and OFMSW to generate renewable energy. Moreover, rural populations with low electrification rates may profit from investments in decentralized bioenergy systems.

- Limitations of the study

Despite the analysis's strength of this study, several limitations should be acknowledged:

- Incomplete data availability: the study relied on secondary data; the accuracy of the data could be impacted by missing data on different feedstocks.
- Economic feasibility analysis: a full economic analysis such as calculating the Levelized Cost of Hydrogen (LCOH) and the Levelized Cost of Electricity (LCOE) could be conducted.

- Environmental impact: the impacts on biomass use could also be assessed through a full Life Cycle Analysis (LCA).

- Directions for future research

Future research should focus on verifying biomass availability on the ground, combining life cycle analysis to assess the environmental impact and economic feasibility assessments. Further work is also needed on integrating bioenergy into Mali’s national grid and exploring hybrid systems that combine hydropower and solar. Moreover, case studies of small-scale pilot projects in high potential areas like Mopti and Koulikoro could provide practical insights into the scaling up of bioenergy technologies.

Conclusion and perspectives

This research assessed livestock waste, cereal crops residues, and MSW potential in Mali for the years 2020, 2025, 2030, 2035, 2040, and 2045. It further estimated how much of this potential could be converted into biomethane, energy and biohydrogen theoretically and technically. According to the findings, biomass resources are abundant and steadily increasing. Livestock waste is the dominant contributor, followed by cereal crops residues and MSW. Although, Mopti and Gao appeared to have the greatest biomethane, energy and biohydrogen, potential theoretically and technically through anaerobic digestion. However, for gasification, Kayes showed the highest biohydrogen potential.

The whole country will produce 9.64 EWh of electricity or 1,080,468.29 Gmol of hydrogen with the combination of all livestock and MSW considered in each region by 2045 through anaerobic digestion technically. On the other hand, 229.33 Gmol of hydrogen will be produced with cereal crops residues in the five regions considered by 2045 through gasification technically.

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APPENDIXES

Appendix 1. Theoretical Methane, Energy and Hydrogen Yield from MSW and Livestock

Theoretical Methane Yield in kt/year						
Year	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Bamako	30663.3	51116.1	87450.4	152555	269886	482175
Kayes	305760	365077	437167	525018	632367	763890
Koulikoro	355396	421306	501237	598412	716841	861523
Sikasso	332408	391993	463453	549371	652926	778047
Ségou	292025	348233	417768	503305	608390	737570
Mopti	639407	765383	918327	1104448	1331482	1609079
Tombouctou	355463	413174	498274	602871	731754	890944
Gao	387154	448889	548730	672771	827204	1019854
Kidal	213842	244148	295655	359804	439925	540249
Total	2912119	3449319	4168059	5068554	6210774	7683330

Theoretical Energy Potential in GWh						
Year	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Bamako	109897107.5	183199975.3	313422330.2	546755574	967269996.8	1728116593
Kayes	1095843564	1308437520	1566806319	1881664073	2266403468	2737781015
Koulikoro	1273739260	1509959324	1796431799	2144707604	2569157225	3087698295
Sikasso	1191351526	1404902051	1661015481	1968945551	2340086706	2788520706
Ségou	1046619280	1248067949	1497279398	1803846674	2180468533	2643450484
Mopti	2291634801	2743133666	3291282947	3958340081	4772032937	5766938219
Tombouctou	1273979671	1480815664	1785812536	2160690439	2622606009	3193142470
Gao	1387559551	1608817475	1966647225	2411211575	2964698025	3655156019
Kidal	766410586.5	875027444.1	1059626220	1289536537	1576689980	1936251031
Total	10437035346	12362361069	14938324256	18165698107	22259412880	27537054830

Theoretical Hydrogen Potential in Mmol						
Year	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Bamako	5749360.395	9584262.102	16396955.05	28603981.62	50603550.34	90407885.37
Kayes	57329985.54	68452018.71	81968801.56	98440852.03	118568819.8	143229336
Koulikoro	66636749.8	78994802.78	93981853.34	112202197.5	134407639.4	161535555.3
Sikasso	62326565.62	73498642.47	86897433.79	103007056.6	122423620.9	145883826
Ségou	54754775.39	65293733.39	78331441.72	94369768.8	114073060.8	138294354.3
Mopti	119888818.4	143509364.5	172186259.1	207083918.8	249652950.8	301702264.5
Tombouctou	66649327.1	77470127.53	93426297.55	113038353.1	137203857.9	167051956.8

Gao	72591354.84	84166650.85	102886817.7	126144578.7	155100691.9	191222587.5
Kidal	40095419.91	45777802.95	55435244.51	67463197.72	82485873.67	101296615
Total	546022357	646747405.3	781511104.4	950353904.9	1164520066	1440624381

Appendix 2. Technical Methane, Energy and Hydrogen Yield from MSW and Livestock

Technical Methane Yield in kt						
Year	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Bamako	21620	36039.7	61656	107555	190274	339939
Kayes	215562	257381	308204	370140	445822	538546
Koulikoro	250556	297023	353375	421885	505380	607384
Sikasso	234349	276357	326737	387311	460319	548531
Ségou	205879	245505	294527	354832	428917	519989
Mopti	450783	539596	647421	778637	938697	1134403
Tombouctou	250602	291288	351283	425025	515887	628116
Gao	272944	316467	386855	474305	583180	718999
Kidal	150759	172125	208437	253662	310147	380875
Total	2053052	2431781	2938497	3573351	4378622	5416784

Technical Energy Potential in GWh						
Year	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Bamako	38463987.62	64119991.37	109697816	191364450.9	338544498.9	604840807.5
Kayes	383545247.3	457953132.1	548382212	658582425.5	793241213.9	958223355.2
Koulikoro	445808741.1	528485763.3	628751130	750647661.4	899205028.8	1080694403
Sikasso	416973034.2	491715718	581355418	689130942.9	819030347.3	975982247
Ségou	366316748	436823782.2	524047789	631346335.9	763163986.6	925207669.3
Mopti	802072180.2	960096783	1.152E+09	1385419028	1670211527.8	2018428376.53
Tombouctou	445892884.9	518285482.5	625034387	756241653.7	917912103.2	1117599864
Gao	485645842.8	563086116.4	688326529	843924051.1	1037644309	1279304607
Kidal	268243705.3	306259605.4	370869177	451337787.9	551841493	677687860.8
Total	3652962371	4326826374	5.228E+09	6357994338	7790794508	9637969191

Technical Hydrogen Potential in Mmol						
Year	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Bamako	4312020.296	7188196.577	12297716.29	21452986.21	37952662.75	67805914.03
Kayes	42997489.15	51339014.03	61476601.17	73830639.02	88926614.88	107422002
Koulikoro	49977562.35	59246102.09	70486390	84151648.1	100805729.6	121151666.5
Sikasso	46744924.22	55123981.86	65173075.34	77255292.45	91817715.71	109412869.5
Ségou	41066081.54	48970300.04	58748581.29	70777326.6	85554795.62	103720765.7
Mopti	89916613.80	107632023.36	129139694.33	155312939.14	187239713.10	226276698.38
Tombouctou	49986995.32	58102595.65	70069723.17	84778764.79	102902893.4	125288967.6

Gao	54443516.13	63124988.14	77165113.3	94608434.06	116325518.9	143416940.6
Kidal	30071564.93	34333352.21	41576433.38	50597398.29	61864405.25	75972461.27
Total	409516767.7	485060554	586133328.3	712765428.7	873390049.2	1080468286

Appendix 3. Theoretical and technical hydrogen potential from cereal crops residues

Theoretical Hydrogen Potential in kmol						
Year	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Kayes	123047.41	529420.12	2445495.86	11654632.04	56362155.41	274581613.4
Koulikoro	202102.69	515077.72	1462983.52	4494230.29	14525653.32	48423486.21
Sikasso	303142.4	609006.57	1269452.43	2703769.75	5831778.25	12674884.53
Ségou	219484.352	337381.22	544822.82	1124756.39	2242407.24	3622041.24
Mopti	116930.381	163168.51	231521.73	333516.64	487177.17	720976.18
Tombouctou	29628.74	71757.58	194265.21	571876.74	1829817.42	6453904.51
Gao	26464.17	124998.90	603186.36	2938663.52	14376810.35	70462847.02
Total	1020800.15	2350810.65	6751727.95	23821445.38	95655799.16	416939753

Technical Hydrogen Gas in kmol						
Year	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Kayes	67676.07	291181.06	1345022.72	6410047.62	30999185.48	151019887.3
Koulikoro	111156.47	283292.74	804640.93	2471826.66	7989109.32	26632917.41
Sikasso	166728.32	334953.61	698198.84	1487073.36	3207478.03	6971186.49
Ségou	120716.39	185559.67	299652.55	618616.01	1233323.984	1992122.67
Mopti	64311.70	89742.68	127336.95	183434.15	267947.44	396536.90
Tombouctou	16295.80	39466.66	106845.86	314532.210	1006399.58	3549647.48
Gao	14555.29	68749.39	331752.49	1616264.93	7907245.69	38754565.86
Total	561440.08	1292945.86	3713450.37	13101794.96	52610689.54	229316864.2