Solid biomass energy consumption and air pollutant emissions projection for household energy use in Rwanda: An application of LEAP model

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Declaration

I hereby declare that this thesis is entirely my own creation and has not been submitted for a degree at the University of Rwanda or any other academic institution. Proper attribution has been given to all the sources used in this research.

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Date……./……../2023

Certification

This is to certify that the master's dissertation entitled "**Solid biomass energy consumption and air pollutant emission projection for household energy use in Rwanda: An application of LEAP model**" was carried out by Evariste MBAHURIRA in partial fulfillment of the requirement for the Award of Master's Degree in Atmospheric and Climate Science in University of Rwanda, College of Science and Technology.

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Date:………./…../2023 Date: ..../…./2023

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Abstract

In Rwanda, the utilization of solid biomass for household cooking needs is prevalent. The combustion of solid biomass releases a complex mixture of air pollutants that significantly degrade indoor and ambient air quality, thus negatively impact public health and the environment. To develop workable prevention and control methods that can enhance the quality of air and reduce human exposure to air pollutants and their effects, it is important to gather local, trustworthy data on solid biomass fuel consumption and emissions. This study seeks to estimate the emissions of seven main air pollutants from household solid biomass use in Rwanda. It uses a LEAP model to analyze the solid biomass energy consumption and air pollutants emissions projection for household energy use in Rwanda. The yearly solid biomass energy consumption in historical year was calculated by multiplying activity data by intensity of solid biomass type consumed and projecting taking the household's growth as driving indicator. The current and projected air pollutants emissions of nitrogen oxides, carbon monoxide, volatile organic compounds, black carbon, organic carbon and particulate matters (PM_{10}&$PM_{2.5}$), from household solid biomass energy use were estimated. The Business As Usual scenario (BAU) was developed by taking into account the historical trends in household consumption and by considering household growth rate as a key factor influencing solid biomass consumption. Additionally, the scenario assumes that the current energy policy remains unchanged. The study focuses on solid biomass fuel consumption, including firewood, charcoal, and agricultural residue. It calculates historical emissions of air pollutants from 2005 to 2022, while also forecasts their potential levels until 2030 under a business-as-usual (BAU) scenario. The study has found that the total energy consumption from solid biomass reached 36.064 thousand Terajoule (TJ) in 2005, with firewood being the dominant fuel source, accounting for 32.38 thousand TJ. Looking at the overall projection for solid biomass energy demand, in the BAU scenario, the demand for solid biomass energy is anticipated to dramatically increase to 84.67 PJ. In the baseline year, the most significant emissions were attributed to CO at a magnitude of 186.19 kilotonnnes (kt), subsequently followed by NMVOCs, PM_{10}, $PM_{2.5}$,OC,NO_X and BC at 20.17 ,18.06,14.5,6.32,3.61 and 1.91 kt respectively. By the end year (2030), there is a notable rise in air pollutant emissions, with carbon monoxide (CO) reaching a substantial level of 456.98 kt. This is slightly closely followed by NMVOCs, PM_{10}, $PM_{2.5}$, organic carbon (OC), nitrogen NO_X, and BC at 42.4, 37.78, 30.5, 13.9, 8.47, and 4.34 kt, respectively.

The findings of the study highlight a striking similarity between the growth in overall air pollutant emissions and the trend of solid biomass energy consumption.

The study's findings also highlight the importance of concentrating efforts on tackling the rising trend in emissions to mitigate any potential environmental effects caused by an increase in household solid biomass use and enhance ambient and indoor air quality in residential areas.

List of symbols and acronyms

μg: Microgram

BAU: Business As Usual

BC: Black Carbon

CO: Carbon Monoxide

Co: Cobalt

CO_2: Carbon dioxide

Cr: Chromium

EF: Emission Factor

HAP: Household Air Pollution

Hg: Mercury

Hh: Household

H_2SO_3: Sulfurous acid

IAQ: Indoor Air Quality

IPCC: Intergovernmental Panel on Climate Change

Kt: Kilotonne

LEAP: Low Emission Analysis Platform

LPG: Liquefied Petroleum Gas

MDGs: Millennium Development Goals

Mn: Manganese

NASA: National Aeronautics and Space Administration

NO_2: Nitrogen dioxide

NO_X: Nitrous oxide

NMVOCS: Non-Methane Volatile Organic Compounds

NST1: National Strategy for Transformation

O: Oxygen

O_2: Oxygen gas

O_3: Ozone

OC: Organic Carbon,

Pb: Lead

PM: Particulate Matter

PM_{10}: Particulate Matter with aerodynamic diameter ≤ 10 μm

$PM_{2.5}$: Particulate Matter with aerodynamic diameter ≤ 2.5 μm

ppb: Part per billion

ppm: Part per millions

TJ: Terajoule

RPHC4 :4th Rwanda Population and Housing Census

REMA: Rwanda Environment Management Authority

SDGs: Sustainable Development Goals

SO_2: Sulphur dioxide

SYB: Statistical Year Book

TED: Technology and Environmental Database

USD: United State Dollar

WHO: World Health Organization

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Chapter 1: Introduction

1.1 Background

Rwanda is a developing country where the majority of the people rely on solid biomass for household energy, to meet their cooking needs. According to recent statistics, 76% of the inhabitant in Rwanda relies on traditional biomass fuels for household energy, and approximately 2.9 billion individuals globally rely on solid biomass fuel for daily cooking [1,2].

The use of traditional biomass fuels including charcoal, firewood, and agricultural wastes (crop residues), has been recognized as a major contributor to air pollution, climate change, and negative health impacts [3].

When solid biomass fuels are completely burned, they produce only carbon dioxide (CO_2) and water (H_2O) as the resulting byproducts, which are non-toxic and pose no harm, whereas incomplete combustion releases health-damaging pollutants such as carbon monoxide (CO), particulate matter (PM_{10} and $PM_{2.5}$), nitrogen oxides (NO_x), organic carbon(OC), black carbon(BC) and non methane volatile organic compounds (NMVOCs) which have severe consequences for both human health and the environment [4].

CO is generated through incomplete combustion, which happens when carbon in the fuel undergoes partial oxidation instead of complete oxidation to CO_2

A study conducted by WHO showed that in the year 2019, 6.7 million premature deaths around the world were associated with poor ambient and household air pollution worldwide, with approximately 89% of these deaths found in low and middle-income countries [5]. Africa is one of the most affected regions with high levels of air pollution and health damage with an estimated number of 780 000 premature deaths [6].

In Rwanda, 2,227 fatalities were linked to the presence of outdoor air pollution, leading to a cumulative loss of 108,622 years of life and acute lower respiratory disease or stroke was identified as the primary cause of mortality and the loss of years of life due to the adverse air quality in Rwanda[7]. In 2017, air pollution (overall) ranked as the second most significant risk factor in Rwanda. The household air pollution (HAP) and outdoor air pollution(ambient) are ranked as the 4th and 17th respectively, most significant risk factor for illness and death [8]. Approximately 7,383 premature deaths in Rwanda are believed to be caused by HAP every year, resulting in an overall economic loss of USD 674 million annually [9]. Among these, respiratory infections stand out as the primary cause of loss of life.

If prompt measures are not implemented by 2030, it is estimated that approximately 870,000 individuals worldwide will lose their lives due to infections resulting from the utilization of solid biomass fuels for cooking practices [10].

Similarly, the issues of the health impact of air pollutants have been directly or indirectly addressed in sustainable development goals(SDGs).These goals are aimed at transforming the world community by 2030 by setting out 17 primary goals with 169 targets that cover a broad range of socio-economic development issues including improving human health, climate change and environment sustainability and universal access to clean modern energy(SDG7) [11].

Efforts to achieve these goals are very crucial for populations from low-income countries that spend a big part of their income on treating health effects such as respiratory illness resulting from a polluted environment.

Rwanda has implemented certain measures at a national level to regulate the release of air pollutants from biomass. Rwanda has integrated the Africa Agenda 2063 and the Sustainable Development Goals (SDGs) into its internal development blueprints, which include the draft Vision 2050, National Strategy for Transformation (NST1, 2017-2024), and related strategies at different levels [12].

The country has set a goal to decrease the percentage of households relying on firewood as their primary cooking energy source from 79.9% of the population in 2016/2017 to 42% by the year 2024.

Despite these efforts, the country's rapidly growing population and increasing energy consumption have overshadowed these interventions. Consequently, the number of individuals relying on biomass for their energy needs is still high, resulting in a simultaneous increase in exposure to air pollutants released from these sources [13].Consequently, this has led to further pollution of the atmosphere.

An essential initial stage in developing an air quality management plan involves creating estimates of various pollutants specific to their sources. These estimates can cover multiple sectors, including the household sector. Emission estimates are generated based on a designated base year or historical data and can be projected for future years, considering different growth scenarios. This serves as a crucial foundation for the air quality management plan, enabling the assessment of progress over time and the pursuit of the ultimate objective of achieving cleaner air.

Rwanda has made considerable attempts to estimate emissions originating from various sources and pollutants [14]. Nevertheless, there have been insufficient endeavours to quantify the mass emissions of each pollutant originating from the sectors under consideration [14] and to comprehend the future course of emissions from energy consumption across different sectors and pollutants, using an integrated model. To address this gap, the study employed a comprehensive modelling tool known as the Low Emission Analysis Platform (LEAP) to accomplish the desired objectives

In Rwanda, where a significant proportion of the people rely on biomass fuel, especially solid biomass, the estimation of air pollutant emissions from household biomass energy use becomes crucial for developing effective mitigation strategies. Estimating air pollutant emissions helps to quantify the pollutants discharged into the atmosphere, providing a clear picture of the extent and severity of air pollution from this particular sector.

Consequently, this research aimed to evaluate the contribution of household burning of solid biomass on local air quality by estimating the release of air pollutants into the atmosphere of Rwanda. The LEAP tool was utilized for this purpose, to provide valuable insights for local air quality policies. By comprehending the magnitude and consequences of these emissions, policymakers and relevant parties can develop targeted strategies to mitigate air pollution, enhance air quality, and safeguard public health**.**

1.2 Problem statement

Many households in Rwanda predominantly depend on solid biomass fuels, including firewood, charcoal, and crop residues, for cooking practices. Around 76 percent of households use firewood, while approximately 17 percent utilize charcoal [1]. In contrast, the usage of modern and clean cooking fuels like LPG, biogas, and electricity is less than 6 percent, indicating a limited adoption of these alternatives. These energy sources possess harmful toxins such as carbon monoxide, particulate matter, nitrogen dioxide and other toxins which are linked with health impacts like pneumonia among children below the age of 5 years and lung cancer among adults caused by the air pollutant released during the combustion.

It is reported that comprehensive knowledge is deficient concerning the trend of household solid biomass energy consumption in Rwanda [16]. The available literature indicates a limited number of studies focusing on household energy consumption patterns and their associated air pollutants emissions [16,17]. Estimating household energy consumption and its related air pollutant emission is paramount in assessing the environmental impact and identifying strategies for mitigating pollution. The current limited commitment to tackling household solid biomass energy consumption problems may be due to a lack of accurate information regarding household energy usage and its role in emitting pollutants in the atmosphere. The absence of dependable and comprehensive data on energy consumption and emission within households significantly hinders energy planning and policy initiatives [19]. The United Nations report emphasized that the attainment of the MDGs necessitates the availability of dependable and up-to-date pertinent information [20]

The essential goals of this study were to estimate the emissions of air pollutants resulting from household solid biomass energy consumption and analyze its changes within the baseline years of 2005 and 2030 using the LEAP tool. These objectives were specifically framed within the scope of this study.

1.3 Objectives

1.3.1 Main objective

The main objective of this thesis is to use a LEAP model to analyze the solid biomass energy consumption and air pollutant emission projection for household energy use in Rwanda

1.3.2 Specific objectives

The specific objectives of this thesis are summarized below:

1. To develop a bottom-up energy accounting model of the household solid biomass sector

2. To analyze the historical household solid biomass energy consumption and the related air pollutant emissions.
3. To estimate air pollutant emission from household solid biomass energy use in historical and project air pollutant emissions in 2030.

1.4 Scope of the study

While there are many sectors considered as source of air pollutant emission, our study is rewarding on air pollutants emitted from household solid biomass and their total contribution in national emissions. This study would calculate the amount of air pollutants emissions from household solid biomass use and would calculate the trends of air pollutant emissions from the household solid biomass fuel in Rwanda (historical and projected). This study would provide the information about the air pollution in Rwanda from the household solid biomass use and would also provide measures to minimize the air pollution in Rwanda.

1.5 Significance of the study

Overdependence on solid biomass fuel poses a significant issue in numerous developing nations, and its repercussions extend to every facet of life for the majority of the global population. The work of estimating air pollutants emitted from household solid biomass fuel intends to understand the actual trends and picture of households ‘air pollutants released to the atmosphere in Rwanda. The research findings from this study will serve as an initial step in raising public awareness and policymakers about the immediate hazards posed by air pollutants discharged into the atmosphere. These key findings will be utilized by researchers, the broader community, urban planners, and local officials to gain insights into household energy consumption and emission levels in Rwanda. Moreover, the thesis will provide well-researched data along with a comprehensive analysis, offering valuable information.

Chapter 2: Literature review

2.1 Definition of Air pollutant

Air is a fundamental necessity for human beings to sustain their biological functions. Nitrogen gas comprises 78% of the Earth's atmosphere, while oxygen gas accounts for 21%. Argon makes up approximately 0.9% of the air, and the remaining 0.1% consists of various trace gases and other minor components [21]. This gas mixture protects the natural characteristics of the earth's atmosphere and sustains life on the planet [22].The primary need for humans is oxygen, which is acquired directly inhaling it from the surrounding atmosphere. However, human activities persistently introduce significant amounts of pollutants into the air, thus compromising its quality. An air pollutant is defined as any atmospheric contaminant or mixture thereof, encompassing physical, chemical, biological, and radioactive components (including source materials, special nuclear materials, and byproduct substances), that is discharged into or infiltrates the surrounding air environment[23]. It either does not occur naturally in the atmosphere or exists in higher concentrations than what is typically found naturally. These pollutants can have detrimental impacts on human health and the environment, both in the short term and over extended periods [24].

Air pollution poses the gravest environmental health hazard globally, resulting in an estimated total of 6.7 million premature deaths annually. Specifically, during 2019, outdoor air pollution resulted in roughly 4.2 million premature fatalities, while household air pollution stemming from incomplete combustion of solid biomass fuels and other cooking sources contributed to an additional 3.8 million deaths [25].

In the year 2017, outdoor $PM_{2.5}$ exposure was responsible for 1,220 deaths, while HAP exposure caused 4,240 deaths, and ozone exposure led to 117 fatalities (Figure1).These estimates reveal an alarming level of the burden the world has.

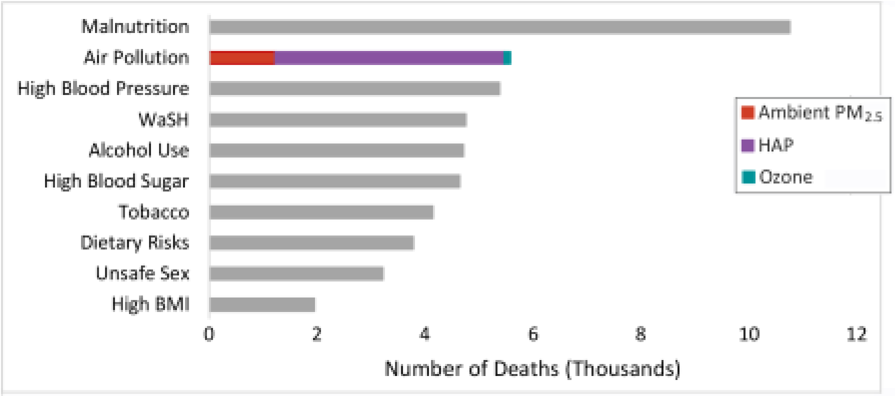


Figure 1 Leading risk factors for death and disability in Rwanda in 2017 [8]

Many studies determine that the particulate matter is identified as the primary cause of most air pollution-related deaths. Ambient air pollution in the form of $PM_{2.5}$ exceeds the WHO guidelines in Rwanda with a daily average of around 42.6 $\mu g/m^3$ [17].

Air pollutants mainly originate from either natural or anthropogenic. Natural sources encompass forest fires, volcanic eruptions, vegetative matter, etc. The anthropogenic sources encompass industrial procedures, power production, and commercial and residential fuel consumption, proper disposal of solid waste, transportation, and so forth. Automobiles stand out among the many mobility sources as the primary contributor to air pollution.

2.2 Classification of air pollutants

Air pollution originates from numerous sources, with the combustion of solid biomass fuels being one contributor. Air pollutants can be categorized based on their source, chemical composition, size, and whether they are released indoors or outdoors. Table1 provides examples that differentiate between primary and secondary pollutants, pollutants found indoors versus outdoors, and gaseous versus particulate pollutants (Table1).

Table 1 Class of air pollutants

Type of pollutants	Description	Pollutants
Primary pollutants	Pollutants emitted directly into the atmosphere	SO_2, NO_X and PM
Secondary pollutants	Pollutants are produced in the atmosphere due to chemical reactions involving other pollutants and gases.	O_3, HNO_3 , SO_3
Indoor pollutants	Indoor pollutants may arise from diverse sources, including the burning of fossil fuels and biomass for cooking and heating, building materials, smoking, etc.	BC, CO
Outdoor pollutants	Pollutants generated by domestic and industrial processes, vehicles, agricultural practices etc.	SO_2, NO_x, CO, PM, NMVOCs
Gaseous pollutants	Pollutants in a state of gaseous	SO_2, NO_X, C_6 H_6 etc.
Particulate matter (PM)	Air pollutants in the solid phase include $PM_{2.5-10}$ µm and, fine particulate matter PM $_{0.1-2.5}$ µm.	BC, OC

Source: [26]

2.3 Characteristics, effect and sources of air pollutants

Air pollution in Rwanda arises from a diverse range of human-made and natural origins of pollutants. The primary anthropogenic sources contributing to air pollution include road traffic, household burning fuels, and industrial activities. The key pollutants that require particular attention are $PM_{2.5}$ and PM_{10}, SO_2,CO, NO_x, BC, NMVOCs, OC and O_3 [14].

2.3.1 *Particulate matter ($PM_{2.5}$& PM_{10})*

Particulate matter consists of a mixture of solid particles and liquid droplets present in the surrounding air [27]. Some particles are large or dark in appearance, resembling soot or smoke, while others are so tiny that they can barely be detected by measuring instruments. Fine particles, referred to as $PM_{2.5}$, have an aerodynamic diameter ≤ 2.5 μm, whereas coarse particles have a size ≥ 2.5 μm [28]. Consequently, PM_{10} encompasses all particles with a diameter equal to or less than 10 μm. Particulate matter can originate from both stationary and mobile sources, as well as natural sources. Fine particles result from fuel combustion in motor vehicles, power generation, industrial facilities, residential fireplaces and wood stoves. Certain gases like SO_2, NO_x, and NMVOCs can interact with other compounds in the air, forming fine particles. The chemical and physical composition of these particles varies based on location, time of year, and weather conditions [29]. During the wet season, towns and cities may experience elevated concentrations of particulates, often associated with smoke and sulfur dioxide. On the other hand, coarse particles primarily stem from unpaved roads, crushing or grinding operations, materials handling, and dust carried by the wind. They are more prevalent in rural areas [30].Several studies confirmed that inhaling these particles can result in their accumulation within the respiratory system, giving rise to various health consequences. Fine particles, in particular, have been strongly linked to adverse effects such as increased mortality among the elderly, heightened hospital admissions and emergency room visits for individuals with heart and lung ailments, as well as reduced lung function across different population groups. On the other hand, coarse particles are associated with the exacerbation of respiratory conditions like asthma [30].

2.3.2 *Sulphur dioxide (SO_2)*

SO_2 is the primary type of SO_x found in the lower atmosphere. It is a colourless gas with a detectable taste and smell at concentrations ranging from one thousand to three thousand micrograms per cubic meter ($\mu g/m^3$). The odour of sulfur dioxide becomes unpleasant as the concentration increases to ten thousand $\mu g/m^3$. In the presence of water in the atmosphere, sulfur dioxide can dissolve and form sulfurous acid (H_2SO_3) known as acid rain. Approximately 30% of the atmospheric SO_2 undergoes a conversion process, transforming into sulfate aerosol, which is then removed using dry or wet deposition techniques [31].

SO_2 is primarily generated through the combustion of fuels that contain sulfur or the roasting of metal sulphide ores. Volcanoes also naturally emit SO_2. However, the main human-made sources of SO_2 are thermal power plants that burn sulfur-containing compounds (such as coal), industrial boilers, and smelting of nonferrous metal. Furthermore, emissions from household coal burning and vehicles can contribute to an elevation in ambient levels of SO_2. The release of SO_2 during the combustion of wood is generally not a major concern due to the naturally low levels of sulfur present in the fuel. Additionally, when wood chips and bark are used, a relatively high amount of sulfur becomes embedded in the resulting ash, further minimizing emissions of SO_2 [32].
Inhalation of sulfur dioxide in the surrounding air has been linked to various health impacts, including decreased lung function, a higher prevalence of respiratory diseases, as well as irritation of the eyes, throat and nose. Additionally, exposure to sulfur dioxide has been associated with premature mortality [33]. Apart from its effects on human health, trees and other vegetables exposed to both wet and dry acidic deposition (resulting from sulfur dioxide) may experience damage, which can have implications for crop production. Moreover, emissions of SO_2 can also affect building materials, such as stone, as well as ferrous and nonferrous metals. This is due to the formation of sulfurous acid when SO_2 reacts with moisture, which can accelerate the corrosion of iron zinc, and steel [31].

2.3.3 Carbon monoxide (CO)

CO is a gas that is colourless, odourless, and highly toxic when present in high concentrations. It is produced as a result of incomplete combustion of fuels that contain carbon [30]. Human activities contribute to the emission of carbon monoxide (CO) through various sources such as motor vehicle exhaust, controlled burning of vegetation, residential combustion of biomass, and industrial processes. On the other hand, natural sources of CO include forest fires, emissions originating from plants and oceans, as well as the oxidation of CH_4 and non-methane hydrocarbons. According to WHO, in non-urban areas, anthropogenic activities Contribute to approximately 60% of CO emissions, the remaining 40% is attributed to natural processes. In Africa, findings from NASA observations suggest that a significant source of CO is seasonal agricultural burning [14].

Both individuals with good health and those with pre-existing health conditions are susceptible to the effects of CO. When the concentration of CO increases, it hampers the ability of red blood cells to carry oxygen, as it binds with hemoglobin. Consequently, vital organs like the brain, nervous tissues, and the heart do not receive adequate oxygen supply, impairing their proper functioning. The adverse health effects become noticeable when around 2.5% of hemoglobin binds to CO. At very high concentrations of CO, up to 40% of haemoglobin can be bound to CO, and exposure at such levels is highly likely to be fatal for humans.

Even a slight elevation in carbon monoxide levels can have an impact on the cognitive abilities of healthy individuals, leading to difficulties in concentration. Consequently, some people may experience a decline in coordination, becoming slightly clumsier, and they may also experience increased fatigue. Individuals with pre-existing heart conditions are particularly vulnerable, as they may experience more frequent and prolonged episodes of angina, and they face a higher risk of heart attacks. Moreover, children and unborn infants are at a heightened risk due to their smaller size and ongoing growth and development processes [34].

2.3.4 Nitrogen oxides (NO_x)

NO_x comprise a mixture of NO and NO_2. NO is a colourless gas lacking taste, whereas NO_2 is a yellowish-orange to reddish-brown gas with a strong, irritating odour and potent oxidizing characteristics. The formation of NO_x occurs when nitrogen present in the atmosphere and fuels undergoes partial oxidation during high-temperature combustion, involving a series of chemical reactions [14].NO_x is mainly produced by human activities through the burning of fossil fuels, fertilizer application, and prescribed burning. Additionally, natural sources of NO_x include emissions from lightning, wildfires, and soil microbial activity [35].

Brief exposure to low levels of nitrogen dioxide (NO_2) lasting less than 3 hours can cause airway responsiveness to change, impact lung function, and lead to increased respiratory diseases in children aged between 5 and 12 years old, especially in those with pre-existing respiratory issues. Prolonged exposure to NO_2 over an extended period may heighten vulnerability to respiratory infections and potentially cause long-term alterations in lung function. Nitrogen oxides play a crucial role as precursors to tropospheric ozone and aerosols, both of which are linked to detrimental health effects [30].

2.3.5 Tropospheric Ozone (O_3)

Ozone plays a crucial role, with stratospheric ozone acting as a protective barrier against the ultraviolet radiation from the sun, while tropospheric ozone (found in the troposphere) functions as a greenhouse gas and participates in various physicochemical processes [13]. This study primarily focuses on stratospheric ozone rather than stratospheric ozone, as stratospheric ozone is considered a significant pollutant of greater health concern. Ground-level ozone is a secondary air pollutant that forms through the photochemical degradation of emitted NMVOCs in the presence of sunlight and NO_x. The formation of ozone is heavily influenced by meteorological factors, particularly temperature, due to its photochemical nature. Temperature impacts ozone formation by accelerating the rates of chemical reactions and increasing the emissions of NMVOCs, such as isoprene, from vegetation [36].

Tropospheric ozone formation occurs when NO and NO_2 are present in the presence of sunlight. The photolysis of NO_2 leads to the production of NO and O, which then react with O_2 to form O_3. Furthermore, a complex sequence of reactions involving NMVOCs and NO_x in the presence of sunlight contributes to the generation of ozone in the troposphere. NMVOCs release radicals that react with NO, resulting in the formation of NO_2. Subsequent photolysis of NO_2 produces NO and O, which combine with O_2 to form ozone. Ground-level ozone is readily formed in the atmosphere, especially during hot summer conditions. NMVOCs are emitted from various sources such as motor vehicles, chemical plants, refineries, factories, consumer and commercial products, as well as other industrial sources [9].

Short-term (1 to 3 hours) and prolonged (6 to 8 hours) exposure to outdoor ozone has been associated with various health issues. Abundant hospital admissions and emergency room visits for respiratory illness have been linked to exposure to ozone in the environment. Ozone exposure can heighten the susceptibility to respiratory infections, trigger lung inflammation, and worsen pre-existing respiratory conditions such as asthma. Additionally, ozone exposure has been connected to significant declines in lung function and an increase in respiratory symptoms like chest pain and cough.

Ozone also has implications for vegetation and ecosystems, leading to reduced yields in agriculture and commercial forestry, diminished growth and survival of young trees, and increased vulnerability of plants to diseases, pests, and environmental stresses. In long-lived species, these effects may become evident after many years or even decades, potentially causing lasting impacts on forest ecosystems. Tropospheric ozone can also harm foliage, resulting in the loss of visual appeal in attractive species and compromising the natural beauty of national parks and recreational areas [30].

2.3.6 Black carbon (BC)

BC is climate forcer but in contrast to other climate forcers, BC is not a greenhouse gas. BC is a major constituent of soot and is released by the incomplete combustion of fossil fuels and biomass. It remains in the atmosphere for days to weeks and harms humans who inhale it [25] and exists in the atmosphere as a component of $PM_{2.5}$. They have the ability, when inhaled to penetrate our lungs and bloodstream causing lung disease and severe cardiovascular and neurological problems. The health impacts increase with the decreasing size of the particles. It also causes warming through the absorption of sunlight and by reducing surface albedo when deposited on snow [37].Finally, the particles are also involved in cloud formation thus, changing regional weather. The global warming potential of black carbon over 100 years exceeds that of carbon dioxide, it varies significantly between 190 and 2,240 GWP.

Africa emits a substantial amount of BC, which is a major air pollutant, predominantly originating from biomass burning. In the context of Rwanda, the primary contributors to black carbon emissions are transportation, household activities like heating and cooking using firewood, forest fires, and certain industrial establishments.

2.4 Biomass energy in Rwanda

Rwanda, a country located in East Africa and landlocked in nature, the availability of modern fuels is constrained due to the country's geographical and socioeconomic conditions, thereby impacting the energy situation [38].Biomass fuels are widely used for cooking due to their availability and affordability.

According to the evaluation of energy supply and demand in Rwanda reveals that currently, around 83 percent of primary energy is sourced from traditional biomass [39]. This primarily involves the direct utilization of wood as fuel or its conversion into charcoal, accompanied by lesser quantities of agricultural waste. The Stockholm Environmental Institute's forecast predicts that Rwanda will experience a minimum 48% surge in biomass energy demand across all sectors by the year 2030 [40]. Solid biomass energy resources vary geographically, and are not uniformly distributed across the country, this affect its consumption.

The predominant use of biomass in cooking is primarily observed in rural households, where wood is extensively utilized, while urban households rely heavily on charcoal. However, this widespread reliance on biomass fuels has detrimental effects on air quality, environmental degradation, and public health. In response to these concerns, the Rwandan government has implemented a ban on the use of firewood for cooking in various institutions, including, prisons, schools, hotels, hospitals, police, and the military has actively encouraged the adoption of alternative energy sources. The Rwandan government also has initiated measures with the objective of decreasing its reliance on biomass as an energy source by the year 2024.

According to the latest national energy balance data, biomass, predominantly wood fuel, constitutes approximately 83% of the overall energy consumption in Rwanda. Petroleum represents 9.7%, electricity accounts for 1.3%, and other energy sources make up less than 0.5%. In rural regions, the dependence on biomass exceeds 90% [39].

Here are the different types of biomass fuels commonly used for cooking in Rwanda:

Firewood remains the prevailing choice for cooking fuel in Rwanda, and it is utilized in a variety of woodstoves. The majority of rural households rely on firewood due to its widespread availability, often being accessible without cost in many instances [41]

Different types of woodstoves are utilized in households. In rural areas, approximately 48 to 49% of households rely on traditional stoves, particularly three-stone fires. Another 52% of households use mud cooking stoves, which was considered improved stoves due to government initiatives following the genocide. Around 4% of households use alternative woodstoves, including non-improved traditional clay stoves and improved clay stoves like the Canarumwe.

Charcoal is the primary cooking fuel for a significant proportion of households residing in major urban areas such as Kigali, Musanze, Rwamagana, and Huye. Approximately 65% of households in these urban centres rely on charcoal to fulfill the majority of their cooking requirements.

Charcoal-burning stoves in Rwanda encompass both traditional stoves and improved Canamake stoves, which are crafted by local artisans. Additionally, traditional clay stoves created by potters across the country are also prevalent. In urban areas, over 90% of households primarily use charcoal stoves for cooking all their meals. Conversely, in rural areas, more than 90% of households depend on biomass as their main fuel source for cooking purposes [42].

A**gricultural residues** such as soya, beans, groundnuts, coffee pulps, and dried cow dung initially were a minor component of household fuel sources. However, their usage has progressively risen in zig zag way over the years as a substitute for wood, primarily driven by the scarcity of wood resources. This trend is particularly notable among poor households residing in rural semi-arid regions of Rwanda. There is no dedicated stove specifically designed for agricultural residues.

2.5 Emission from biomass combustion

Combustion involves the combination or reaction of fuel with oxygen from the air, resulting in the liberation of thermal energy. This procedure is employed daily in residential settings to provide heat and facilitate cooking, as well as in various industries to produce heat or generate steam. Combustion plays a crucial role, constituting 85 percent of global energy consumption, and is indispensable for sustaining our present lifestyle [43].

Biomass combustion has emerged as a substantial contributor to air pollution. The process of biomass combustion involves numerous intricate chemical and physical factors. Figure 2 illustrates the emissions of pollutants from biomass combustion under both ideal and actual conditions. In an ideal scenario, only CO_2 and H_2O are released through the complete combustion of fuels containing carbon (C), hydrogen (H), and oxygen (O) exclusively (equation1). However, the presence of crucial inorganic elements like nitrogen (N), sulfur (S), and chlorine (Cl) in biomass fuels significantly impacts the combustion process and the characteristics of emitted pollutants [32].

$$\mathbf{Fuel + Oxygen\ (O2) \rightarrow Carbon\ Dioxide\ (CO2) + \quad Water\ Vapor(H2O) + Heat} \tag{1}$$

During complete combustion, carbon (C) and hydrogen (H) undergo oxidation, resulting in the production of carbon dioxide CO_2 and H_2O, accompanied by the release of heat at elevated temperatures. In addition to CO_2 and H_2O, other gaseous emissions that occur include NO_x, primarily consisting of NO and NO_2, SO_x, predominantly sulfur SO_2, hydrogen chloride (HCl), and PM [32].

Incomplete combustion takes place when there is an insufficient supply of oxygen, a low temperature for combustion, and a limited duration for the fuel to undergo a complete reaction. As a result, incomplete combustion products are formed, including CO, polycyclic aromatic hydrocarbons (PAHs), PM, NMVOCs, ammonia (NH_3), and O_3. These products are generated due to the incomplete transformation of the fuel under suboptimal combustion conditions [44].

Overall, the primary pollutants generated during biomass burning are PM and gaseous pollutants such as CO, NO_x, and SO_x. These pollutants have a detrimental impact on human health [26]. Furthermore, the presence of various mineral elements in biomass fuel, such as aluminium (Al), calcium (Ca), cadmium (Cd), iron (Fe), arsenic (As), Pb, Cr, Mn, Hg, Co, and plays a significant role in determining the toxicity of PM [32].

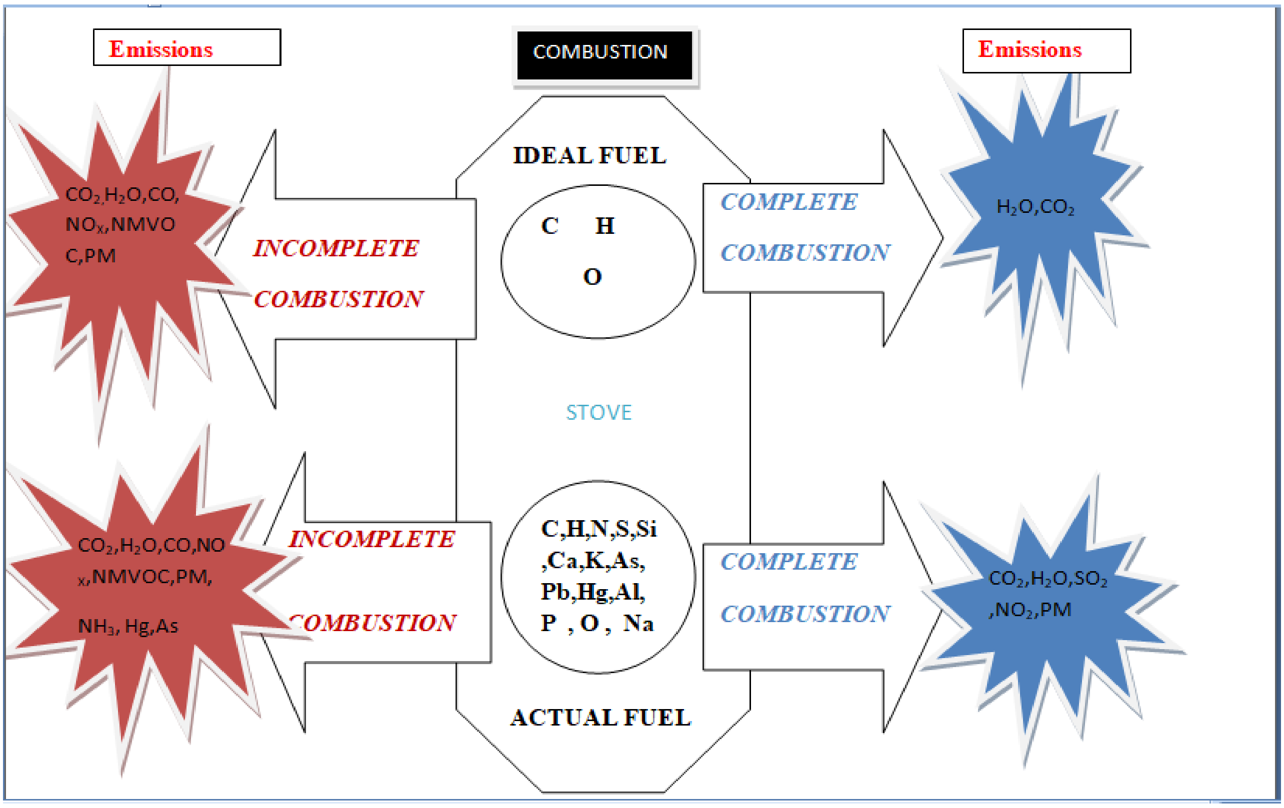


Figure 2 Emissions from solid biomass fuel combustion

In addition, suitable fuels for combustion consist of substances abundant in hydrogen and carbon, known as hydrocarbons. These types of fuels encompass a variety of resources such as, coal, agricultural residues, natural gas, propane, wood, diesel, and municipal solid waste and gasoline [45].

2.6 Review of the Related Studies and gaps in Rwanda

Studies conducted by [14] revealed that the mean concentration in Kigali is 133$\mu g/m^3$ for $PM_{2.5}$ and 156$\mu g/m^3$ for PM_{10} and in Musanze is 45$\mu g/m^3$ for $PM_{2.5}$ and 54$\mu g/m^3$ for PM_{10}.The study determined that the levels of $PM_{2.5}$ and PM_{10} in Rwanda surpassed the recommendations set by the World Health Organization. On Kigali car-free days and public holidays, air pollution decreases compared to regular working days due to a decrease in the number of vehicles on the streets.

According a study conducted by DeWitt in 2016 at MUSANZE on Mt. Mugogo, it was found that the average concentration of black carbon levels in Rwanda was similar to that of major cities in the United States. The study concluded that agricultural burning, cooking fires, charcoal manufacturing, kerosene utilization, lightning, brick kilns, and older diesel vehicles generators were identified as significant sources of air pollution in Rwanda [46].

In a separate study conducted by the World Health Organization (WHO) in 2016, using satellite sensing data from 2014 and modelling techniques, it was discovered that the average concentration of $PM_{2.5}$ in urban areas of Rwanda was measured at $51\mu g/m^3$. The study concluded by highlighting that air pollution is escalating at a concerning pace, negatively impacting the economy, and quality of life, and posing a significant public health emergency [7].

Nduwayezu et al. conducted a study in 2015 in Kigali and Nyamagabe, using a 9-month Gray Wolf-Advanced Sense HVAC system to measure CO, O_3, SO_2, and NO_2 levels. The study found that the concentrations of NO_2 ranged from 0.119 to 0.050 ppm, SO_2 ranged from 0.014 to 0.000 ppm, O_3 ranged from 0.033 to 0.009 ppm, and CO ranged from 3.148 to 0.000 ppm. Furthermore, the study noted that both petrol and diesel vehicles make a substantial contribution to the air pollutants present in the atmosphere of Kigali city [18].

Currently, there have been some researchers conducted in Rwanda focusing on the quantitative investigation of emission levels, specifically in the areas of air quality, climate, and environmental studies. However, there is a lack of research that quantifying the air pollutant emissions associated with Fuel consumption Patterns in Rwanda. Furthermore, there has been no formal research conducted to estimate the discharge of air pollutants into the atmosphere from the use of solid biomass in households in Rwanda. The existence of these gaps in knowledge has inspired me to undertake this study to address these areas of research that have not been adequately explored**.**

Chapter 3: Methodology

3.1 Introduction

This part aims to discuss the methodology to estimate solid biomass air pollutant emissions from household sector sources in Rwanda by developing a comprehensive historic (2005–2022) emission inventory of significant air pollutants from household solid biomass. Emissions are then projected for a baseline scenario (2023–2030) based on anticipated based on demographic growth, assuming no new implementation of emission-reducing policies and measures. The research utilizes the Low Emissions Analysis Platform(LEAP), software system developed by Stockholm Environment Institute (SEI) which is a widely accepted tool for energy and emissions modeling [47]. This methodology outlines the steps involved in data collection and the application of the LEAP tool to complete household solid biomass emission estimation and projection for major air pollutants from household solid biomass fuel use.

3. 2 Data Collection

This study predicts the demand for solid biomass from 2005 to 2030 and calculates the corresponding air pollutant emissions. The base year for the analysis is 2005, the first scenario year is 2023, and the end year is 2030. The research explains the process of obtaining secondary data required to populate the LEAP tool and estimate air pollutant emissions. For this purpose, national historical and projected household data are downloaded from the National Institute of Statistics for Rwanda (NISR) website [48](Table 2) and are entered into the “Key Assumption” module of the data tree in the LEAP system (Figure 3)

Table 2 Rwandan historical and projected households till 2030

Years	2005	2008	2011	2014	2017	2020	2023	2026	2029	2030
Household(Million)	1.89	2.28	2.42	2.63	2.95	3.31	3.72	4.18	4.69	4.87

The secondary data on solid biomass consumption involved in this study for the base year include firewood ,charcoal and crop wastes (Table 3) were taken from the literature**s**[49] and its consumption fraction shares were from different published NISR household survey [ECV1-4(Integrated Household Living Condition Survey)] and Statistical Year Book(SYB) [50], [51].

Table 3 Activity rate for household solid biomass fuel (kg/Hh.year)

Fuel type Consumed	Annual Energy Intensity per Household	Share of Households
Wood	1248	88.2%
Charcoal	677	7.8%
Crop waste	1165.76	2.7%

To estimate the environmental effect of energy consumption, emission factors (EFs) related to each fuel is needed.

Emission factors refer to the calculated average rate at which a specific pollutant is emitted from a unit of a particular source of fuel burnt.

Default emission factors utilized in our study are derived from the LEAP Technology and Environmental Database (TED), and followed IPCC Tier 1 standards. Tier 1(tier corresponds to a degree of methodological complexity) emissions were created using straightforward estimation techniques that rely on factors like fuel consumption and average emission factors. Table 4 shows the emission factors related to main air pollutants BC, $PM_{2.5}$, PM_{10}, NMVOCs, NO_x, OC and CO.

Table 4 Emissions factors of major air pollutants (kg/TJ)

Fuel	NO_X	NMVOC	OC*	$PM_{2.5}$*	PM_{10}*	CO	BC*
Wood	100	600	2.89	6.64	8.3	5000	0.83
Charcoal	100	100	0.85	2.38	2.38	7000	1.19
Crop waste	47	600	3.3	6.44	8.05	5000	1.0

(*) The units are kg per metric tone

3.3 Emissions calculation

This research will employ the Low Emission Analysis Platform (LEAP) system downloaded from [52]. It is a software tool developed by the Stockholm Environment Institute (SEI), for analyzing energy policies and assessing climate change mitigation strategies [53]. LEAP allows the creation of various scenarios that project future energy demand and environmental impact based on how energy is consumed, converted, and produced within a specific region or economy. These scenarios consider parameters such as population growth, economic development, technology usage, etc. To compile emission inventories, a base year needs to be determined. The base year selected for this study will be 2005, as it represents the most recent year with comprehensive and reliable energy data available.

The LEAP has been widely applied on local, national, and global levels to project energy supply and demand, predict the environmental consequences of energy policies, and identify possible issues or challenges.

With a flexible data structure, LEAP is user-friendly and rich in technical specifications and end-use details. It encompasses all sectors responsible for emitting anthropogenic air pollutants, which are divided into four main categories: i) Energy, ii) Industrial Processes and Product Use (IPPU), iii) Agriculture, and iv) Waste.

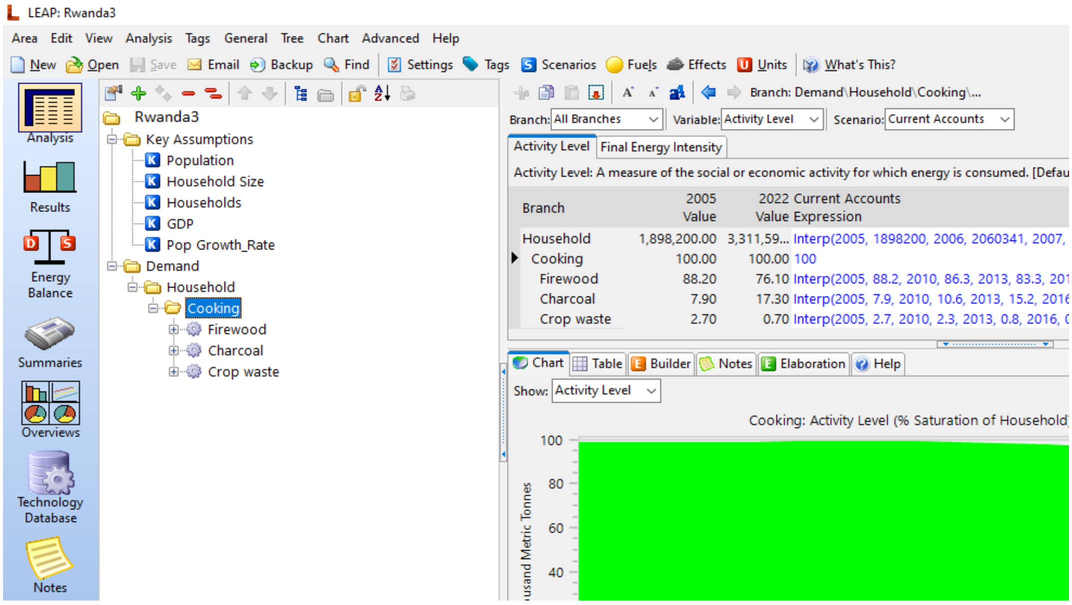
LEAP features a sectoral breakdown framework that is well-suited for creating inventories of air pollution emissions, as well as greenhouse gas (GHG) emissions. Within this structure, it encompasses the necessary emission factors for key air pollutants, essential for accurately estimating the environmental impacts of pollution.

To estimate current and past emissions, the LEAP system is populated with various data pertaining to activities associated with air pollutants. This comprehensive dataset encompasses all significant sectors and includes default emission factors for key pollutants. By conducting an emission analysis using the activity data and default emission factors, it becomes possible to calculate emissions for both present and historical years.

3.3.1 LEAP‘s data sets

LEAP comes equipped with a pre-designed hierarchical structure called a template tree. This structure consists of various modules, categorized based on different factors: key assumptions, effects, demand, transformation, and resources (Figure 3) .Our study will only cover two first modules:

Key assumption module consists of Rwandan household as independent variable and the LEAP demand module. The later consists of: households, industry, services, transport, agriculture and non-energy. Household for our case consists of one end-user sector called household and which in turn includes cooking as end use and then firewood, charcoal and crop waste as fuel type (Figure 4).



Branch: Demand\Household\Cooking\...

Branch: All Branches Variable: Activity Level Scenario: Current Accounts

Activity Level | Final Energy Intensity

Activity Level: A measure of the social or economic activity for which energy is consumed. [Defau

Branch	2005 Value	2022 Value	Current Accounts Expression
Household	1,898,200.00	3,311,59...	Interp(2005, 1898200, 2006, 2060341, 2007,
Cooking	100.00	100.00	100
Firewood	88.20	76.10	Interp(2005, 88.2, 2010, 86.3, 2013, 83.3, 201
Charcoal	7.90	17.30	Interp(2005, 7.9, 2010, 10.6, 2013, 15.2, 2016
Crop waste	2.70	0.70	Interp(2005, 2.7, 2010, 2.3, 2013, 0.8, 2016, (

Show: Activity Level

Cooking: Activity Level (% Saturation of Household

Figure 3 Screenshot of LEAP interface

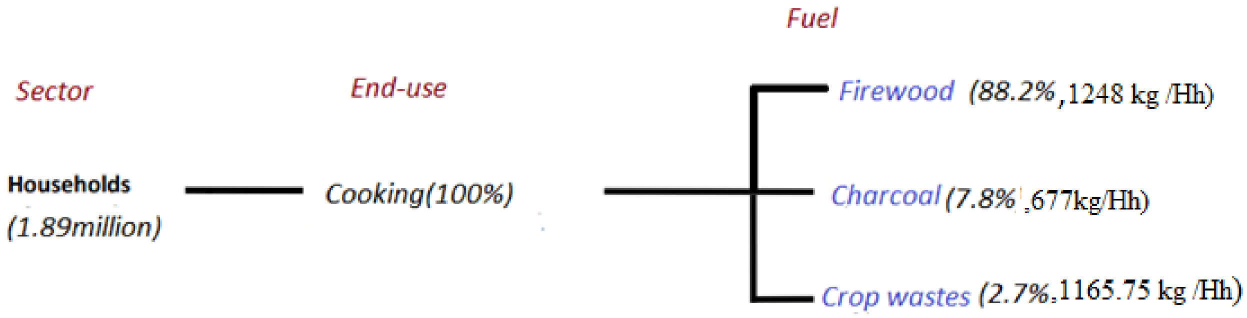


Figure 4 Schematic of household solid biomass demand Structure for Rwanda

In figure 4, the initial level represents households, totaling 1.89 million in 2005. Moving to the second level, it involves cooking end-uses, where every household (100%) engages in cooking. At the third level, specific fuel shares are accounted for. In Rwanda during 2005, 88.2% of households relied on firewood, 7.8% on charcoal, and 2.7% on crop wastes for cooking, with energy intensities of 1248 kg, 677 kg, and 1165.75 kg per household, respectively, for each respective fuel source.

3. 4 The Algorithm of the LEAP Model

The LEAP tool employs a methodology to compute energy consumption and air pollutant emissions, which is presented as follows:

3.4.1 Energy consumption calculation

The final energy consumption for fuel type x is calculated by Applying a Tier 1 emission estimate as follows:

$$EC_x = AL_x * EI_x \tag{2}$$

Where EC_X is total energy consumption for fuel type x, AL_x is total activity level for fuel x and EI_x is energy intensity for fuel type x in unity of mass

Activity level for blank years was calculated by interpolation the preceding non-blank value and the subsequent non-blank value.

The future activity level is calculated by grow rate

$$FV_t = BY * (1+GR)^t \tag{3}$$

Where FV_t and BY are activity levels in future year and base year activity respectively and GR is growth rate, considering t=0 in base year.

To convert the final energy consumption in unity of energy requires calorific values and is calculated as follow:

$$EC(J)_x = EC_x * CV_x \tag{4}$$

Where CV is net calorific value and the default Net Calorific values were taken from the Technology and Environment Database (TED) of LEAP system.

3.4.2 Air pollution emission calculation

The study also examines annual air pollutant emissions with the help of a Technology and Environment Database (TED) of LEAP. The air pollutant emission from fuel type x is calculated as in the equation below:

$$E_Y = EC_X * EF_Y \tag{5}$$

Where EF_Y is the emission factor for pollutant y. In this study we focused on air pollutants BC, $PM_{2.5}$, PM_{10}, NMVOCs, NO_x, OC and CO from firewood charcoal and crop wastes.

3.5 BAU Scenario (2005 – 2030) construction

The process of creating the emissions baseline commenced by constructing an inventory of historical emissions related data from 2005 to 2022 as current accounts (Figure 4) considering 2005 as the base year and while 2023 was designated as the first Scenario year. Additionally, the study forecasted future emissions on an annual basis until 2030.

The purpose of this baseline is to provide a credible and coherent depiction of how the household solid biomass sector could progress in the future if there are no new specific policies or regulations targeting air pollutant emissions.

The Business as Usual scenario (BAU) was formulated by taking into account the past patterns of household energy consumption in line with the government policy of reducing the reliance on biomass in cooking practices and the growth of Rwandan households.

3.5 .1 Historical air pollutant emission estimation

To develop this emissions baseline projection, it was necessary to reproduce historical emissions estimated in the inventory using appropriate activity data, emission factors and LEAP model as methodology shown in Figure 5.

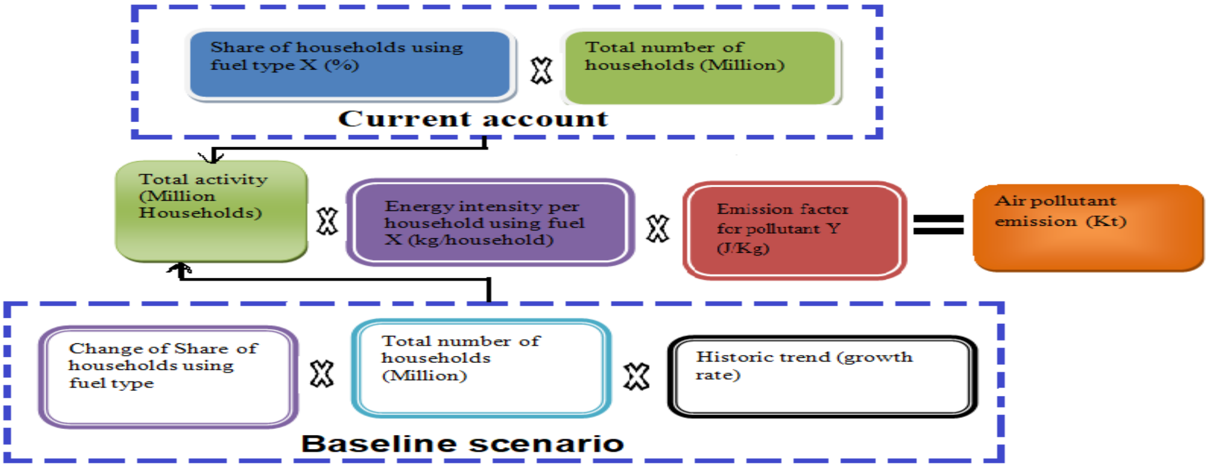


Figure 5 LEAP estimate of the demand for solid biomass in the current account and baseline scenario

3.5 .2 Projections of baseline emissions

To forecast annual emissions until 2030 for a business as usual scenario, the study utilized projections of activity level growth rate while keeping emission factors constant. These growth projections were based primarily on household (population) change that is assumed to grow from 3.72 million in 2005 to 4.87 million at a growth rate of 3.8% in 2030(Figure 6) as projected by RPHC4 [54].

The share of households utilizing traditional cooking systems such as firewood, charcoal, and crop wastes will fluctuate based on historical patterns. The growth rate of this share, derived from the historical data provided in Table 5, is estimated to be -0.8%, 0.23%, and -0.01% respectively, calculated from historical growth rates for 2005- 2022 and will remain consistent until 2030. It is assumed that the intensity of solid biomass fuel consumption will remain unchanged.

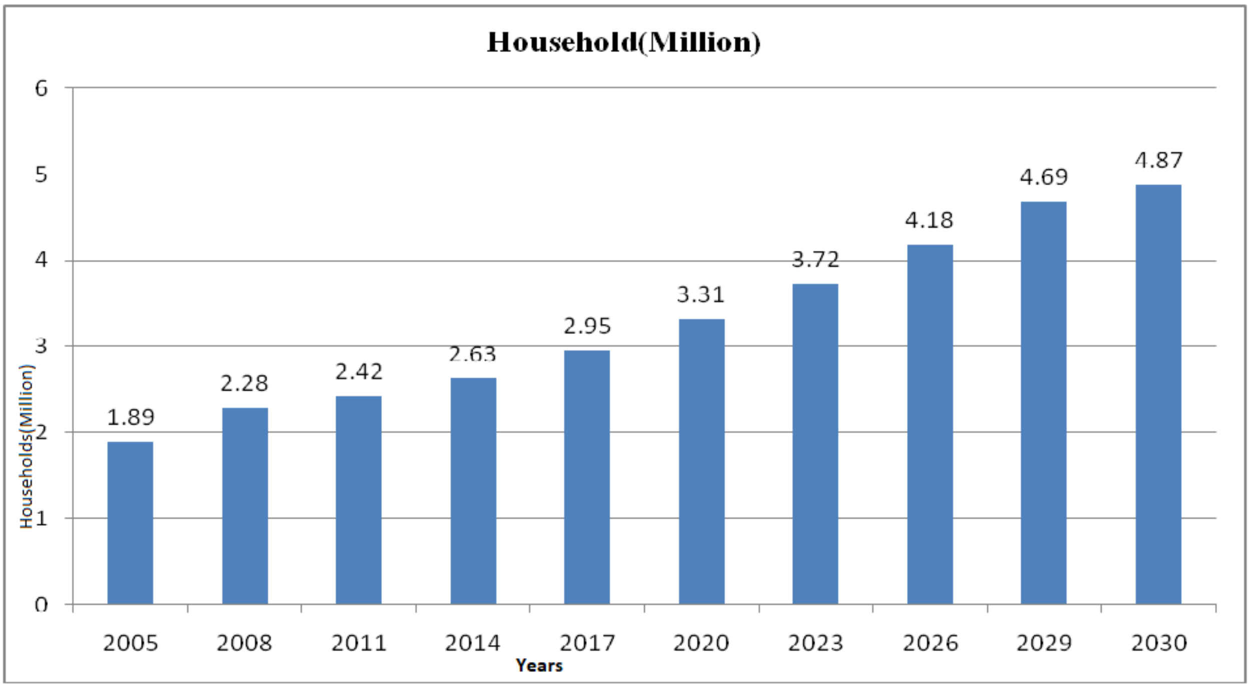


Figure 6 Rwanda households historical and projected trend until 2030

Table 5 Percentage of Households using different solid biomass Fuels from2005 to 2022

Years	Firewood	Charcoal	Crop waste
2005	88.2	7.9	2.7
2006	87.8	8.4	2.6
2007	87.4	9	2.5
2008	87.1	9.5	2.5
2009	86.7	10.1	2.4
2010	86.3	10.6	2.3
2011	85.3	12.1	1.8
2012	84.3	13.7	1.3
2013	83.3	15.2	0.8
2014	82.2	15.9	0.7
2015	81	16.7	0.7
2016	79.9	17.4	0.6
2017	79.2	17.4	0.6
2018	78.4	17.5	0.5
2019	77.7	17.5	0.5
2020	77.2	17.4	0.6
2021	76.6	17.4	0.6
2022	76.1	17.3	0.7

Chapter4: Results and discussion

4.1 Household Solid biomass energy use trends for BAU scenario in Rwanda

Firstly, in the initial year, the total energy consumption from solid biomass reached 36.064 thousand Terajoules (TJ), with firewood being the primary fuel source accounting for 32.38 thousand Terajoules (TJ). Looking at the overall projection for solid biomass energy demand, it is expected to rise significantly to 84.67 thousand Terajoules (TJ), in the baseline scenario(Figure 7).

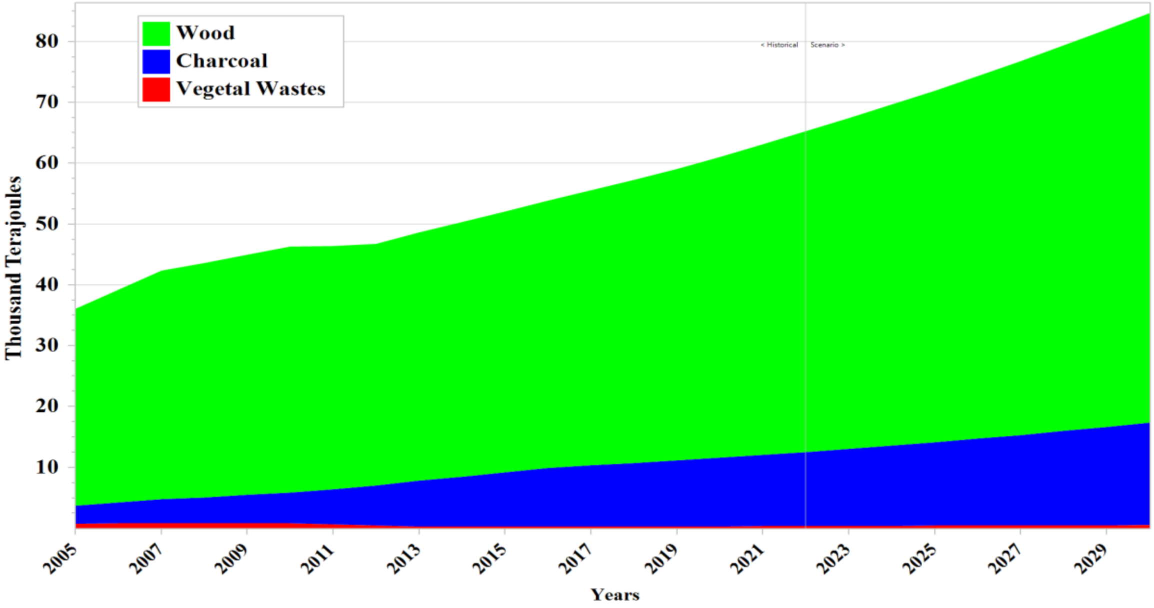


Figure 7 Total household solid biomass Energy consumption historical and future Projections

The forecasts for household solid biomass energy usage, as depicted in the BAU scenario, indicate a rising trend, which corresponds to the simultaneous increase in both the number of households and their fuel consumption. By the year 2030, the distribution of fuel types is projected to be as follows: firewood will account for 79.6%, charcoal for 19.8%, and crop wastes for 0.6% of the total (Figure 8) compared to 89.8%, 8.1% and 2.1% for firewood, charcoal and crop waste respectively in 2005.

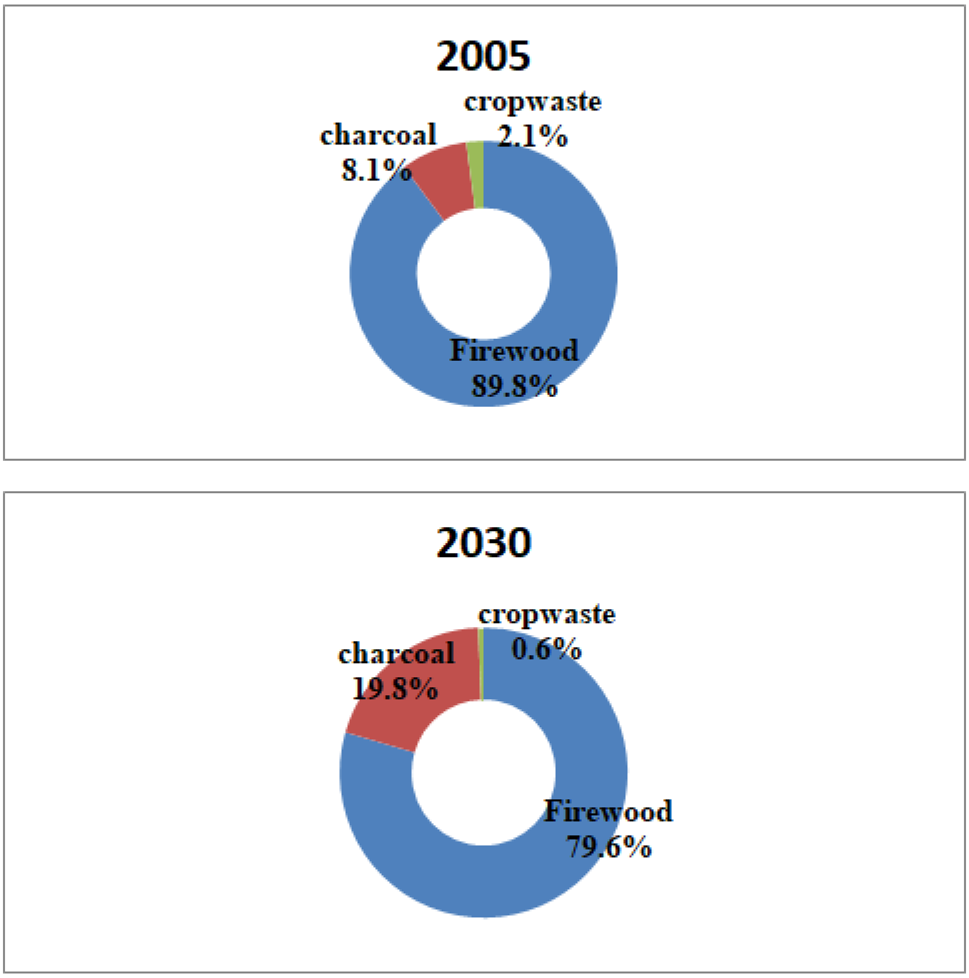


Figure 8 Percentage shares of three solid biomass energy uses in Rwanda in 2005 and 2030

The decline in the proportion of firewood usage by the end year, as compared to the base year, can be attributed to the adoption of alternative modern and efficient energy sources. This shift aligns with Rwanda's policy objective of reducing the consumption of biomass energy.

4.2 Total air pollutants Emission Estimate from household solid biomass fuel consumption in Rwanda by category and trends

The results presented in both Figure 9 and Figure 10 provide an overview of the estimated levels of NMVOC, OC, CO, NO_X, $PM_{2.5}$, PM_{10}, and BC emissions in Rwanda, as determined by this study specifically for the years 2005 to 2022 as historical and 2023 to 2030 as future projection. Current account (base year), the most significant emissions were attributed to CO at a magnitude of 186.19 kilotonnes (kt), subsequently followed by NMVOCs, PM_{10}, $PM_{2.5}$, OC,NO_X and BC at 20.17 ,18.06,14.5,6.32,3.61 and 1.91 kt respectively . By the end year (2030), there is a notable rise in air pollutant emissions, with CO reaching a substantial level of 456.98 kt. This is slightly closely followed by NMVOCs, PM_{10}, $PM_{2.5}$, OC, NO_X, and BC) at 42.4, 37.78, 30.5, 13.9, 8.47, and 4.34 kt, respectively.

The Figure 7 (energy demand), Figure 9 and Figure 10, exhibit a significant similarity, highlighting that the trend in solid biomass energy demand closely resembles the trends observed in total air pollutant emissions.

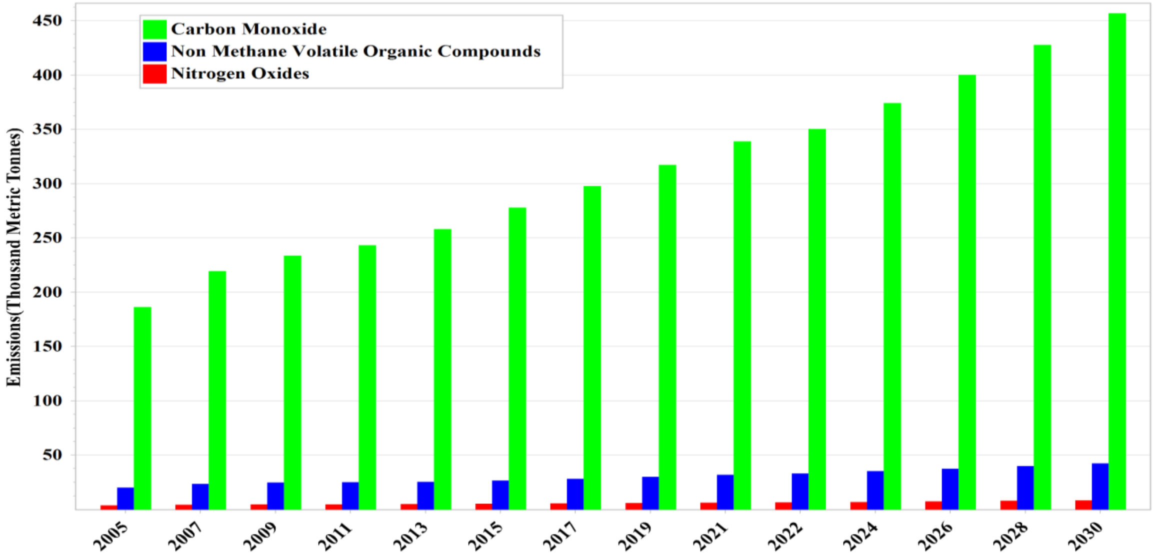


Figure 9 Total emissions of gaseous air pollutants covering CO, NMVOCs and NO_X

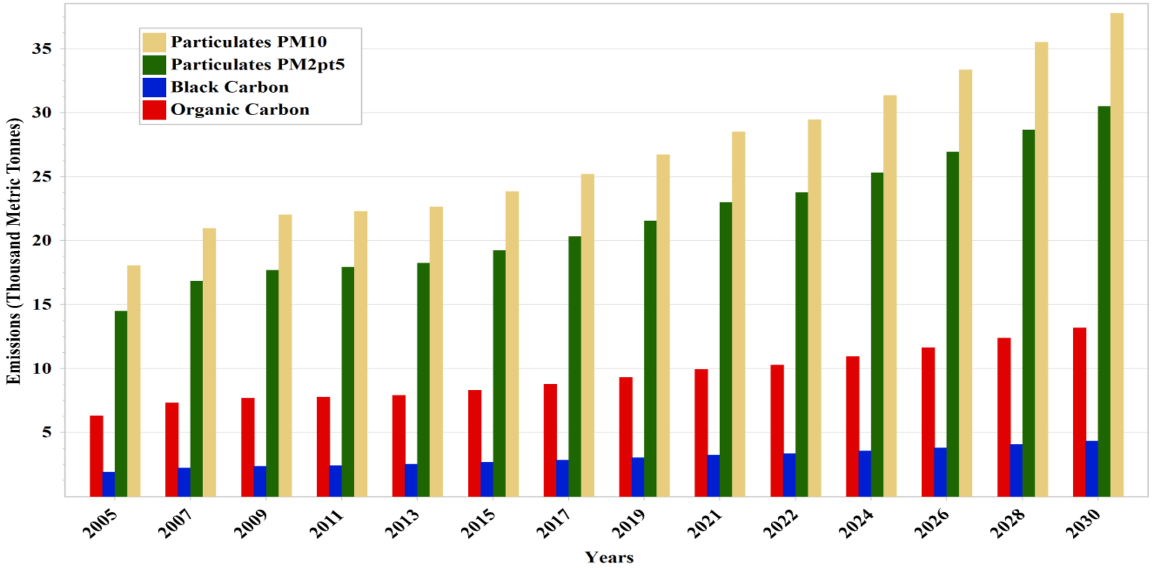


Figure 10 Total emission of solid air pollutants covering PM10, PM2.5, BC and OC

4.2.1 CO Emission

In 2005, the CO emissions, is approximately 186.19 kt (Figure 11) predominantly arose from combustion of firewood fuel (87%), followed by charcoal (11%), and crop waste (2%).

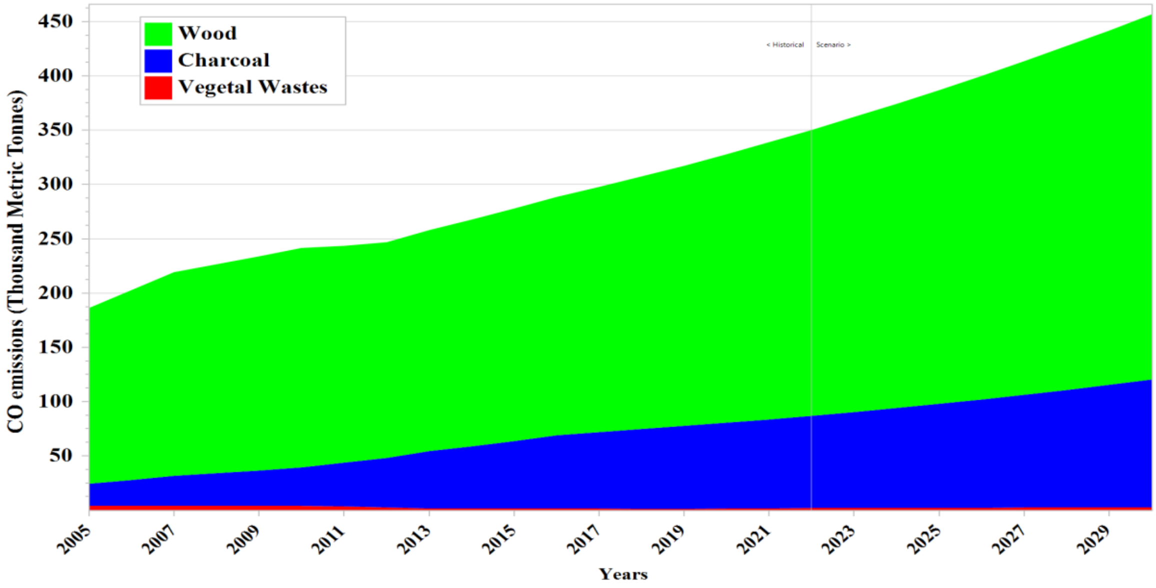


Figure 11 CO emission from household solid biomass uses in 2005 and 2030

4.2.2 NMVOCs emission

In 2005, the emission of NMVOCs amounted to 19.43 kilotonness emitted by from firewood (96.3%) charcoal 0.29kt (1.5%) and crop wastes 0.45kt (2.2%). And in 2030 NMVOCs emission is 40.42kilotonnes emitted by firewood (95.3%), charcoal 1.68kt (4%) and crop wastes0.30kt (0.7%)(Figure 12).

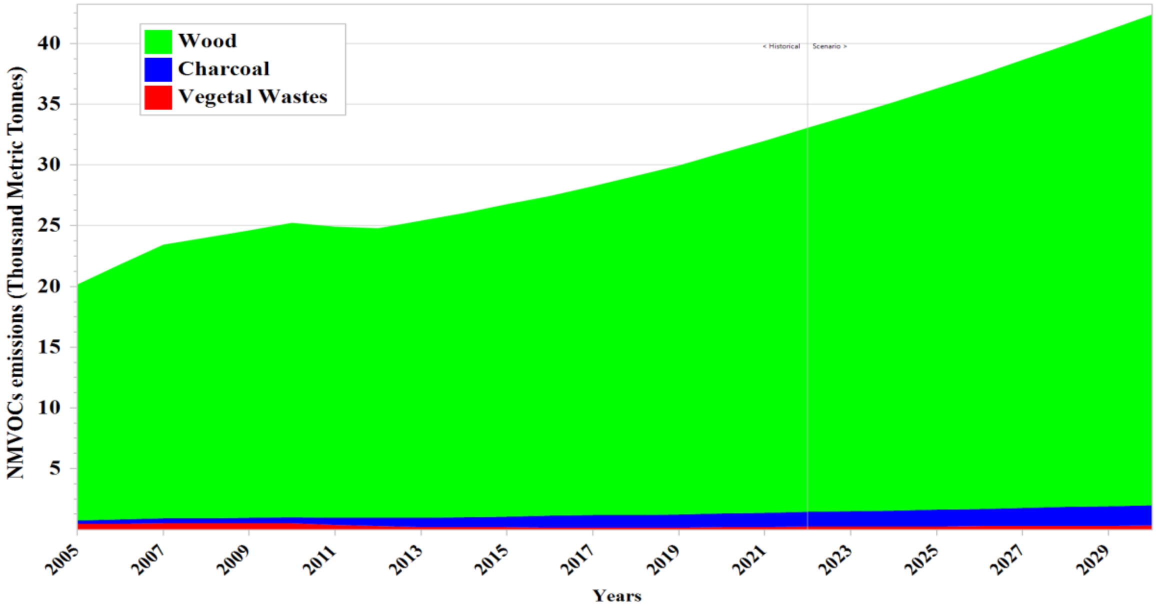


Figure 12 NMVOCs emissions trends from household solid biomass uses in 2005 and2030

4.2.3 $PM_{2.5}$ and PM_{10} Emissions

The $PM_{2.5}$ and PM_{10} emissions were 32.56kt correctively in 2005, with most of them (Figure 13) originating from firewood 31.22kt(95.9%),Charcoal 0.48kt (2.7%) and crop waste 0.87kt (1.4%)(Figure 14).In 2030 the total particulate matter is 68.28 kilotonnes are mostly emitted from firewood 64.93kt (95.1%),charcoal 2.77kt (4.1%) and crop wastes 0.58kt (0.8%).In 2005 the particulate matter $PM_{2.5}$ were 14.5kt(44.53%) and PM_{10} 18.06KT(55.47%) and in 2030 ,$PM_{2.5}$ is 30.5Kt(44.67%) and 37.78Kt (55.33%).

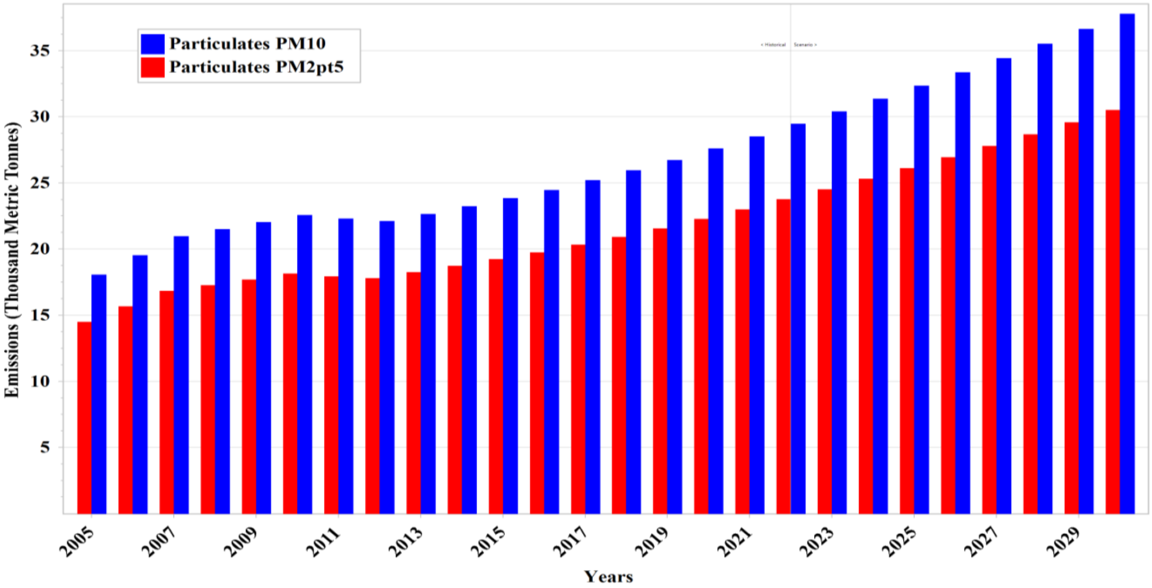


Figure 13 PM2.5 and PM10 emissions from household solid biomass uses in 2005 and2030

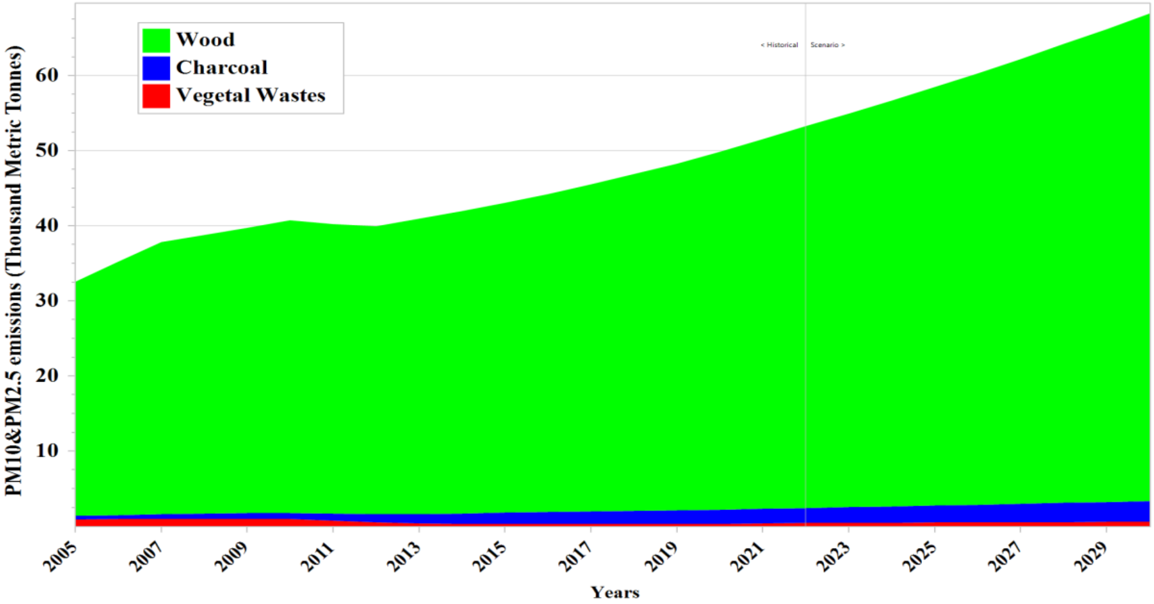


Figure 14 PM2.5 and PM10 emissions share according to solid biomass fuel types in 2005-2030

4.2.4 NO_X emission

In 2005, the NO_X emissions from solid biomass used in households amounted to 3.6 kt. By 2030, this figure increased to 8.47 kt. The emissions can be attributed to different fuel types in the following proportions: firewood accounted for 3.24 kt (89.8%), charcoal for 0.29 kt (8.1%), and crop waste for 0.07 kt (2.1%). In 2030, the distribution of emissions among the three fuel types changed: firewood contributed 6.74 kt (79.6%), charcoal contributed 1.68 kt (19.9%), and crop waste contributed 0.05 kt (0.6%) (Figure 15).

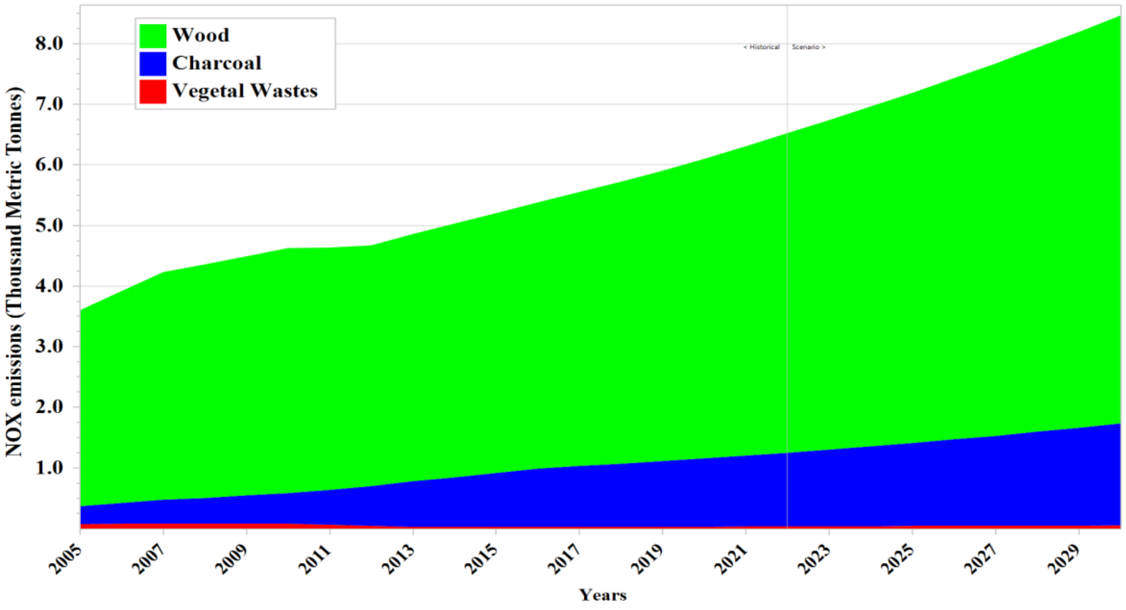


Figure 15 NO_X emissions from household solid biomass use in 2005 -2030

4.2.5 Organic Carbon (OC) emissions

The emissions of OC (organic carbon) from the use of solid biomass in Rwanda experienced changes between 2005 and 2030. In 2005, the total OC emissions were 6.32kt. However, in 2030, the total OC emissions reached 13.19 kt.

In terms of the distribution of emissions by fuel type, in 2005, firewood contributed 6.03 kt (95.5%) to the OC emissions, while charcoal contributed 0.08 kt (1.4%) and crop waste contributed 0.19 kt (3.1%) (Figure 16). These proportions indicate that firewood was the primary source of OC emissions during that period.

By 2030, the share of OC emissions remained predominantly attributed to firewood, which contributed 12.56 kt (95.3%). The contribution of charcoal increased to 0.49 kt (3.8%), suggesting a slight shift in fuel usage. Crop waste, on the other hand, contributed 0.13 kt (1%) to the OC emissions, indicating a decrease in its share.

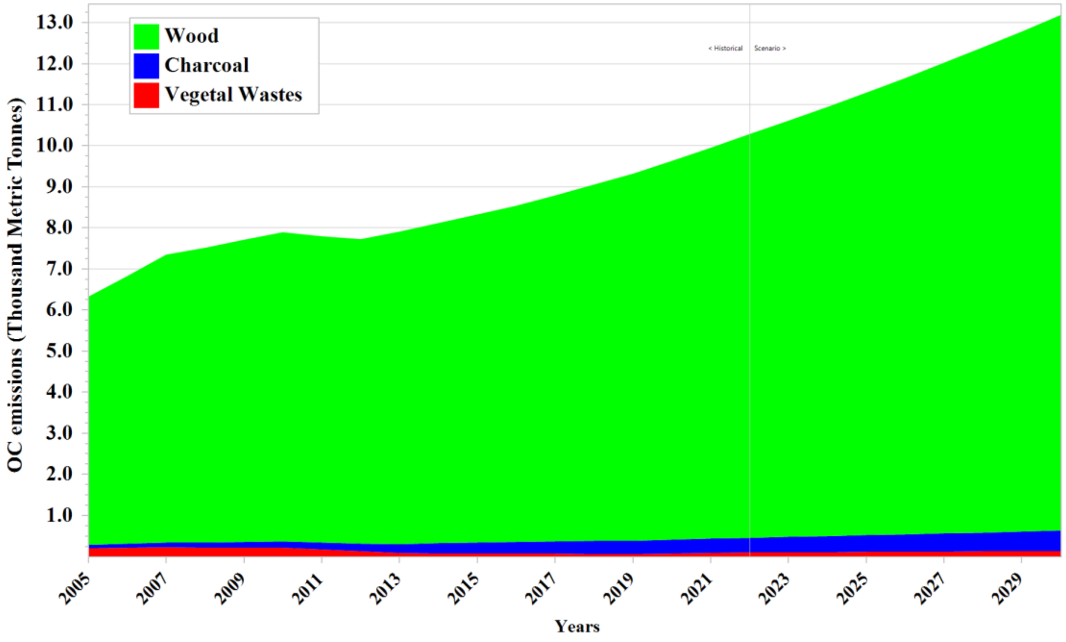


Figure 16 Organic carbon (OC) emissions from household solid biomass use in 2005 -2030

4.2.6 Black carbon (BC) emission

The emission of black carbon (BC) arising from the utilization of solid biomass fuels in households in Rwanda was 1.91 kilotons (kt) in 2005, increasing to 3.35 kt in 2022. Projections indicate that this emission is expected to reach 4.33 kt by 2030. In 2005, the proportion of emissions from different fuel types was 1.73 kt (90.6%) from wood, 0.12 kt (6.3%) from charcoal, and 0.059 kt (3.1%) from crop wastes.

In 2022, the proportions of emissions from the different fuel types changed (Figure 17). The emission from wood was 2.61 kt (84.2%), charcoal contributed 0.46 kt (14.9%), and crop wastes accounted for 0.027 kt (0.9%) of the total emissions. Looking ahead to 2030, the projected emission shares indicate that wood will contribute 3.60 kt (83.1%), charcoal will contribute 0.69 kt (16%), and crop wastes will contribute 0.039 kt (0.9%) to the total emissions.

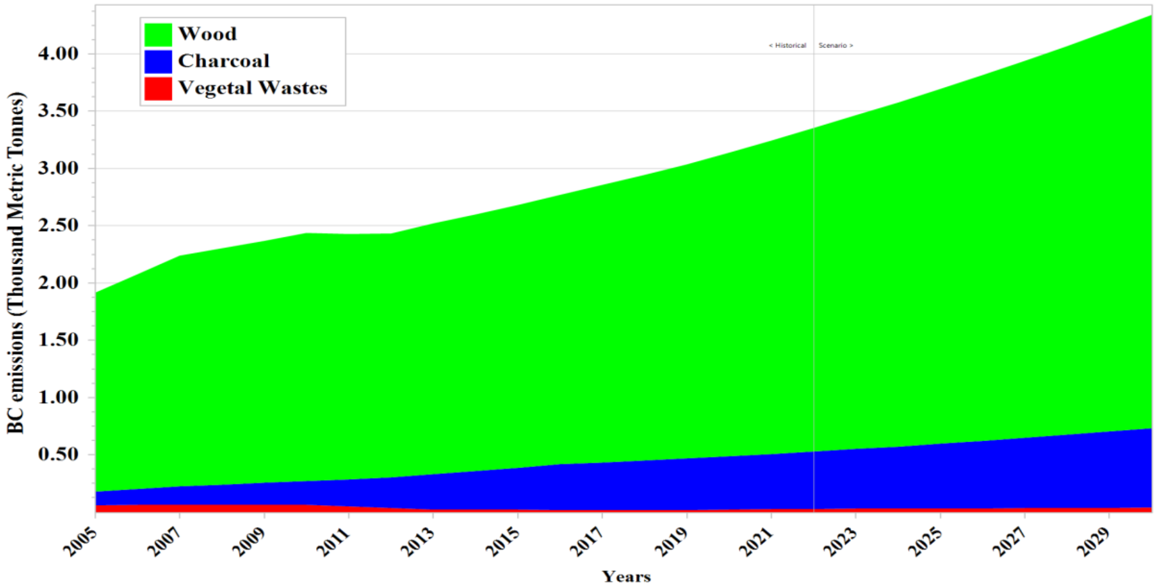


Figure 17 BC emissions from household solid biomass uses in 2005 -2030

4.2.7 Total historical air pollutant emissions and projections to 2030

Between 2005 and 2022, aggregate air pollutant emissions in Rwanda from household solid biomass ranged between 250.77kt in 2005 and 456.7 kt in 2022(Figure 18). On average, wood was the largest net air pollutant emitting source among household solid biomass fuels with a 2005–2022 average net emission of 293.59kt(growth rate of 28.14%).This fuel emissions reflects the significant portion of the population still relying on wood for cooking in Rwanda.

Charcoal was the second largest source, emitting around 56.7kt air pollutant emissions on average between 2005 and 2022 (growth rate of 8.7%)

Crop waste, while accounting for a relatively small proportion of emissions, still plays a role in air pollutant emissions from household solid biomass energy use. Between 2005 and 2022 the average emission was 3.47kt (growth rate of -23%).

Total air pollutant emissions in the business as usual scenario are approximately 593.65kt in 2030, Wood is still the largest source of air pollutant emissions in 2030, accounting for 78.3 % of Rwanda's solid biomass emissions, and charcoal contributes 21.1% in 2030(Figure 19).The smallest contributor to air pollutant emissions is crop wastes accounting 0.6% .This decline indicates a potential decrease in the use of crop waste as a fuel source.

The baseline scenario underscores the importance of implementing additional policies and measures alongside the existing ones initiated in 2005 and beyond. These supplementary actions aim to achieve the desired emission reductions in household sector which is responsible for major air pollutants. Without such complementary interventions, the intended targets for reducing emissions in these sectors may not be met.

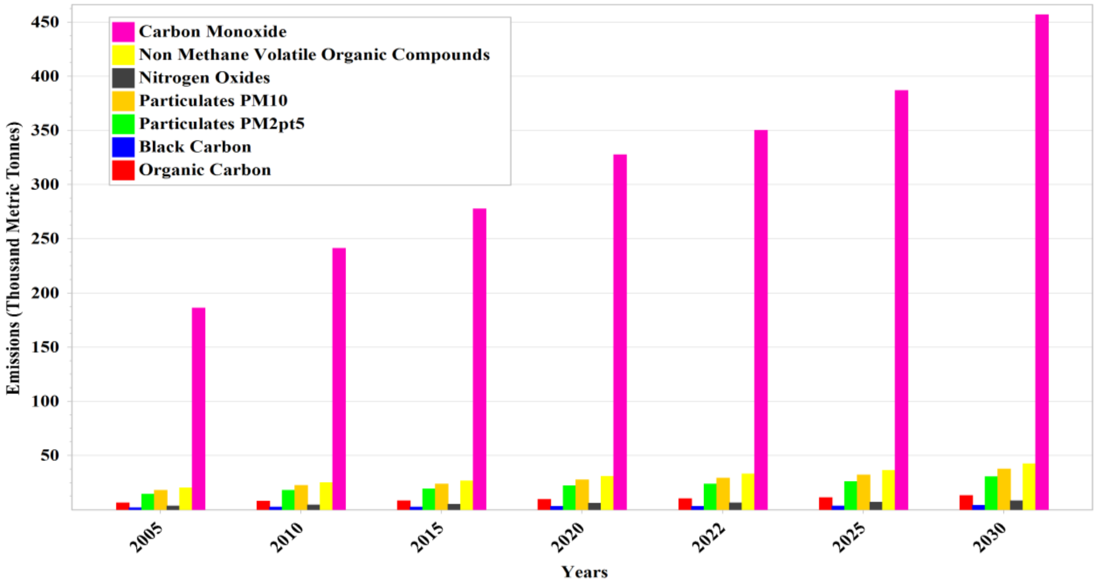


Figure 18 Contribution of different air pollutants to total emission

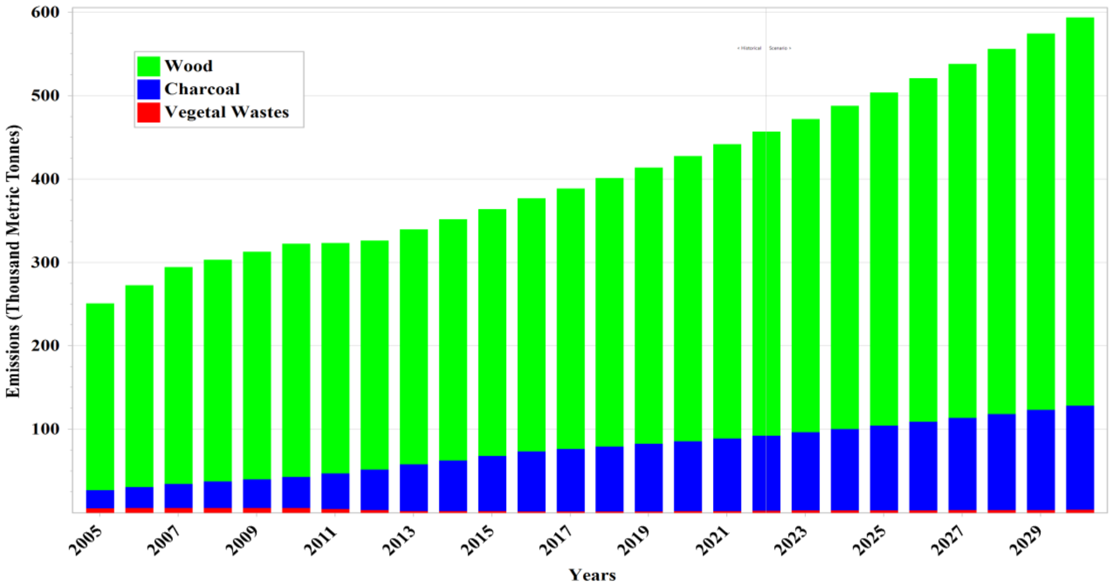


Figure 19 Contribution of different solid biomass fuels to total air pollutant emissions

4.3 Suggestions on Air Pollution Control

Household solid biomass energy, such as firewood, charcoal, and agricultural residues, is still a significant energy source for millions of people in Rwanda, especially in rural areas where solid biomass fuels are obtained at moderated cost. However, its unsustainable use has negative impacts on health as well as the environment. To promote a health and environmentally friendly trajectory for household solid biomass energy consumption, here are some proposed measures:

Improved Cookstoves: Encourage the use of improved cookstoves that are more fuel-efficient and produce less emission. These stoves are designed to burn biomass more cleanly, reducing indoor and in turn household air pollution and health risks for the household members.

Education and Awareness: Conduct awareness efforts to inform people about the negative effects of traditional biomass burning has on their health and the environment. Tell them about the advantages of sustainable biomass management techniques and cleaner alternatives.

Diversification of income: Help households diversify their income sources to reduce their reliance on biomass energy for cooking and heating. This can be achieved through training and support for income-generating activities.

Community-Based Energy Projects: Promote neighborhood-based initiatives that open up access to cleaner and more effective energy sources. These initiatives might involve micro-hydropower systems, solar cookers, or methane digesters.

Subsidies and Incentives: Make cleaner cooking technologies more accessible and cheap by offering households subsidies or financial incentives.

Monitoring and Evaluation: Create monitoring mechanisms to evaluate how these actions affect human health and the environment. This information will be used to improve the tactics and guarantee their success.

Collaboration with NGOs and Governments: Collaborate with non-governmental organizations (NGOs) and government agencies to implement these measures effectively. NGOs can provide support at the grassroots level, while governments can create policies and regulations to promote sustainable solid biomass use.

Research and Innovation: Invest in research and development to continuously improve biomass energy technologies and find innovative solutions for sustainable solid biomass management.

By implementing these measures, we can promote a transition towards a more health-conscious and environmentally friendly trajectory for household solid biomass energy consumption. This will not only improve the well-being of people and ecosystems but also contribute to global efforts in mitigating climate change.

Chapter 5: Conclusion and recommendation

5.1 Conclusion

In this thesis, Rwanda's household solid biomass air pollutant emissions was estimated through inventory for a period between 2005 and 2022 historical values and then 2023-2030 as future emissions projections for select components. This has been achieved by LEAP system using households and energy intensities. The contribution of household solid biomass energy to atmospheric emission was described. Estimates of air pollutants were produced on a gas-by gas basis considering main air pollutants including CO, NO_x, OC, NMVOCs, $PM_{2.5}$&PM_{10} and BC. Estimates of key household fuel type sources, and its aggregated emissions in metric tonnes (kilotonnes) were reported. In general, we relied on the default emission factors outlined in the 2006 IPCC Revised Guidelines due to the absence of specific emission factors for Rwanda.

Air pollutant emissions trends over historical years 2005-2022 , and future years 2023- 2030 indicate an upward trend with annual average rates of of 3.59%.and 3.33% respectively .The annual growth rate for the whole baseline 2005-2030 is 3.51%. A majority of these emissions are coming from wood fuel. The annual average air pollutant released into atmosphere for CO, NO_x OC, $PM_{2.5}$&PM10, NMVOCs and BC are 311.36kt,5.84kt, 9.38kt,26.87kt,21.66kt,30.12kt and 3.02kt respectively.

The findings reveal that the emissions of air pollutants from solid biomass are currently at a high level especially from firewood. The primary factors responsible are the increasing activities associated with the consumption of solid biomass fuel, which align with the growing population and if certain conditions persist, they are projected to further increase in the future. Thus, promoting improved cookstoves, education and awareness diversification of income, community-based energy projects ,subsidies and incentives, monitoring and evaluation, collaboration with NGOs and governments ,research and innovation, will be the most important driving forces for future energy sustainable development and household and ambient environmental protection.

5.2 Recommendation

By utilizing the findings of this emission estimation study, the implementation of existing policy options in Rwanda can be enhanced, particularly with a focus on reducing emissions in the residential sector precisely from solid biomass cooking practice. This can be achieved by emphasizing the substitution of solid biomass fuels. Replacing wood fuels with cleaner alternatives, such as natural gas or sustainable renewable energy sources, would result in a significant reduction in emissions.

Raise awareness of the negative impacts of household burning solid biomass on human health and the climate via different campaigns.

Additional research is necessary to investigate the estimation of criteria air pollutant emissions in various energy sector and sub-sectors, such as manufacturing and transportation etc, to understand their current and future aggregate status in Rwanda. It is essential to develop Rwanda-specific emission factors to transition from default emission factors in Tier 1 to more precise Tier 2 factors in upcoming air pollutant estimation or inventory. Lastly, we encourage other researchers to conduct studies on air pollutant emissions in Rwanda, including assessments of their impact on both public health and climate change.

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Appendices

Table 6 annual energy consumption by solid biomass fuel type (thousand TJ)

Years	Wood	Charcoal	Vegetal Wastes	Total
2005	32.4	2.9	0.7	36.1
2006	35	3.4	0.8	39.2
2007	37.6	3.9	0.8	42.3
2008	38.5	4.3	0.8	43.6
2009	39.5	4.6	0.8	44.9
2010	40.4	5	0.8	46.3
2011	40	5.7	0.6	46.4
2012	39.8	6.5	0.5	46.7
2013	40.8	7.5	0.3	48.6
2014	41.8	8.2	0.3	50.3
2015	42.8	8.9	0.3	52
2016	43.9	9.7	0.2	53.8
2017	45.2	10.1	0.2	55.5
2018	46.6	10.5	0.2	57.3
2019	47.9	10.9	0.2	59.1
2020	49.5	11.3	0.3	61.1
2021	51.1	11.7	0.3	63.1
2022	52.7	12.1	0.4	65.2
2023	54.4	12.6	0.4	67.4
2024	56.1	13.2	0.4	69.6
2025	57.8	13.7	0.4	71.9
2026	59.6	14.3	0.4	74.3
2027	61.5	14.9	0.4	76.8
2028	63.4	15.5	0.5	79.3
2029	65.3	16.1	0.5	82
2030	67.4	16.8	0.5	84.7

Table 7 Annual emissions by air pollutants (Kt)

years	CO	NMVOCs	NO_X	PM_{10}	$PM_{2.5}$	BC	OC
2005	186.19	20.17	3.61	18.06	14.5	1.91	6.32
2006	202.74	21.81	3.92	19.53	15.68	2.08	6.83
2008	226.41	24.02	4.36	21.5	17.27	2.3	7.52
2010	241.32	25.24	4.63	22.58	18.15	2.44	7.9
2012	246.68	24.78	4.67	22.12	17.8	2.43	7.73
2014	267.85	26.08	5.03	23.25	18.73	2.6	8.11
2016	288.42	27.46	5.38	24.47	19.73	2.77	8.54
2018	307.32	29.12	5.73	25.95	20.93	2.94	9.05
2020	327.88	30.98	6.11	27.6	22.27	3.14	9.63
2022	350.26	33.07	6.52	29.47	23.77	3.35	10.28
2024	374.34	35.19	6.96	31.36	25.3	3.58	10.94
2026	400.12	37.45	7.43	33.37	26.93	3.81	11.65
2028	427.66	39.85	7.93	35.51	28.67	4.07	12.39
2030	456.98	42.4	8.47	37.78	30.5	4.34	13.19

Table 8 Total annual emission by solid biomass fuel type (Kt)

years	Wood	Charcoal	Vegetal Wastes
2005	223.59	21.8	5.38
2006	241.64	25.28	5.67
2007	259.53	29.01	5.93
2008	265.83	31.64	5.9
2009	272.36	34.41	5.88
2010	279.09	37.32	5.85
2011	276.05	42.74	4.58
2012	274.45	48.43	3.33
2013	281.7	55.96	2.13
2014	288.69	60.94	2.03
2015	295.83	66.23	1.91
2016	303.12	71.86	1.79
2017	312.14	74.82	1.76
2018	321.41	77.92	1.72
2019	330.94	81.14	1.67
2020	341.62	84.01	1.97
2021	352.64	86.99	2.29
2022	364.01	90.08	2.63
2023	375.35	93.85	2.74
2024	387.05	97.78	2.84
2025	399.11	101.88	2.95
2026	411.55	106.14	3.07
2027	424.37	110.58	3.19
2028	437.57	115.21	3.32
2029	451.13	120.01	3.45
2030	465.06	125	3.58