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**Modeling Carbon Emission from Cooking Fuels in Rural Communities: A
Pathway to Low-Carbon Emission**

By

Brenda Cheronno Rono

094187

**A Dissertation Submitted in Partial Fulfillment of the Requirements for the
Award of the Degree of Master of Science in Sustainable Energy Transition
at Strathmore University**

**School of Computing and Engineering Sciences
Strathmore University
Nairobi, Kenya**



March, 2025

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Brenda Cherono Rono..... *Burt*
.....3/28/2025.....

Approval

The dissertation of Brenda Cherono was reviewed and approved (for examination) by the following:

Dr. Victor Rop

Victor Rop
.....
28/03/2025
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Abstract

The availability of clean, sustainable cooking fuel remains a fundamental obstacle throughout Kenyan rural areas since traditional biomass fuels like firewood and charcoal control household energy usage patterns. Using these fuels causes significant carbon pollution, deforestation damage, and health risks from indoor air contamination. The transition must establish low-carbon energy alternatives for effective change between environmental responsibility and reasonable cost-effectiveness. This research evaluates carbon emissions across cooking fuel types within Kenyan rural areas while identifying methods to decrease emissions. The analysis uses Microsoft Excel Software to evaluate four energy transition strategies, from Business-As-Usual (BAU) through Liquefied Petroleum Gas (LPG) use and bioethanol and electricity combination to an extensive clean energy implementation. The study presents data-driven emission projections that combine literature research with energy consumption surveys and policy guidelines for different intervention approaches. The KNBS data shows that cooking fuel emissions will increase because of population expansion and the continued use of biomass in the Business-As-Usual context. The complete electrification of cooking equipment offers the most lasting solution against emissions reduction since it effectively surpasses LPG and bioethanol systems. The transition to sustainable cooking needs improvements in infrastructure systems, a solution for affordability, and better policy enforcement. The investigation demonstrates the pressing requirement for government-backed programs, financial resources from the private sector, and active community participation to enhance clean cooking technology adoption rates. Governments should provide financial support for green energy fuels, develop expanded power grid systems, and launch information programs to change public cooking behavior. Implementing such measures will lead rural communities towards sustainable, low-carbon cooking solutions that support countrywide and global climate objectives.

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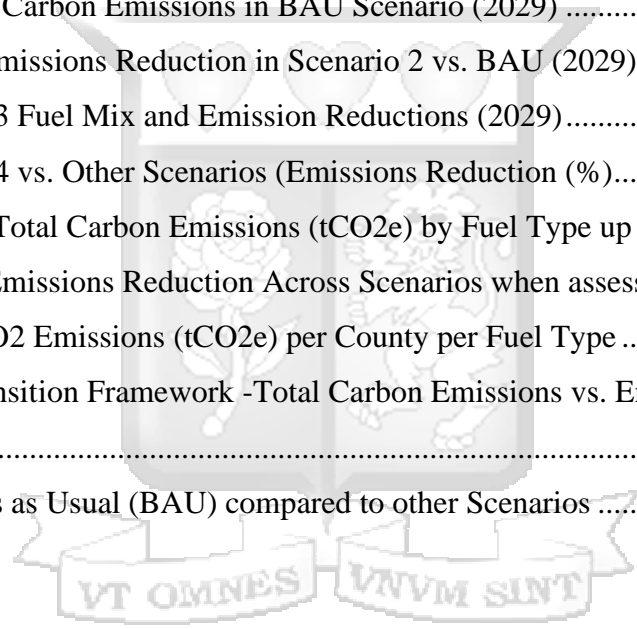
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Abbreviations

BAU: Business As Usual

CO: Carbon Monoxide

CO₂: Carbon Dioxide

FOLU: Forests and Other Land Use

GHG: Greenhouse Gas

GIS: Geographic Information System

ICS: Improved Cookstove

IoT: Internet of Things

IPCC: Intergovernmental Panel on Climate Change

KNBS: Kenya National Bureau of Statistics

LEAP: Long-range Energy Alternatives Planning

LPG: Liquefied Petroleum Gas

MoE: Ministry of Energy

NVivo: Qualitative Data Analysis Software

PAYG: Pay-As-You-Go

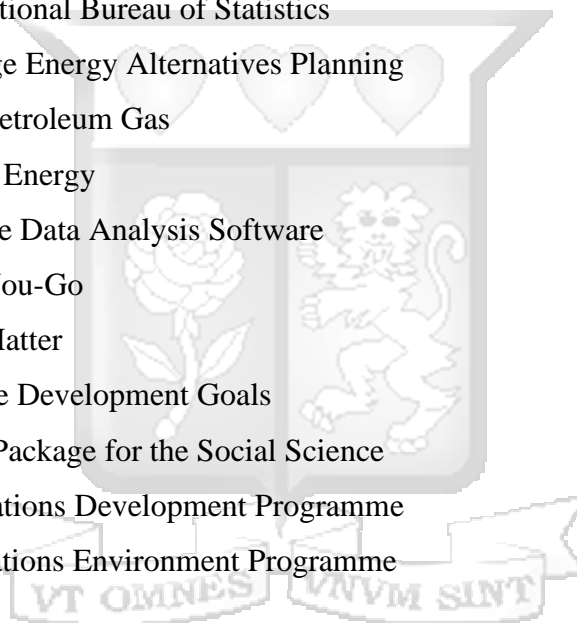
PM: Particulate Matter

SDGs: Sustainable Development Goals

SPSS: Statistical Package for the Social Science

UNDP: United Nations Development Programme

UNEP: United Nations Environment Programme



Definition of Terms

Carbon Emissions	Carbon dioxide (CO ₂) and other carbon-containing species are emitted into the atmosphere mainly due to burning fossil fuels and biomass (Byravan et al., 2017).
Carbon Sink	Arises from the role of forests, soils, or oceans as sinks, the ability to capture and store more carbon dioxide than they emit into the atmosphere (Dioha et al., 2019).
Cooking Fuels	Means utilized in preparing food, namely firewood, Charcoal, Kerosene, and Liquefied Petroleum Gas (LPG) (Gachanja et al., 2023).
Emission Factor	It is a coefficient expressing the emission amount per energy or fuel consumed to measure carbon emissions (Fragkos et al., 2021).
Combustion Efficiency	The energy efficiency utilized for fuel combustion and the nature of emissions are provided as a percentage of the total heat generated (Hollands & Daly, 2023).
Deforestation	Deforestation with the firewood and biomass fuel collections, including bush and forest clearance, reduces carbon reservoirs (Lindstad & Rialland, 2020).
Geographic Information System	A technique of recording and processing spatial and geographic information concerning the earth commonly utilized about deforestation and changes in land use (Mandegari et al., 2023).
Low-Emission Technology	Reducing carbon and particulate carbon emissions through technologies used in kitchens, including improved cookstoves or LPG systems (Shakya et al., 2023).
Mixed-Methods Approach	This popular research type is characterized by integrating quantitative and qualitative analysis methodologies to gain a broad understanding of a particular subject (Tang et al., 2022).
Particulate Matter	Soots are tiny particles produced during the burning process and are known to cause air pollution and health risks (Byravan et al., 2017).

Qualitative Data	Information contained in words obtained by surveys such as interviews, focus group discussions, or observation yields details on behaviors and attitudes (Mandegari et al., 2023).
Quantitative Data	Data that can be quantified and used to make statistical computations, for instance, emission quantity and fueling rate (Shakya et al., 2023).
Improved Cookstove	A type of cooking stove designed to improve fuel efficiency, reduce indoor air pollution, and minimize carbon emissions compared to traditional open-fire or rudimentary stoves (Dioha et al., 2019).
Triangulation	An approach of using an assortment of data sources or techniques to increase the credibility of the results (Hollands & Daly, 2023).



Chapter 1: Introduction

1.1 Background of the Study

The combustion of traditional cooking fuels in rural residences is primarily responsible for global carbon emissions, both to the climate and their environment. Most rural communities use kerosene, charcoal, and firewood in cooking, even though they are inefficient and carbon-based. The combustion of these fuels is primarily responsible for greenhouse emissions and immensely damages indoor air quality and public health. With an increased global focus on discovering cleaner sources of energy, carbon emissions from cooking fuels and discovering cleaner substitutes must be measured (Byravan et al., 2017).

Earlier studies have established the connection between cooking fuel consumption, combustion efficiency, and carbon stocks and sinks in biophysics. Methodological limitations remain in accurately calibrating emissions estimates of various fuels used in the rural economy. These emissions result in global warming, rising sea levels, extreme climatic conditions, and ecological chaos. They are also responsible for environmental degradation, deforestation, and loss of carbon sinks, as well as their impact on human health and respiratory and cardiovascular diseases due to the absorption of toxic gases. Carbon emissions must be addressed in preventing climate change as a process of achieving the United Nations Framework Convention on Climate Change Paris Agreement and beyond-sustainable development agenda goals (Shakya et al., 2023). Reducing emissions from cooking fuels can significantly contribute to environmental sustainability, fair access to equitable energy, and global improvement in rural community welfare.

Carbon footprint information about energy sources like firewood, kerosene, charcoal, and LPG is essential in developing effective greenhouse gas emission reduction policies for these energy sources (Duan et al., 2019). Research shall address the deficits that have been identified by producing a valid framework for the approximation of carbon emissions from rural domestic cooking fuels, assessing quantification of emissions, the net carbon sink benefit, and mitigation means to facilitate productive energy use and the shift toward low-carbon economies in the rural areas.

1.2 Problem Statement

Kenyan rural communities still rely strongly on traditional biomass fuels such as firewood, charcoal, and kerosene for cooking, with long-term environmental, health, and economic

consequences. The combustion of firewood and charcoal results in forest loss, and Kenya alone loses about 50,000 hectares of forest cover annually due to harmful logging. Further, the combustion is inefficient, releasing large amounts of carbon dioxide (CO₂) and particulate matter into the atmosphere, causing air pollution and global warming. Households that employ firewood have been found to release 1.6 kg of CO₂ for each kg of wood, while kerosene emits 2.4 kg of CO₂ per liter and plays a significant role in the amount of greenhouse gas (GHG). Government initiatives to introduce clean cooking technologies have not achieved considerable uptake due to high initial capital, inadequate infrastructure, and a lack of information. Without physical interventions, the emissions of CO₂ from cooking fuel will continue and undo efforts by Kenya to reduce carbon footprints. This dissertation examines sustainable substitutes for rural homes to shift to low-carbon cooking options in alignment with domestic and foreign sustainability goals.

1.3 Research Objectives

1.3.1 General Objective

To model carbon emissions profile from rural cooking fuels to enhance the adoption of cleaner cooking fuel options in rural communities.

1.3.2 Specific Objectives

The specific objectives of this study are as follows:

- i. To quantify the amount of energy from different fuel sources used in rural communities.
- ii. To evaluate the carbon emissions from fuel sources used in rural communities.
- iii. To model the carbon emissions from different cooking fuel sources under different scenarios.
- iv. To develop a framework for reducing carbon emissions from cooking fuels in rural households.

1.4 Research Questions

The research questions for this study are as follows:

- i. How much energy is produced by fuel sources used in rural communities?
- ii. How much carbon emissions are emitted from using different fuel sources in rural communities?
- iii. How can carbon emissions profile be modeled for different fuel sources?

- iv. What other measures can be included in a framework to lower carbon emissions from cooking fuel in rural regions?

1.5 Justification

Clean cooking fuels must be introduced in rural households in Kenya due to the enormous environmental, health, and socio-economic impacts of reliance on traditional biomass and fossil fuels. The burning of firewood and charcoal as the primary household energy source by over 85% of the households in rural areas has contributed to widespread deforestation, land erosion, and biodiversity loss. Kenya loses about 50,000 hectares of forest annually, leading to reduced carbon sequestration and increased impacts of climate change. Also, the combustion of the fuels in the unconventional method leads to the high emission of carbon dioxide (CO₂), carbon monoxide (CO), and particulate matter (PM_{2.5}) with serious health consequences. Projected by the World Health Organization, indoor air pollution caused by solid fuel kills more than 21,500 people prematurely each year in Kenya, primarily women and children.

From an economic perspective, using traditional fuels involves a household cost, as charcoal and firewood are price-volatile with over-harvesting and scarcity. Furthermore, kerosene, although prevalent, is an expensive and toxic fuel. Manufacturing clean fuel alternatives such as liquefied petroleum gas (LPG), bioethanol, and electric stoves can reduce emissions, health risks, and energy efficiency. The Kenyan government has devised strategies like the Kenya Clean Cooking Strategy (2022-2027) and Vision 2030 to facilitate clean energy resources, but they are slow to be adopted at a large scale. This research is pertinent because it presents facts established by evidence using Microsoft Excel to facilitate the assessment of different transition options to assist policymakers in formulating interventions in a low-carbon and sustainable rural Kenya future.

1.6 Scope

This dissertation compared the effects of four primary cooking energy sources: firewood, kerosene, charcoal, and liquefied petroleum gas (LPG). The research put a value on carbon emissions of these fuel types in terms of combustion efficiency, usage rates, and fuel sources. It also quantified local carbon impacts on carbon storage pools, including forests and soils, to comprehensively view their environmental impacts. The information for this investigation was pulled from periodical publications, laboratory experimentation, and observations from selected regions, which made the results realistic.

Also included in the study were past techniques and instruments used to estimate carbon emissions and their deficiencies. Measures of emissions were examined to provide tactics for utilizing cleaner and renewable power and sustainable fuel sources and provide prescriptive suggestions. This dissertation was devoted to rural settings; some described communities act as examples. Even though the results portrayed specific regional contexts, the suggested framework was scalable to most rural communities. By identifying these study specifications, the proposed and actual study raised a methodological barrier to diversifying yet integrating an extensive approach in response to carbon emissions via rural cooking fuels while providing policy implications for the involved and concerned policymaking, research, and developmental organizations worldwide.

1.7 Limitations and Delimitations

1.7.1 Limitations

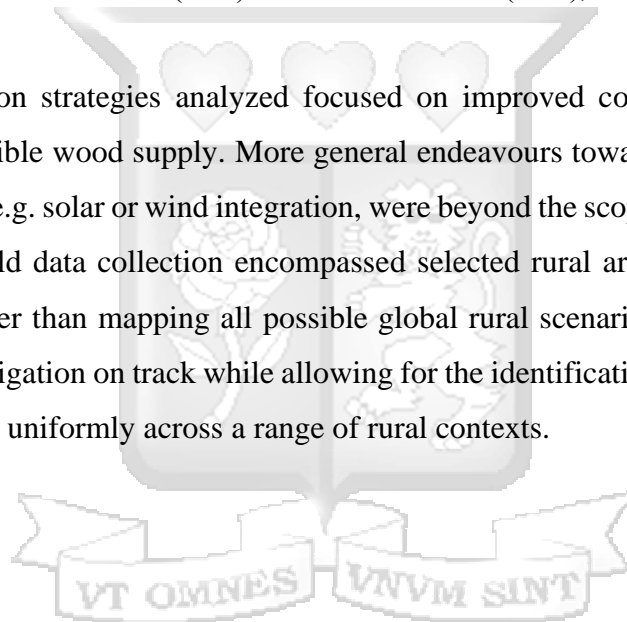
Several limitations to this study impacted the generalization of its results based on the following limitations. First, the research targeted concrete rural communities for data collection, which might have reduced the external validity of the proposed framework for other areas that practiced different cultural habits, lived in different territories, and existed under different economic conditions. Despite this, the framework proved relatively flexible; however, national and regional differences in fuel supply and consumption profiles limited the framework's overall versatility. Second, data accessibility and credibility limited the study because collecting primary data was significantly challenging.

All the calculations relied on emission factors, combustion efficiency indicators, and secondary data, which differed in quality and availability. Fluctuating or partially assessed data evolved into an issue of imprecise evaluation of carbon emissions and their eventual contribution to the carbon sink within local communities. Third, four kinds of cooking fuels, namely firewood, kerosene, charcoal, and LPG, were chosen as the main subjects of the research. Although these were primarily found in rural areas, the absence of other possible fuels, such as biogas or agriculture residues, made the study incomplete. These limitations put into perspective the careful interpretation of the results and served as guidelines on the need to upscale future studies to fill the gaps noted herein.

1.7.2 Delimitations

To avoid endowing the study with a vast scope that was not easily manageable, this research work set certain limitations. First, it targeted only rural people, not urban or peri-urban people. Such delimitation enabled an understanding of the specific energy issues and prospects in rural areas where traditional cooking fuel forms are most significant. This paper focused on four principal cooking fuels: firewood, charcoal, kerosene, and liquefied petroleum gas (LPG). Other promising choice options, for example, biogas or residues of agriculture used in rural regions, were left out to get a detailed analysis of the most popular fuels. Furthermore, this research considered carbon dioxide (CO₂) emissions as the key indicator of the environmental cost of cooking fuels. Some other greenhouse gases were not measured directly, even if relevant, but others, like methane (CH₄) and nitrous oxide (N₂O), could only be discussed regarding impact.

The emission reduction strategies analyzed focused on improved cook stoves, sustainable energy, and a responsible wood supply. More general endeavours towards the transformation in the energy system, e.g. solar or wind integration, were beyond the scope of the present study. Last but not least, field data collection encompassed selected rural areas only and provided only case studies rather than mapping all possible global rural scenarios. Such delimitations helped keep the investigation on track while allowing for the identification of a framework that could be implemented uniformly across a range of rural contexts.



Chapter 2: Literature Review

2.1 Introduction

The literature review studies three main aspects related to cooking fuels: their carbon emissions release effects, carbon reservoir interactions, and emission reduction techniques. The review emphasizes how inefficient biomass fuel usage primarily leads to greenhouse gas emissions despite different cooking fuel levels of carbon output. This dissertation addresses carbon storage changes from deforestation and analyzes how combustion efficiency and usage behaviours influence emission levels.

2.2 Carbon Emissions from Cooking Fuels

2.2.1 Overview of Emission Profiles

The cooking fuels for which various alternatives, including firewood, charcoal, kerosene, and Liquefied Petroleum Gas (LPG), show distinct carbon output. When used inefficiently, biomass fuels such as firewood and charcoal are primary GHG emissions sources. When burnt incompletely, biomass emits sizeable quantities of carbon dioxide (CO₂), methane (CH₄), and black carbon – all known to cause climate change. Kerosene, another fossil fuel, mainly outputs CO₂ and is lower in carbon than biomass (Elizondo et al., 2017). However, because of its higher combustion efficacy, LPG is another fossil fuel with a relatively minor greenhouse impact compared to other fuels.

Figure 2.1 below shows two pie charts that separate the composition of world greenhouse gas (GHG) by applying the Global Warming Potential (GWP) time frames of GWP20 and GWP100. The GWP20 assessment method determines the climate impact of gases during their first twenty years by emphasizing how short-lived gases such as methane (CH₄) affect the environment. This sector contains 40% of CH₄ emissions that exhibit considerable warming power during the first twenty years. The CO₂ emissions remain considerable at 45% yet are less prominent than shown in the 100-year analysis. The GWP100 metrics evaluate the total environmental impact of long-lasting GHGs, including CO₂, across an entire century. The outlined data shows CO₂ emissions taking the lead with 62% of total contributions because of its extended warming effects on Earth. The environmental lifetime of CH₄ shortens, so its proportion drops to 20%. The land use activities of forestry and other land sectors produce the emissions in Forests and Other Land Use (FOLU). The emission of GHG from this source

stands at 9% in both the GWP20 and GWP100 measurement periods. The analysis shows that the evaluation duration is essential in determining GHG influence. The GWP20 indicator demonstrates how urgent action is needed for fast-decaying GHGs in climate mitigation, yet GWP100 emphasizes CO₂ as the primary contributor to long-term effects.

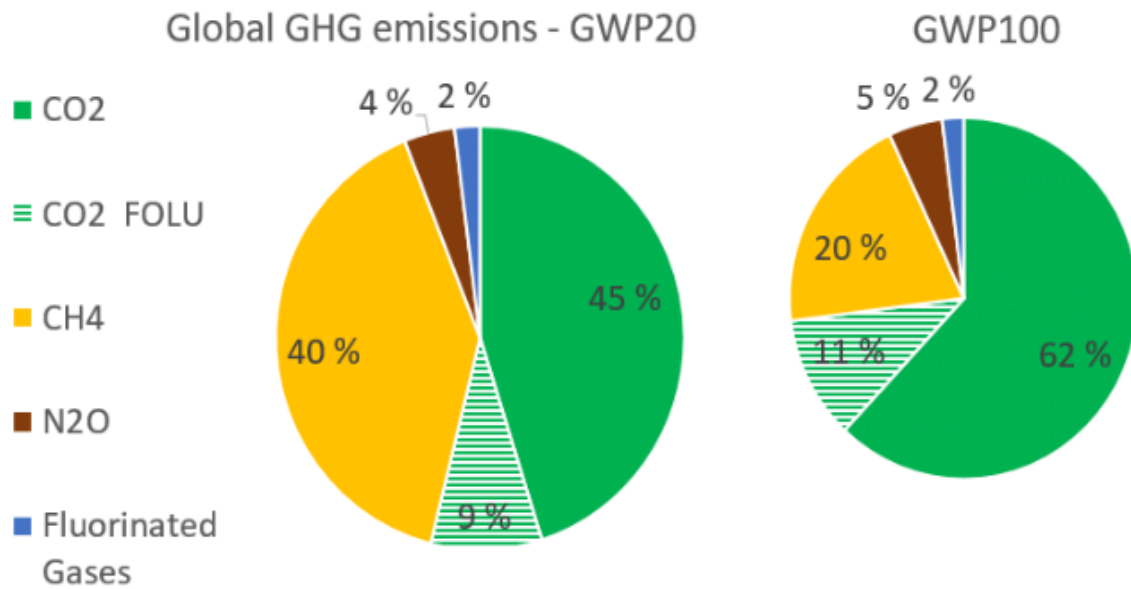


Figure 2. 1: Global greenhouse gas (GHG) emissions shares in 2010 (Lindstad & Riialand, 2020).

2.2.2 Combustion Efficiency and Pattern of Usage

Combustion efficiency is the primary determinant of emission intensity. According to Hollands and Daly (2023), traditional stoves have poor thermal efficiency and thus emit more than improved stoves. Specifically, the nature and extent of fuel consumption, the frequency of fuel use, the amount used, and the cooking method influence households' total emissions. Hence, these variations provide a rationale for models that capture regional endogenous aspects.

2.3 Impact on Carbon Sinks

2.3.1 Deforestation and Carbon Storage

Forests play a central role in atmosphere carbon dioxide sequestration, which makes deforestation a key factor in carbon storage. Emitted sequestered carbon from deforestation produces greenhouse gas emissions that create global warming. Based on Lee et al. (2017), the quantity of carbon loss after deforestation depends on the forest ecology, clearing methods, and what happens to the land afterwards. The ability of the planet to store carbon drops while biodiversity decreases after deforestation. The conservation measures alongside replanting

programs should serve as remedies for climate change by protecting and enhancing carbon storehouses. All ecosystems require forestry management for sustainability purposes.

2.3.2 Soil Carbon and Ecosystem Effects

Besides deforestation, biomass fuels' extraction influences soil characteristics and its cumulative capability of holding the carbon cycle. According to Shakya et al. (2023), the carbon stocks in soil are indispensable parts of global sinks within the physical world. Their reduction due to biomass stacking is a concealed cost related to traditional cooking practices. These environmental impacts articulate the symbiotic relations between the cooking fuel and carbon reserves.

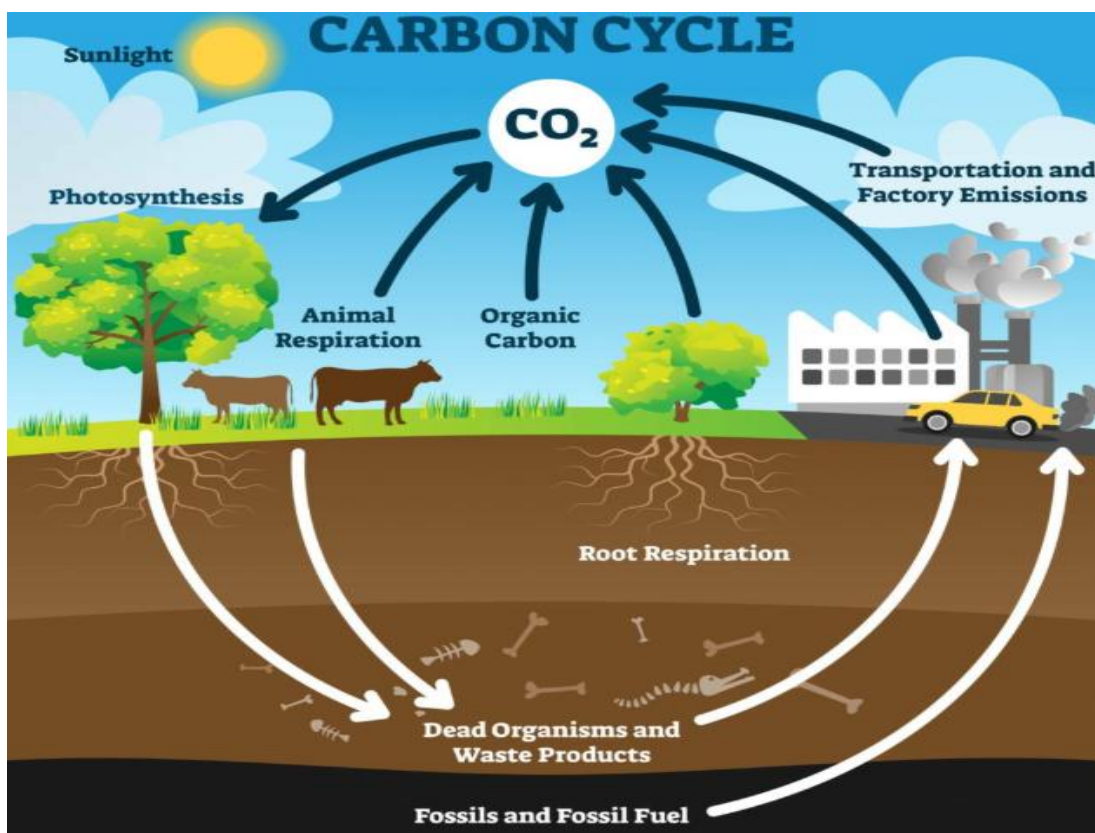


Figure 2. 2: The Soil Carbon Cycle (Tracextech, 2023).

Figure 2.2 facilitates the explanation of the carbon cycle using illustrations that depict how carbon circulates through different earth systems. The processes involve fixing atmospheric CO₂ by plants through photosynthesis and liberating similar gas via respirations, among other animal and plant activities. Decomposition processes move carbon from the remains of plants and animals and the wastes into the ground, where fossil fuels are formed over millions of years (Tracextech, 2023). Transport and other industries emit carbon stored for a long time, making

a reverse balance. These processes present very profound aspects of natural climate change and human influence on carbon cycling for the specific effects of a balance to be achieved on the carbons.

2.4 Strategies for Reducing Carbon Emissions

2.4.1 Reduced Emissions from Cooking

Using an improved cook stove (ICS) is one of the well-researched emission reduction strategies. ICS are well-made cooking stoves designed to save fuel when using them. Figure 2.3 below is an example of an ICS that can use firewood and charcoal indoors and outdoors. The figure is an improved version of the traditional firewood placed that was limited only inside the houses.



Figure 2. 3: COOKSTOVE, clean, efficient, wood/charcoal, 500W

ICS designs improve combustion, thus reducing CO₂ and particulate emissions. Research by Elizondo et al. (2017) further shows that ICS adoption can lower emissions by 30-50% depending on the type of technology and usage. Switching from traditional fuels such as wood or charcoal to LPG or electricity is possible depending on a region's resources. Based on Zhou et al. (2021), the World Health Organization's 2018 similar report shows that LPG can go a long way in eradicating indoor airborne pollutants and carbon dioxide. However, affordability, availability of infrastructure, and the culture of using such services hamper rural growth.

2.4.2 Sustainable Biomass Sourcing

Biomass procurement needs to be sustainable to prevent damages from fuel use of biomass. The process of obtaining biomass resources addresses ecosystem impacts as well as biodiversity loss and carbon cycle disturbances to the least extent possible. The three essential practices involve utilizing waste materials along with tree planting and using sustainable forestry methods (Mandegari et al., 2023). Organizations must manage biomass production energy requirements alongside their carbon reduction abilities relative to fossil fuels in sustainable sourcing. The environmentally friendly nature of biomass production stems from its sustainable acquisition practices, which avoid deforestation and environmental destruction. Sustainable sourcing guarantees the fulfilment of both energy demand and environmental protection.

2.5 Existing Research on Carbon Emission Estimation

Current research functions as an essential tool for environmental studies of energy usage effects and their subsequent reduction. Multiple scientific investigations study carbon emissions from cooking fuels and investigate both geographical differences and clean alternative options' effectiveness and cooking efficiency rates.

Studies conducted by Gupta et al. (2020) demonstrate that traditional cooking fuels in India release considerably more significant amounts of CO₂ and airborne particles when compared to improved cooking models. The evaluation by Mugo and Gathui (2019) in Kenya demonstrated lower carbon emissions from using liquefied petroleum gas as a substitute for firewood. Alem et al. (2018) conducted Ethiopian research which established that inferior combustion practices result in higher CO₂ emissions when using charcoal for cooking.

Analysis by Zhang et al. (2021) showed that modern biomass stoves minimised air pollution better than coal-based stoves in their Chinese assessment. The authors Rahman and Salam (2019) recommended government policies supporting clean fuel utilization due to their examination of kerosene and biomass emissions in Bangladesh. The research by Silva et al. (2020) in Brazil determined that ethanol reduces emissions to a greater degree than charcoal by 70%.

The study by Sanga et al. (2022) proved that Tanzanian rural communities choose clean cooking methods due to financial incentives from carbon credit programs. Shrestha et al. (2021) investigated dung cooking methane emissions in Nepal to evaluate its adverse environmental effects. The Indonesian government's LPG promotion program received an evaluation from Susanto et al. (2020) regarding its effect on deforestation-related emissions.

The study conducted by Okello et al. (2018) in Uganda established that electric cookstoves emit less pollution compared to biomass cookstoves. The collected research demonstrates that contaminants from transition to cleaner fuels require policy intervention through reliable emission measurement methods for realizing sustainable outcomes.

2.6 Gaps in Current Research

The current analysis of cooking fuel carbon emissions faces multiple obstacles that block the creation of successful mitigation approaches. Research lacks fundamental local emission data. Studies generate large-scale regional forecasts without understanding the cookstove dispersion, stove efficiency, and fuel choices across individual communities. Mugo and Gathui (2019) studied the reduction of carbon emissions after Kenyan households switched from firewood to LPG, yet they neglected to consider alternative cleaner cooking solutions like improved cookstoves. Research also lacks proper examination of emissions expected to occur over extended periods. Research depends on scattered and insufficient data records as its main focus is short-term observations, which negatively impacts the development of future carbon emission forecasting models.

Research does not correctly connect household energy affordability against carbon emission analysis. The research on clean cooking fuel supports these initiatives yet fails to address how rural families can afford them. The World Bank (2020) reported that people skip cleaner cooking methods due to expensive initial expenses and lack of basic amenities, yet research studies usually exclude financial obstacles from their examinations. Numerous evaluations of government policies and clean cooking adoption strategies fail to establish evidence showing whether these programs deliver their intended impact. Research conducted about clean energy projects in various nations fails to show such programs' sustainability and future effectiveness. The performance of improved cookstoves suffers from limitations since they show better results in laboratory settings than in actual household environments. Incorrect results occur from this mistake in emission measurements.

2.7 Conceptual Framework

This study integrates carbon emission estimation, reduction strategies, and sustainability practices. The framework adopted highlights the relationship between human activities,

greenhouse gas emissions, and environmental impacts, emphasizing the importance of localized models for accuracy. Key components include energy efficiency, renewable energy, and sustainable practices in transportation and agriculture.

The framework in Figure 2.4 below presents an organized procedure to model carbon emissions, which centers on analyzing conventional and green technological systems. The research begins by defining the Goal and Scope and then establishing clear boundaries for the study. Data collection for fuel consumption and emission factors happens in Inventory Accounting following Goal and Scope Definitions.

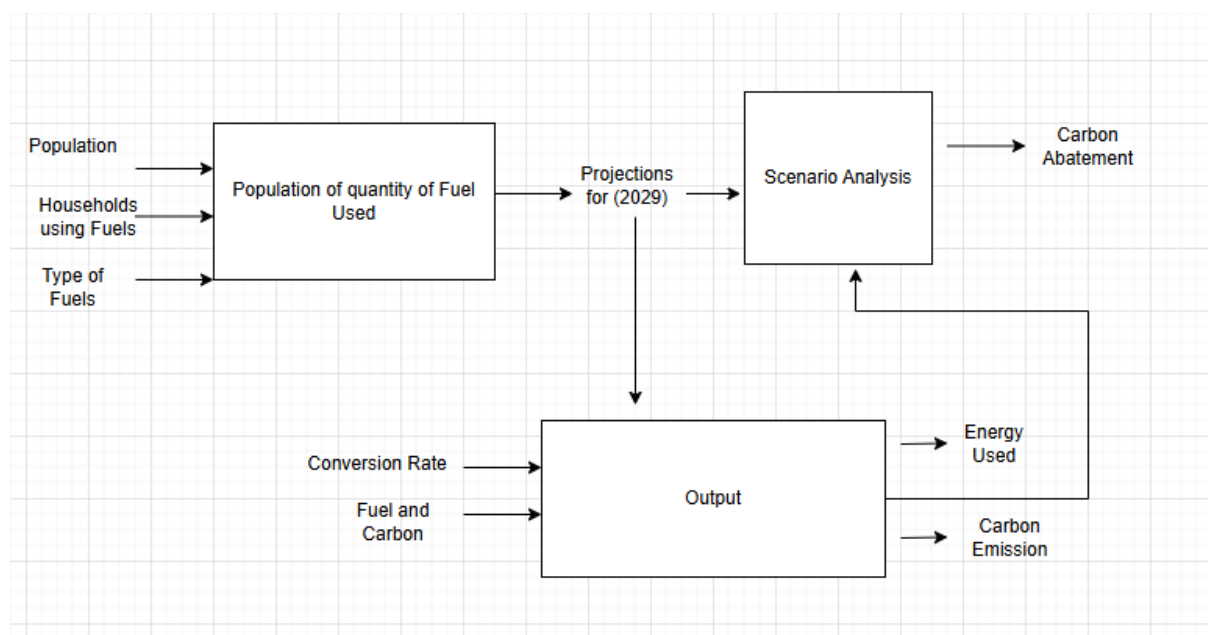


Table 2. 1: Framework for project-specific estimation of carbon emissions.

The framework prioritizes the identification of System Boundaries as well as System Units to establish precise definitions of included items during analysis. Accurately determining carbon emissions depends on Carbon Emission Factors and proper Basic Assumptions. The evaluation of context and study goals is a key requirement according to Input: Context and Goals. The Impact Assessment process uses measurements to determine carbon emissions, which become part of the output as Carbon Emissions. Researchers understand the results through Interpretation, enabling them to compare conventional and green technology carbon emissions. The framework presents an organized method to analyze the environmental effects of various energy technologies as part of promoting sustainable energy transition plans.

Chapter 3: Methodology

3.1 Introduction

This chapter outlines the research approach for creating models that evaluate carbon emission levels during rural cooking operations. The research design section outlines the combination of qualitative and quantitative approaches to evaluate the carbon emissions produced by firewood, kerosene, charcoal, and LPG. The research methodology describes the use of secondary data statistics from the Kenya National Bureau of Statistics and scientific publications. A detailed description of the data analysis procedure includes its primary execution in spreadsheet software. The chapter focuses on the procedures used to verify data quality and the ethical principles that guided the research activities.

3.2 Research Design

The research uses a quantitative design approach to evaluate rural cooking fuel use data and create carbon emission prediction models. The analysis consists of descriptive evaluation for fuel amount measurements and emission patterns but also includes scenario estimations to model reductions in carbon dioxide from specific interventions. Research data was obtained from various secondary sources such as government reports, energy surveys, and carbon emission databases. The study utilized statistical methods to measure cooking emissions by implementing established emission factors for firewood, charcoal, kerosene, and liquefied petroleum gas (LPG). Essential to this model was its use of scenarios for distinguishing between actual (BAU) projections and envisioned cleaner energy transitions. The research approach delivers an organized system to study rural householder energy consumption patterns and create low-carbon kitchen solution transition strategies. The study provides empirical evidence and modeling recommendations through its data application for policymakers, environmental agencies, and rural development stakeholders.

3.3 Methodology

This research examined the carbon emissions from rural households within five Kenyan counties; Bungoma and Murang'a, Kisii, Narok, and Kitui constitute the counties studied. The study seeks to create a predictive model for rural stove emission carbon levels because the objective is to boost the adoption of carbon emission-free cooking fuels across the selected areas. The research targets counties with high traditional cooking fuel consumption, especially

firewood charcoal and kerosene, which serve as main contributors to environmental and carbon emissions issues. Developing an emission estimation model for rural cooking fuels required specific steps. The system integrated data collection methods with scenario-building simulations to perform calculations that help achieve alternative clean cooking methods. The analysis included four primary variables: fuel type (FT), household fuel consumption (HFC), emission factor (EF), and household count (HC). Total baseline carbon emissions (TCE) were calculated through Step 2 as part of the Baseline Emissions determination using historical and survey data. The third step of scenario modeling presented two separate scenarios for analysis: Business-as-usual (BAU) and low-carbon scenario (LCS). BAU maintained current fuel usage levels while LCS evaluated adoption rates for clean cooking technology. The rate of change (ROC) method was applied to calculate projected emissions, which led to future emissions (FE) calculation. The last step analyzed Energy Efficiency Adjustments by incorporating cooking fuel type efficiency calculations into the model.

3.5 Data Collection and Analysis

The study aimed to gather more elaborate information for developing the Total Carbon Mitigation (TCM) for carbon emissions from rural cooking fuels. This information included the amounts of cooking fuels (firewood, kerosene, charcoal, and LPG) used in rural homes, fuel consumption rates, and emission factors derived from combustion tests and field measurements. Quantitative data comprised of cooking practices obtained from a cross-section of households. In contrast, quantitative data involved socio-economic data, such as fuel choice and perception of clean cooking technology. Environmental data checked on the effects of the use of cooking fuel on carbon pools, such as deforestation rates, soil carbon depreciation, and changes in land use. Information was collected from secondary data sources, including emission factors from publications and national energy plans and reports. Furthermore, the selected rural areas' secondary demographic and geographic data was included to create context. This data set guided the design of a localized and feasible anti-carbonization agenda for rural cooking practices.

3.5.1 Data Collection

An analysis of rural cooking fuel emissions depended on data gathered from secondary sources. The study utilized second-hand materials such as reports from the Kenya National Bureau of Statistics (KNBS) and documents about energy strategy and scientific research papers. The

study depends on the 2019 Kenya Census research, the Kenya National Cooking Transition Strategy (2024–2028), and the World Bank’s Poverty Report. Data about fuel combustion efficiency and carbon emission factors originated from research papers and worldwide databases. The study combines survey results with secondary data to create a thorough and empirically based method of carbon emission modeling and clean energy cooking transition evaluation in Kenyan rural areas.

3.5.2 Data Analysis

Data analysis is always a vital stage of every research methodology. This study combined qualitative methods with quantitative methods for evaluating cooking fuel emissions to achieve complete knowledge of the subject. Statistical analysis of quantitative data about fuel consumption rates and emission factors allowed researchers to determine carbon emission levels and establish strong patterns. The research evaluated qualitative data through thematic analysis to support the understanding of quantitative results, combining qualitative and quantitative analysis strengthened the research results through their joint application.

3.5.3 Data Quality

Concerning this study, it was of the essence that data quality is highly maintained. This meant scientific methods were used to collect the relevant data to increase reliability and validity. Thus, standard procedures for the emission measurements were adopted, and the measurements were calibrated to reduce variability. Data collected from field measurements, surveys, and secondary sources were used to reduce social validity. The accuracy of the data was even more enhanced through cross-checks, documentation, and consultations during the analysis. These measures guaranteed accurate, advanced, detailed information concerning emissions that applied to different contexts. This information helped build accurate models for carbon emissions and appropriate approaches to promoting low-emission cookery for rural consumers.

3.6 Tools of Technology Used

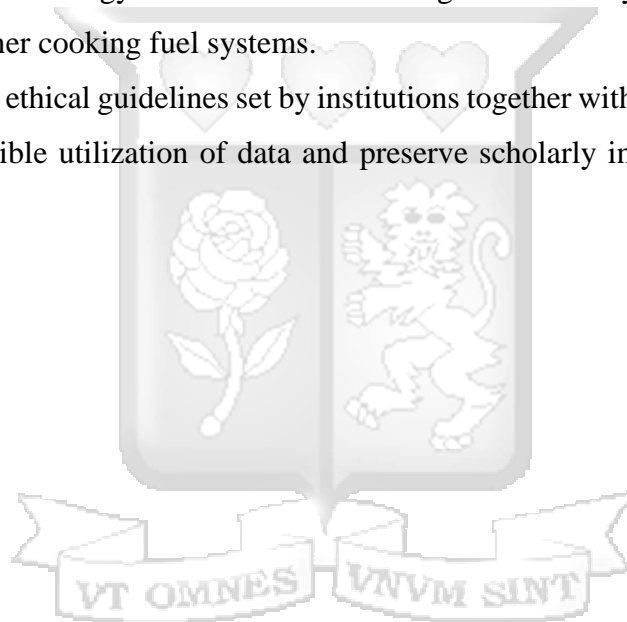
The research collected data, analyzed, and modeled using important technological equipment. Spreadsheet software was essential in organizing data and manipulating and analyzing it for preliminary assessments. Its massive data management strength and calculation functions enabled to analyze quantitative data from fuel consumption and carbon emissions. Laptops served as fundamental tools that was used for data collection, data entry functions, and document report production. The integration of spreadsheet software and a laptop were also used to source secondary data from publications and government sites like the KNBS statistics.

3.8 Ethical Considerations

The study upholds ethical research principles for maintaining integrity and delivering accurate results as well as respecting all stakeholders involved. The research obtained consent when needed to maintain both participant privacy and the protection of their autonomy for any filed data collected from rural households. Personal information received protection through data anonymization as part of maintaining confidentiality policies.

The study-maintained data integrity and displayed transparency through secondary data collection from peer-reviewed studies along with government reports. The modeling framework included all necessary assumptions which received explicit documentation to prevent fraudulent information. This research supported environmental ethics through its promotion of sustainable energy solutions while working to reduce any bias that could affect the promotion of cleaner cooking fuel systems.

The research followed ethical guidelines set by institutions together with the national standards to protect the responsible utilization of data and preserve scholarly integrity throughout the reporting phase.



Chapter 4: Results and Discussion

4.1 Introduction

This chapter presents the research findings on rural cooking fuel carbon emissions, followed by a detailed discussion of the results. Data analysis is focused on household fuel consumption patterns, emissions levels, and potential reductions based on different scenarios. Trends are established by statistical analysis and graphical presentations in the form of graphs and tables. The findings are then compared with the literature to approximate their importance for clean cooking transitions. The conclusion discusses the environmental implications, policy implications, and how to promote the adoption of low-carbon cooking solutions in rural communities.

4.2 Fuel Consumption and Carbon Emissions

4.2.1 Overview of Household Fuel Use

A higher percentage of Kenyan rural communities use the most common fuels for cooking are firewood, charcoal, and kerosene. When used inefficiently, biomass fuel products such as firewood and charcoal are the main contributors to greenhouse gas emissions. Each year, sustained CO₂ emissions from firewood and charcoal production amount to 356,400 tons, causing major deforestation problems throughout Kenya (KNBS, 2019). Kerosene is a fossil fuel that produces mostly CO₂ with a lower carbon content than biomass fuels. Adopting these resources has led to multiple difficulties regarding building ventilation quality.

Table 4.1 below provides an overview of total carbon emissions (tCO₂e) across different years, offering insights into the overall environmental impact of cooking fuel consumption. The results show changing patterns of total emissions throughout time, which stem from shifts in fuel quantities and connected elements. Total emissions analysis reveals information that helps authorities evaluate the success of programs created to decrease carbon emissions. The table enables examination between years for better monitoring sustainable energy goal advancement and identifying any obstacles to reaching these targets. These data points are essential in creating strategies that combat climate change and develop more environmentally friendly cooking systems.

Table 4. 1: Household Fuel Consumption Across the counties (2009-2019)

2019 Data				
County	Households Using Firewood	Households Using Charcoal	Households Using Kerosene	Households Using LPG
Bungoma	120,000	80,000	10,000	30,000
Murang'a	100,000	60,000	8,000	40,000
Kisii	90,000	70,000	12,000	35,000
Narok	110,000	50,000	9,000	25,000
Kitui	130,000	75,000	7,000	20,000
2009 Data				
County	Households Using Firewood	Households Using Charcoal	Households Using Kerosene	Households Using LPG
Bungoma	140,000	85,000	15,000	15,000
Murang'a	120,000	65,000	12,000	20,000
Kisii	110,000	75,000	18,000	18,000
Narok	130,000	55,000	14,000	12,000
Kitui	150,000	80,000	10,000	10,000

Table 4.1 shows the household fuel consumption for Bungoma, Kisii, Kitui, Murang'a, and Narok counties from 2009 to 2029. According to the data, most households are substituting their traditional energy consumption of charcoal, firewood, kerosene, and alternate clean energy sources. The reduction of traditional fuel use happens because people switch to cleaner forms of energy while also becoming more efficient in their energy consumption. Due to ongoing changes in kitchen preferences, the use of LPG as a cooking fuel has increased, showing a slow shift towards contemporary cooking technology. The data implies that regions are shifting toward less polluting energy supplies, yet this change happens at different rates across the selected counties.

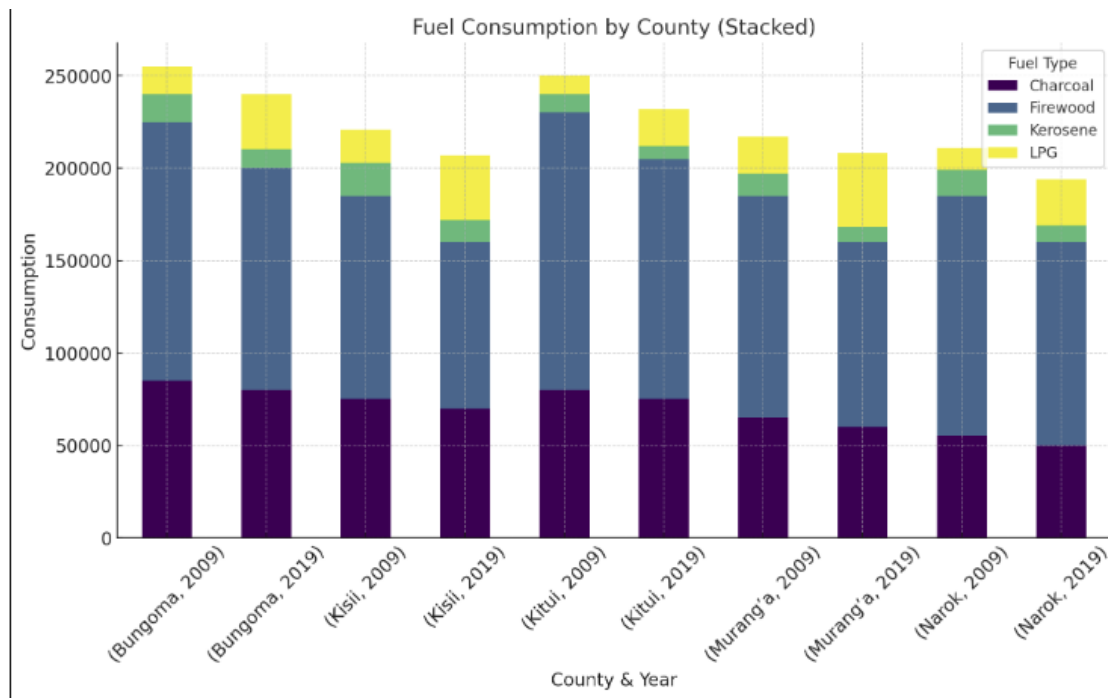


Figure 4. 1: Fuel Consumption Data Across counties in 2009 -2019

The graph in Figure 4.1 above demonstrates how fuel use developed within the Kenyan counties of Bungoma, Kisii, Kitui, Murang'a, and Narok during the twelve years from 2009 to 2019. Each bar shows the separation of fuel consumption between Charcoal and Firewood and Kerosene and LPG varieties of energy types. The chart shows the continuous use of Firewood and Charcoal as primary cooking fuels across all counties, yet their combined usage decreased from 2009 to 2019. The consumption of LPG has experienced a growing trend for the duration spanning 2009 to 2019. The usage of Kerosene shows limited changes across the board during the analyzed periods. The bar graph shows how LPG adoption for alternative energy purposes is gradually increasing. In contrast, biomass fuels, including Firewood and Charcoal, remain the leading energy source in these areas.

4.2.3 Total Carbon Emissions from Cooking Fuels

The total carbon emissions resulted from multiplying household numbers by average monthly consumption and emission factor using equation 1

$$Total\ Emissions = Households \times Avg.\ Monthly\ Use \times Emission\ Factor \dots\dots\dots 4.1$$

This means that in one year, households in Bungoma County using charcoal emit 18,000 metric tons of CO₂ equivalent emissions. Table 4.1 below presents county-level total carbon emissions during different years:

$$\text{Total Emissions} = \text{Households} \times \text{Avg. Monthly factor} \times 12 \dots \dots \dots 4.4$$

Where:

Households = Number of households using a specific fuel type,

Avg. Monthly Use = Average monthly consumption per household (e.g., kg, litres, or m³),

Emission Factor = CO₂ emissions per unit of fuel (e.g., kg CO₂ per kg fuel)

12 = Conversion factor for annual emissions (since monthly consumption is given)

Table 4. 2: Total Carbon Emissions (tCO₂e) per Year

County	Year	Charcoal	Firewood	Kerosene	LPG
Bungoma	2009	13,090	39,270	900	225
	2019	11,200	29,700	480	900
	2024	10,359.89	25,828.70	350.54	1,800
	2029	9,963.84	24,086.74	299.56	2,545.58
Kisii	2009	10,500	25,480	1,123.2	324
	2019	8,820	23,760	633.6	945
	2024	8,083.66	22,975.62	475.88	1,613.89
	2029	7,738.88	22,593.20	412.41	2,109.10
Kitui	2009	11,200	47,025	1,320	360
	2019	10,080	36,465	792	1,080
	2024	9,562.73	32,110.71	588.22	1,811.52
	2029	9,314.13	30,103.85	504.66	2,269.17
Murang'a	2009	6,500	28,060	780	600
	2019	5,460	21,450	420	1,200
	2024	4,997.77	18,346.42	309.28	1,777.67
	2029	4,772.36	16,990.27	266.36	2,133.01
Narok	2009	12,600	41,610	990	270
	2019	10,584	34,650	594	945
	2024	9,705.57	29,977.26	436.58	1,595.73
	2029	9,278.47	27,698.88	373.91	2,030.73

As Figure 4.2 illustrates, firewood consumption is always the greatest among all the counties, way beyond other fuel sources. This is trailed by charcoal, kerosene, and LPG, in that order in terms of its usage. Narok and Kitui have the most significant firewood consumption, whereas

Murang'a has the least. The graph points towards the persistence in using old fuels such as charcoal and firewood in the counties and points towards interventions to shift toward cleaner options.

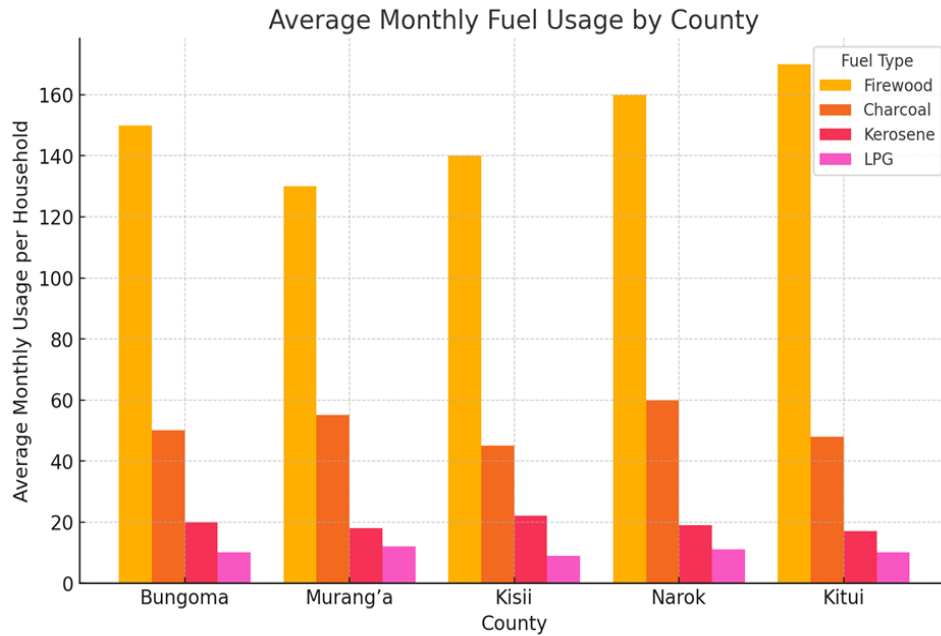


Figure 4. 2: The average monthly fuel usage per County

Most households have switched from firewood, charcoal, and kerosene to LPG appliances in selecting energy sources. This is because LPG energy produces efficient combustion with fewer greenhouse gases than traditional fuels. The avoidance of modern cooking technologies occurs among the public because they do not have sufficient LPG access and must pay steep initial expenses to adopt new equipment. These communities demonstrate resistance to cultural customs alongside limited knowledge about new technology systems. Firewood remains the highest source of emissions in the area, while its use significantly lessened from 2009 until 2029 because most households acquired alternative fuel types. The adoption rate of LPG has experienced a dramatic upward trend throughout the Murang'a area.

2019			
Avg. Monthly Firewood Use (kg/HH)	Avg. Monthly Charcoal Use (kg/HH)	Avg. Monthly Kerosene Use (L/HH)	Avg. Monthly LPG Use (kg/HH)
150	50	20	10
130	55	18	12
140	45	22	9
160	60	19	11
170	48	17	10
2009			
Avg. Monthly Firewood Use (kg/HH)	Avg. Monthly Charcoal Use (kg/HH)	Avg. Monthly Kerosene Use (L/HH)	Avg. Monthly LPG Use (kg/HH)
170	55	25	5
150	60	22	7
160	50	26	6
180	65	22	8
190	50	20	7

Table 4.3 shows the use of different cooking fuels in rural households. These include firewood, charcoal, kerosene, LPG, and electricity, with their average monthly household consumption, energy content (MJ/kg or MJ/kWh), and total energy demand per month and year. Due to its abundance, firewood requires the highest energy demand, whereas LPG and electricity are more efficient but less common. The total energy demand was determined using equation 4.1. This table highlights the energy intensity of biomass fuels, which suggests that cleaner alternatives are needed.

$$\text{Total Energy Demand} = \text{Household Use} \times \text{Energy Content} \dots\dots\dots 4.2$$

Table 4. 3: Energy Demand Table

Fuel Type	Average Monthly Use per Household (kg)	Energy Content (MJ/Kg)	Total Energy Demand (ML/Month)	Total Energy Demand (MJ/Year)
Firewood	120	16	1,920	23,040
Charcoal	30	28	840	10,080
Kerosene	10	43	430	5,160
LPG	8	50	400	4,800
Electricity	20kWh	3.6 MJ/kWh	72	864

Table 4.4 shows the energy demand for firewood, charcoal, kerosene, LPG, and electricity in average monthly household consumption. Firewood records the most tremendous cumulative energy demand monthly and yearly since it is used intensively despite its lower energy per kilogram than any other fuel. Even though it is less consumed, charcoal also has more energy requirements as it contains more energy. Kerosene and LPG both have moderate energy requirements, while electricity has the lowest overall energy requirement since it is used less. This proves that older fuels of biomass contain higher requirements than newer ones.

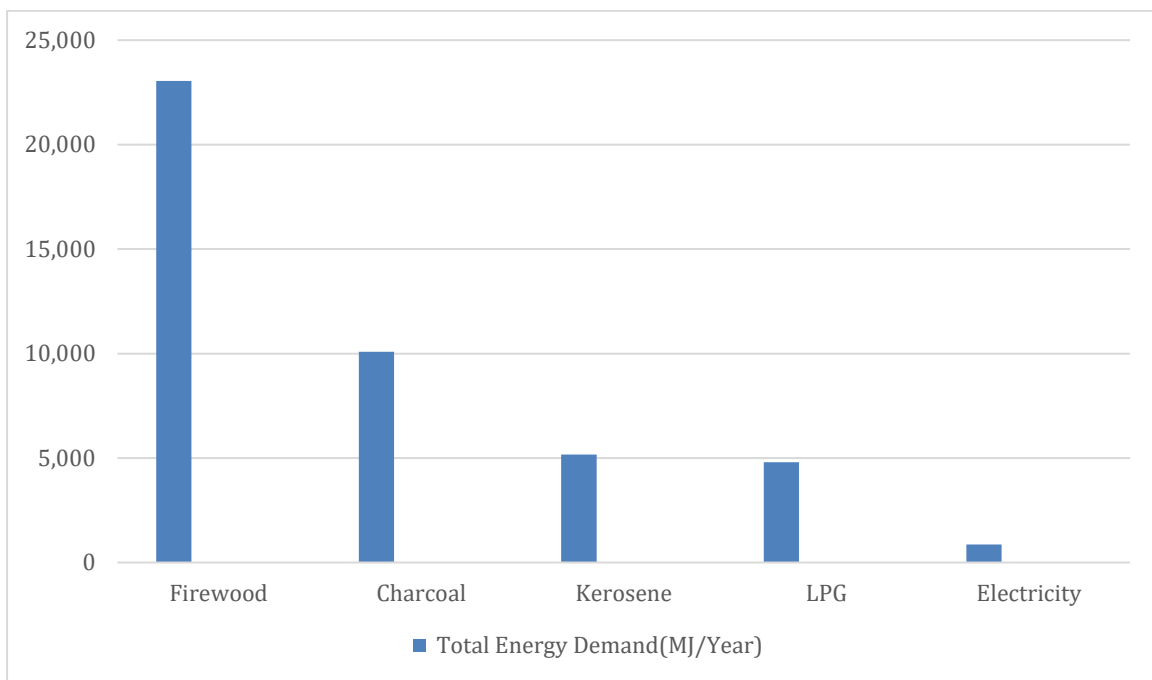


Figure 4. 3: Total Energy Demand per Fuel Type

The graph in Figure 4.3 above shows an apparent energy demand ranking by fuel type. Firewood is consistently in the highest demand throughout, far above other sources in all counties. This shows continued reliance on customary biomass for cooking. Charcoal is the next most demanded fuel, which shows continued use but at decreasing volumes compared to firewood. Kerosene and LPG show much lower energy demands, indicative of their bridging role or restricted use. Electricity illustrates the low energy demand. These trends show the dominance of traditional biomass fuels and the gradual but varied shift towards potentially cleaner alternatives. Standard alternative energy options are steadily replacing older traditional biomass energy sources.

Table 4. 4: Total Carbon Emissions Across the Counties in the Years 200-2029

County	Year	Charcoal	Firewood	Kerosene	LPG	Grand Total
Bungoma	2009	13,090	39,270	900	225	53,485
	2019	11,200	29,700	480	900	42,280
	2024	10,359.89	25,828.70	350.54	1,800	38,339.12
	2029	9,963.84	24,086.74	299.56	2,545.58	36,896.73
Kisii	2009	10,500	25,480	1,123.2	324	37,357.2
	2019	8,820	23,760	633.6	945	34,158.6
	2024	8,083.66	22,975.62	475.88	1,613.89	33,149.06
	2029	7,738.88	22,593.20	412.41	2,109.10	32,853.59
Kitui	2009	11,200	47,025	1,320	360	59,906
	2019	10,080	36,465	792	1,080	48,417
	2024	9,562.73	32,110.71	588.22	1,811.52	44,073.18
	2029	9,314.13	30,103.85	504.66	2,269.17	42,191.85
Murang'a	2009	6,500	28,060	780	600	35,930
	2019	5,460	21,450	420	1,200	28,530
	2024	4,997.77	18,346.42	309.28	1,777.67	25,431.14
	2029	4,772.36	16,990.27	266.36	2,133.01	24,162
Narok	2009	12,600	41,610	990	270	55,470
	2019	10,584	34,650	594	945	46,773
	2024	9,705.57	29,977.26	436.58	1,595.73	41,715.34
	2029	9,278.47	27,698.88	373.91	2,030.73	39,381.99

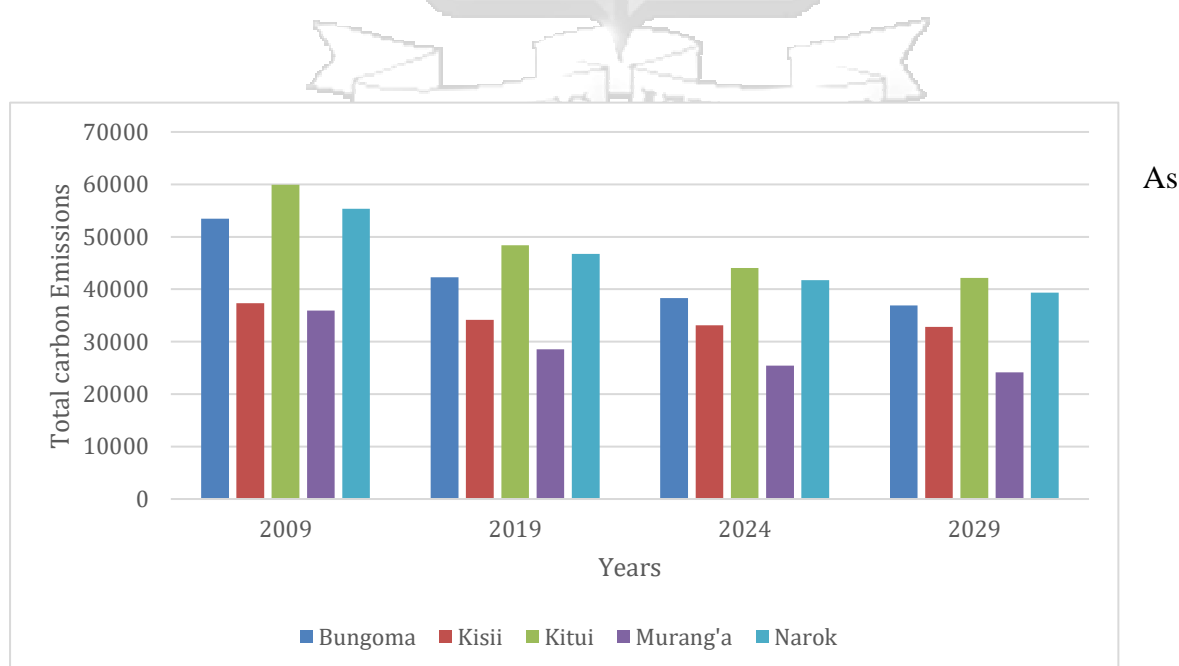


Figure 4. 4: Total Carbon Emissions across Counties in the Years 2009-2029

Figure 4.4 shows that, as of 2009, Kitui County had the most carbon emissions, followed by Narok and Bungoma. The carbon emissions kept reducing, and by 2019, they were lower, probably because households were switching to LPG and electricity for cooking. The emissions are projected to continue decreasing by 2029 based on the 2024 projections.

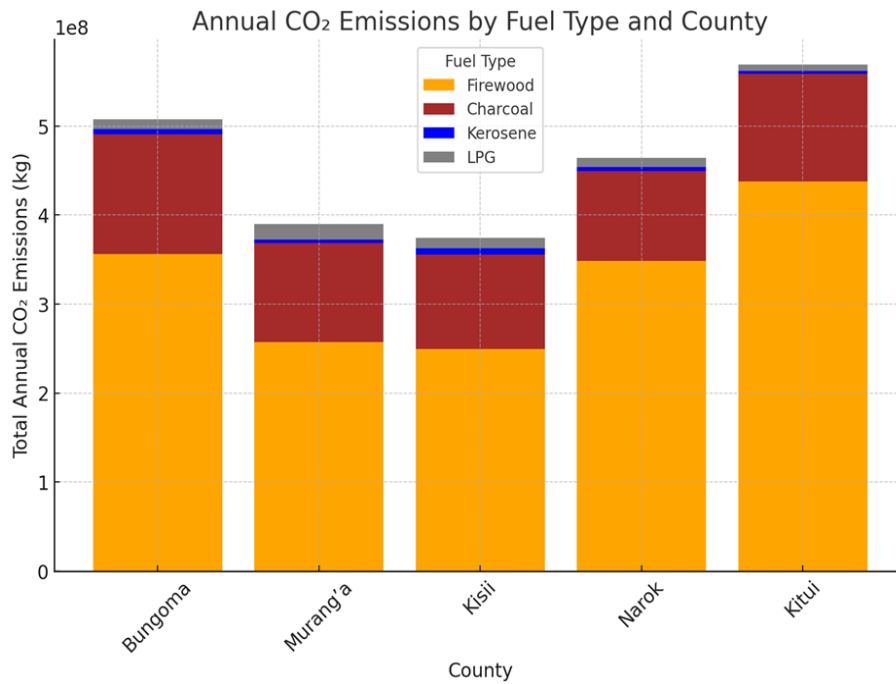


Figure 4. 5: The annual CO2 Emissions by Fuel Type and County

Figure 4.5 above shows that firewood is utilized most in all the areas, with the highest percentages being from Narok and Kitui. Charcoal is the second most utilized after firewood, followed by kerosene, and the least LPG is utilized. The significant difference between firewood use and cleaner options of LPG indicates the continued dependence on conventional energy sources. This calls for interventions to promote cleaner energy sources and reduce the environmental impact of domestic cooking in the selected counties.

The Rate of Change (ROC) formula calculates how fuel consumption and emissions change over time across different years. The ROC formula is written as:

$$ROC = \left(\frac{New\ Value - Old\ Value}{Old\ Value} \right) \dots\dots\dots 4.3$$

Firewood continues to cause the most emissions, although its usage steadily decreased from 2009 through 2029 when households started obtaining alternative fuel sources. The regulated

logging activities and enhanced cookstove developments have resulted in declining charcoal consumption patterns. The usage of kerosene has declined substantially because consumers now take advantage of more environmentally friendly alternatives that have become available. People are adopting LPG equipment faster, yet the transition process continues slowly since it requires expensive infrastructure.

The projected data reveals that LPG and other clean energy sources are replacing firewood and charcoal for cooking. The current emissions reductions are insufficient because more substantial interventions must be developed and established. LPG and bioethanol thus require governmental backing, including distribution infrastructure improvements, to enhance market penetration. Strategic awareness efforts within communities regarding clean energy systems must drive people toward cutting their usage of firewood and charcoal. The government should apply deforestation laws to limit biomass consumption and mitigate carbon pollution.

4.3 Scenario Analysis

This section evaluates total emission changes through analysis of four different transition approaches: The Business-As-Usual (BAU) (scenario 1), LPG introduction (scenario 2), Bioethanol and Electricity Introduction (Scenario 3), and the Ambitious Plan (Scenario 4). Scenario analysis is an essential assessment method to evaluate multiple energy transition plans and their corresponding effects on carbon dioxide emissions from cooking fuel consumption. The analysis permits the evaluation of distinct strategies incorporating regular operations and advanced mitigation methods. The study creates insights regarding policy effectiveness through simulations of fuel acceptance patterns and intervention measures.

The evaluation model provides strategies to reach sustainable energy goals by comparing different methods. The scenario analysis serves as a tool to support decision-making because it shows the advantages and disadvantages of various energy policies and thus helps develop successful strategies for the energy transition. This analysis examines how fuel consumption and carbon release levels shift and which year provides the most reduction.

4.3.1 Business-As-Usual (BAU) Scenario

Under the BAU scenario, households do not change their usage of firewood charcoal and kerosene while no primary market or policy reforms occur. Natural cooking fuel preference changes lead to minor emission reductions, yet using firewood and charcoal maintains dominant positions, thus causing high emissions. In 2029, firewood will be the principal

cooking fuel since 55 percent of rural households continue to use it. Decreased charcoal use following deforestation regulations does not lower its substantial impact on carbon emissions.

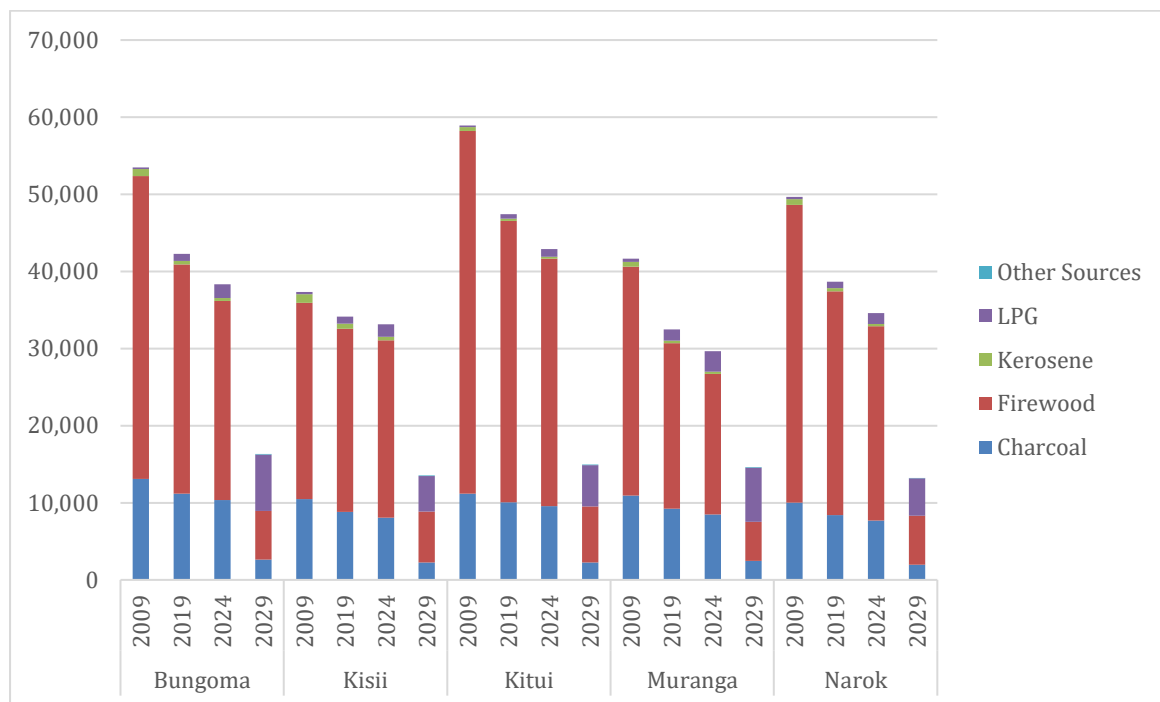


Figure 4. 6: Projected Carbon Emissions in BAU Scenario (2029)

Figure 4.6 indicates that 30,000 tCO_{2e} emissions per county under BAU surpass sustainable environmental objectives. This fig is derived from Table 4.2, firewood contributes the most to emissions, and Kitui is notably more than the others. Charcoal is the second highest, with a specific prevalence in Kitui. LPG shows an increase and a positive movement towards cleaner fuels, but still less than traditional sources. Other Sources of fuel provide an added layer, revealing emissions beyond typical cooking fuels. The figure illustrates the difficulty and advancement in the move towards cleaner energy for these Kenyan counties.

4.3.2 Scenario 2: 50% LPG Adoption by 2029

The Cooking Transition Strategy of Kenya works towards reaching 50% LPG adoption by 2029 as part of Scenario 2. Household migration to LPG results in a 15-20% reduction in emissions because they abandon their current use of firewood and charcoal. When households use firewood at rates between 35% and 40%, the result is decreased forest clearance and decreased carbon emission output. The adoption of LPG increases by two times while reducing home air pollution with its clean operation. Emission reductions get additional support from the decreasing usage of charcoal together with kerosene.

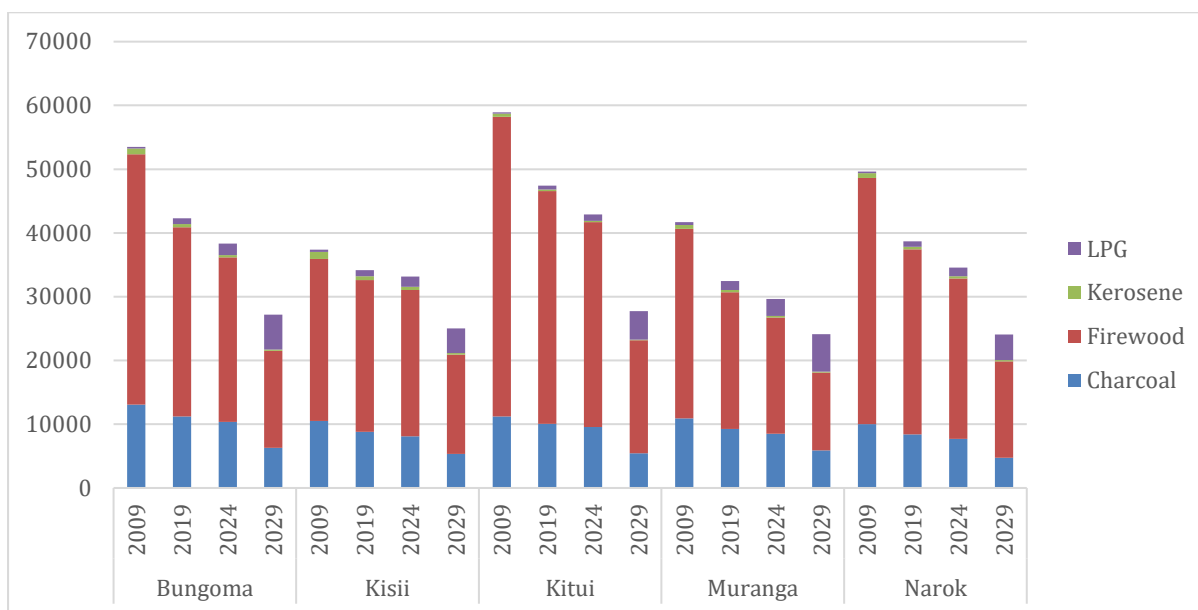


Figure 4. 7: Carbon Emissions Reduction in Scenario 2 vs. BAU (2029)

The positive effects of Scenario 2 depend on firewood and charcoal usage, yet these components diminish its complete success. As shown in Figure 4.6 above, Scenario 2, aiming for 50% LPG penetration by 2029, sees a dramatic shift in the fuel consumption pattern across the five Kenyan counties. As the graph shows, LPG use increases while traditional fuels like charcoal and firewood show a corresponding decline. Kitui, which had the highest emissions, sees a decline, albeit still high. Murang'a and Kisii, having lower initial emissions, see a higher spike in LPG. This scenario indicates the promise of LPG in reducing carbon emissions and the varying rates of adoption and ongoing use of traditional fuels across various regions.

4.3.3 Scenario 3: Introduction of Bioethanol and Electricity

Scenario 3 develops Scenario 2 by implementing bioethanol and electricity as substitute energy sources. The 25-30% carbon reduction figure results when transitioning to alternative fuels reduces dependence on traditional biomass commodities. Bioethanol functions as a substitute for firewood and charcoal, lowering the tree-cutting rate. More households are moving towards electrical power use, most notably in semi-urban and peri-urban regions. The household cooking sector uses LPG as its primary transition fuel, which constitutes between 40 and 45 percent of total energy usage.

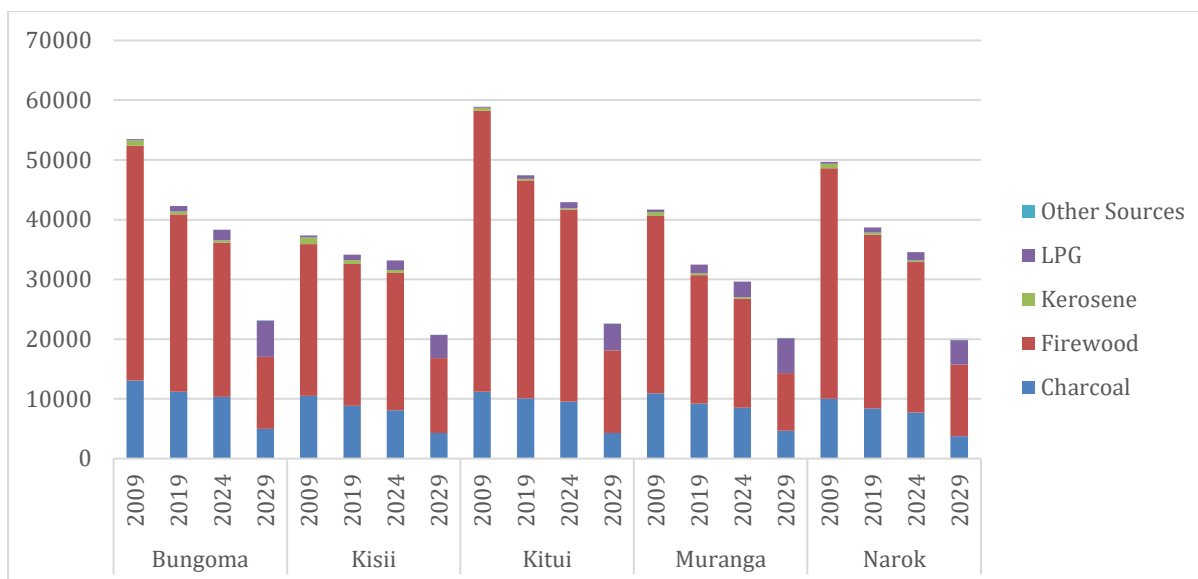


Figure 4. 8: Scenario 3 Fuel Mix and Emission Reductions (2029)

The successful implementation of Scenario 3 depends on adequate bioethanol resource development alongside rural energy installation projects. The graph in Figure 4.8 indicates a sharp reduction in emissions compared to the baseline and Scenario 2. Kitui, even with high emissions, exhibits a remarkable drop. Murang'a and Kisii, with initial lower emissions, further drop their carbon emissions. This scenario validates reducing emissions by diversifying the fuel mix using cleaner resources. However, the varying emission cuts suggest the need for particular methods to have an optimum impact on electricity and bioethanol consumption in various areas.

4.3.4 Scenario 4: Ambitious Clean Energy Plan

Scenario 4 shows the highest commitment to fuel transition by aiming to achieve. This vision projects a massive shift to clean cooking technologies with massive adoption of LPG, biogas, and electric cooking. Government subsidies, international aid, and private-sector investment drive affordability and availability. Policies include phasing out charcoal and firewood use through enforcement policies and incentives for adopting clean energy. Awareness raising contributes to a behavior change that guarantees community involvement. As a result, carbon emissions are significantly reduced, improving air quality and well-being and reducing deforestation. Biomass fuel reliance will be zero in 2029, a complete switch to a low-carbon sustainable future for rural residences. The most efficient plan for sustainable long-term development achieves more than half of emission reduction.

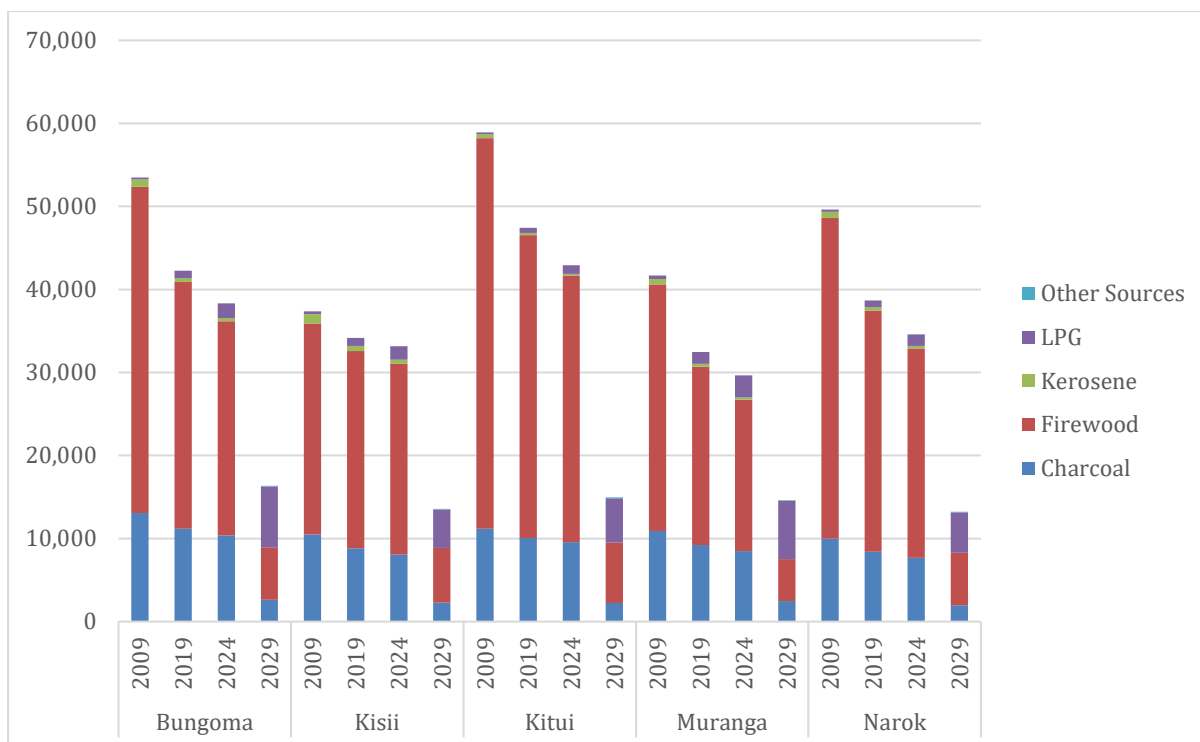


Figure 4. 9: Scenario 4 vs. Other Scenarios (Emissions Reduction (%))

Figure 4.9 illustrates a steep decline in traditional fuels like charcoal and firewood, LPG increases proportionally, and electricity and bioethanol are included. Kitui, although with high emissions initially, illustrates a sharp decline, indicating the viability of aggressive clean energy policies. Murang'a and Kisii, with lower initial emissions, illustrate even lower emissions. This case illustrates the strength of a comprehensive clean energy plan to shift, showing the capability of significant emission reductions through aggressive policy measures.

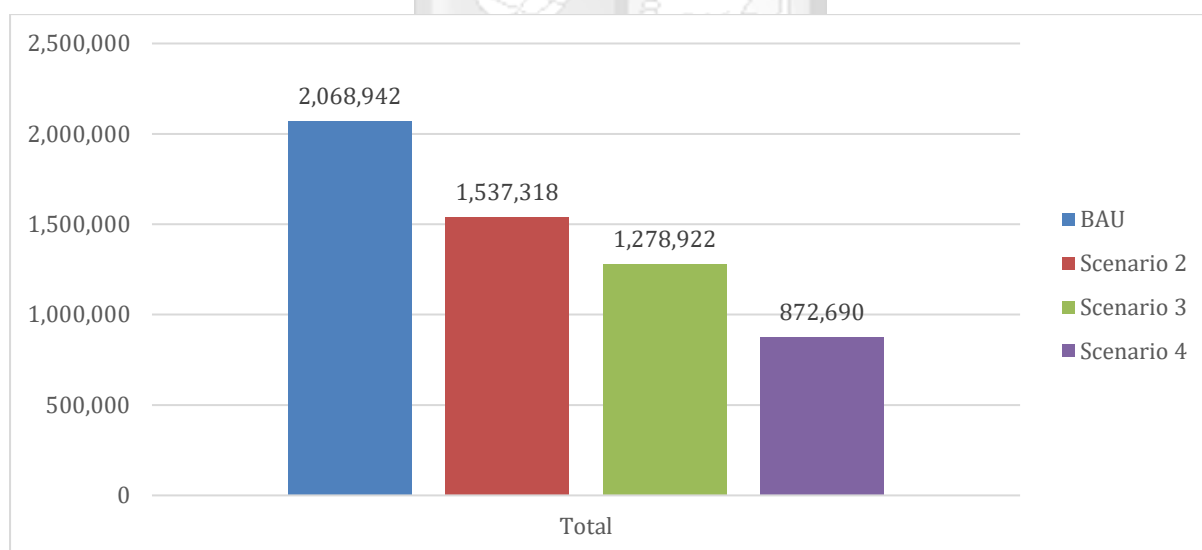
4.3.5 Scenario Comparisons

Table 4.3 below firmly compares carbon emissions across four scenarios, giving insight into the potential impact of different energy transition strategies. Scenario 1, the Business As Usual (BAU) scenario, is a reference case, with estimated emissions assuming trends continue. Scenarios 2, 3, and 4 introduce progressively more ambitious interventions, with Scenario 4 being the most aggressive clean energy approach.

Table 4. 5: Comparison of Total Carbon Emissions Across Scenarios (tCO₂e, 2029)

County	Scenario 1 (BAU)	Scenario 2 (50% LPG)	Scenario 3 (Bioethanol & Electricity)	Scenario 4 (Ambitious Plan)
Bungoma	36,470	29,600	25,800	15,500
Kisii	33,740	28,220	24,560	13,800
Kitui	39,120	31,940	26,980	17,400
Murang'a	30,500	26,700	21,400	12,900
Narok	35,200	29,100	24,600	14,200

Scenario 2, 50% LPG penetration, records a slight reduction in emissions compared to BAU. Significant gaps between counties persist, and this justifies differentiated strategies. Scenario 3, incorporating bioethanol and electricity, records a more profound emissions reduction, showing the leverage of fuel diversification. Scenario 4, the ambitious one, records the most significant emission reductions, which indicates the revolutionizing nature of an integrated clean energy approach.



The comparison of scenarios finds the potential for carbon emissions reduction from cooking fuel through targeted interventions. It sets the potential for significant reductions through goal-oriented energy transitions, each scenario corresponding to a progressively lower carbon path. Research finds that it can be encouraged through policy action, infrastructure growth, and awareness creation to speed up and accelerate the transition towards cleaner cooking fuels.

4.4 Carbon Emissions Trends

Environmental impact results from multiple factors in the analysis of carbon emission trends. Traditional cooking fuels consisting of firewood and charcoal supply the highest emissions because they are the principal causes of environmental deterioration. Observations demonstrate a replacement trend from polluting fuels toward cleaner alternatives such as LPG, showing that sustainable energy practices might increase in use. Policy implementations that stimulate clean energy use guide these changing patterns. Proper assessment of these patterns allows us to design powerful methods that reduce carbon emissions and build sustainable power solutions. The research demonstrates that the world requires ongoing efforts to abandon toxic fuel types.

4.4.2 Carbon Emissions Trends by Fuel Type

The data in Figure 4.10 below shows how different types of fuels generated emissions during the 2009 to 2029 timespan. The data shows that firewood is the top source of emission pollutants, and its quantities have dramatically dropped. The downward pattern shows a decreasing use of firewood for energy generation.

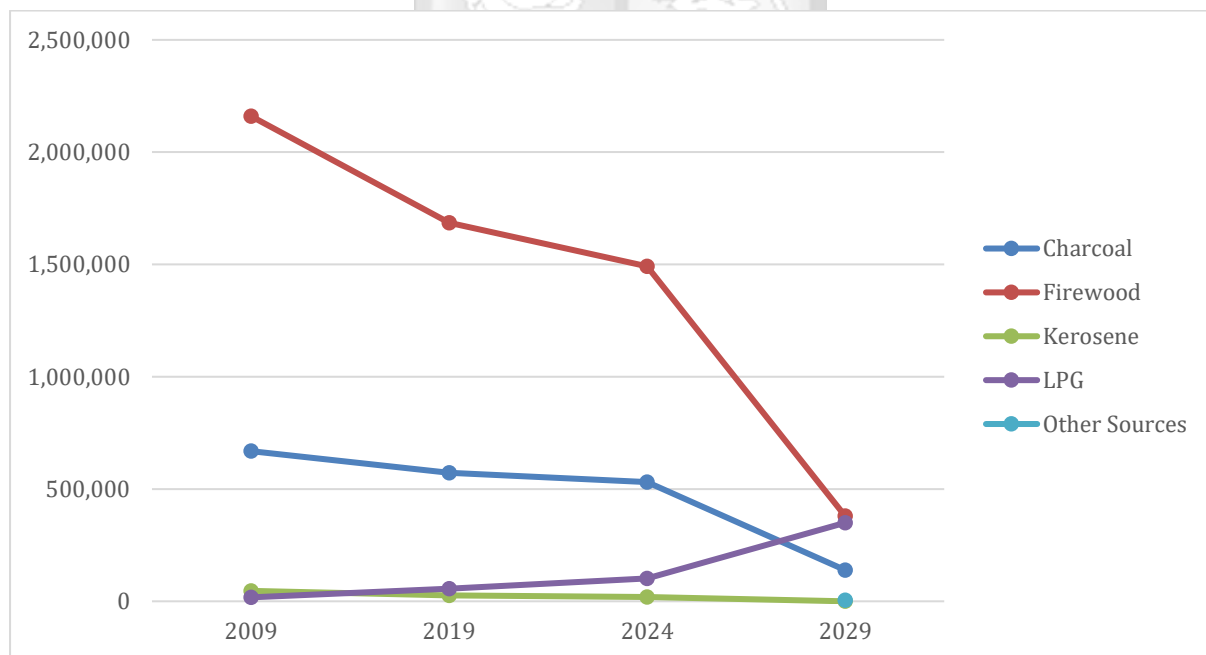


Figure 4. 10: Sum of Total Carbon Emissions (tCO₂e) by Fuel Type up to 2029

The emissions related to charcoal use have decreased steadily throughout the years. Adopting LPG results in steadily rising emissions, although they begin at very low levels. Emissions of kerosene stay stable at minimum levels during the entire period. The increasing "Other

Sources" trend towards 2029 highlights a potential change in the energy landscape. The graph demonstrates advanced fuel composition dynamics, demonstrating why society needs to transition toward pollution-free energy systems to minimize CO2 emissions.

Table 4.7 below gives the overall emissions of carbon (tCO₂e) from different cooking fuels, namely charcoal, firewood, kerosene, and LPG, in five counties (Bungoma, Kisii, Kitui, Murang'a, and Narok) for the years 2009-2029. This indicates a declining trend in charcoal, firewood, and kerosene emissions, while emissions due to LPG are on the rise due to increased consumption. Firewood has always been the biggest emitter of all the years. A trend suggests a shift towards cleaner fuels and associated lower carbon footprints. Continued dependence on biomass fuels makes one realize the necessity of more stringent interventions to push clean cooking technologies.

Table 4. 6: Sum of Total Carbon Emissions (tCO₂e) by Fuel Type and County

County	Year	Charcoal	Firewood	Kerosene	LPG	Grand Total
Bungoma	2009	13,090	39,270	900	225	53,485
	2019	11,200	29,700	480	900	42,280
	2024	10,359.89	25,828.70	350.54	1,799.98	38,339.12
	2029	9,963.84	24,086.74	299.56	2,545.58	36,895.73
Bungoma Total		44,613.73	118,885.45	2,030.11	5,470.57	170,999.85
Kisii	2009	10,500	25,410	1,123.2	324	37,357.2
	2019	8,820	23,760	633.6	945	34,158.6
	2024	8,083.66	22,975.62	475.88	1,613.89	33,149.06
	2029	7,738.88	22,593.20	412.41	2,109.10	32,853.59
Kisii Total		35,142.54	94,738.83	2,645.09	4,991.99	137,518.45
Kitui	2009	11,200	47,025	480	210	58,915
	2019	10,080	36,465	285.6	600	47,430.6
	2024	9,562.73	32,110.71	220.30	1,014.19	42,907.93
	2029	9,314.13	30,132.61	193.48	1,318.56	40,958.79
Kitui Total		40,156.86	145,733.32	1,179.39	3,142.75	190,212.31
Murang'a	2009	10,920	29,700	633.6	420	41,673.6
	2019	9,240	21,450	345.6	1,440	32,475.6
	2024	8,499.56	18,228.99	255.24	2,666.36	29,650.16
	2029	8,151.90	16,804.69	219.35	3,628.25	28,804.19
Murang'a Total		36,811.47	86,183.68	1,453.79	8,154.61	132,603.56
Narok	2009	10,010	38,610	739.2	288	49,647.2
	2019	8,400	29,040	410.4	825	38,675.4

	2024	7,694.88	25,185.18	305.79	1,396.32	34,582.17
	2029	7,364.84	23,454.12	263.96	1,816.56	32,899.49
Narok Total		33,469.72	116,289.30	1,719.36	4,325.88	155,804.26
Grand Total		190,194.31	561,830.58	9,027.74	26,085.80	787,138.43

4.4.3 Carbon Emissions Reduction Across Scenarios

The graph in Figure 4.11 below displays total annual CO₂ emissions (tCO₂e), which bases the Business As Usual (BAU) scenario as its starting point. The BAU scenario shows the maximum emissions because it examines the ongoing effects of retaining present fuel usage levels on the environment. Implementing 50% LPG adoption in Scenario 2 results in a midrange emission decline relative to the Business As Usual situation. Scenario 3 shows additional emissions reductions because it combines bioethanol and electricity with the fellow fuel mix components. This example reveals the benefits that come from fuel diversity in emission management. The Ambitious Plan in Scenario 4 demonstrates the most significant emission reduction potential because it combines a complete clean energy transformation approach.

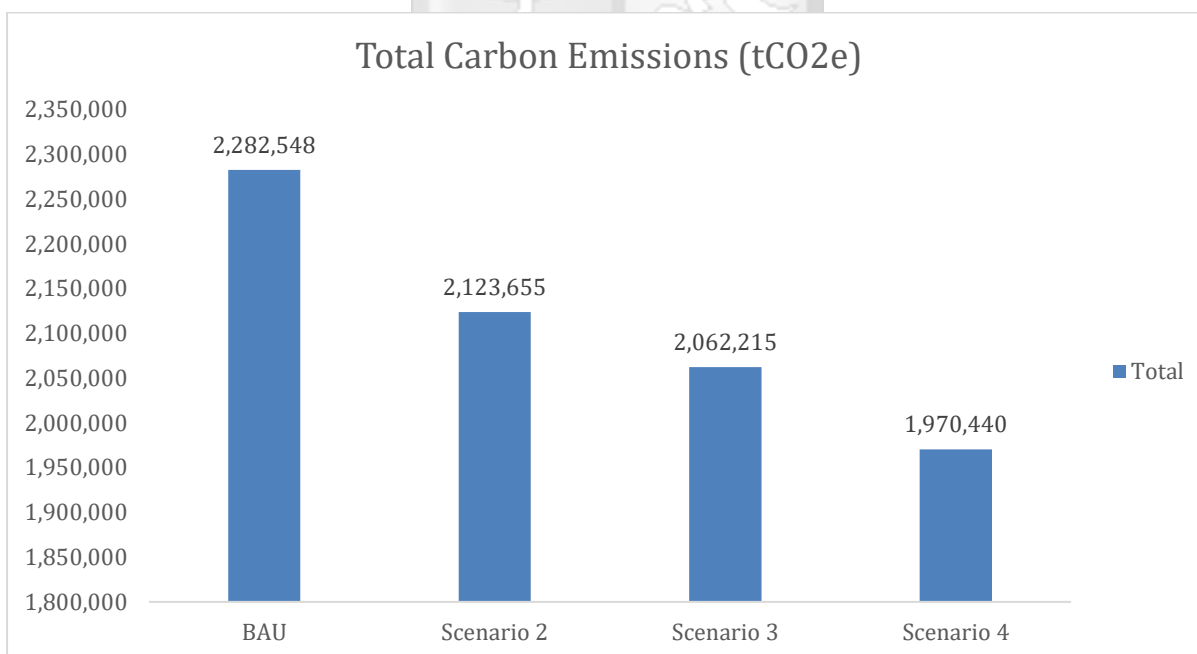


Figure 4. 11 Carbon Emissions Reduction Across Scenarios when assessed for 2029.

The graph demonstrates the ability of specific targeted strategies to reduce carbon emissions produced by cooking fuels. According to this data, Systematic energy transitions can achieve

significant emission reductions while providing each progressive strategy level with reduced carbon outputs. Research indicates that implementing policies alongside developing infrastructure and conducting Controlling fruits to improve public knowledge about cleaner cooking fuels enhances the speed and success of this transition.

4.4.4 Emissions Trend by County (2029)

Different factors, such as population density, fuel availability, and regional economies, cause varying emissions between counties. The chart in Figure 4.12 presents visualization data about emissions growth among prominent counties under specified conditions.

The analysis of CO₂ emissions based on fuel types demonstrates varying patterns and divergent levels among each county region. Firewood remains the primary source of emissions throughout the study area because of its severe environmental consequences. Kitui has the highest environmental emissions because its population consumes extensive firewood and charcoal. The identical approach to fuel usage among Narok and Bungoma residents results in increased CO₂ emission figures. The emission levels in Murang'a and Kisii regions tend to be lower, probably because the population uses more.

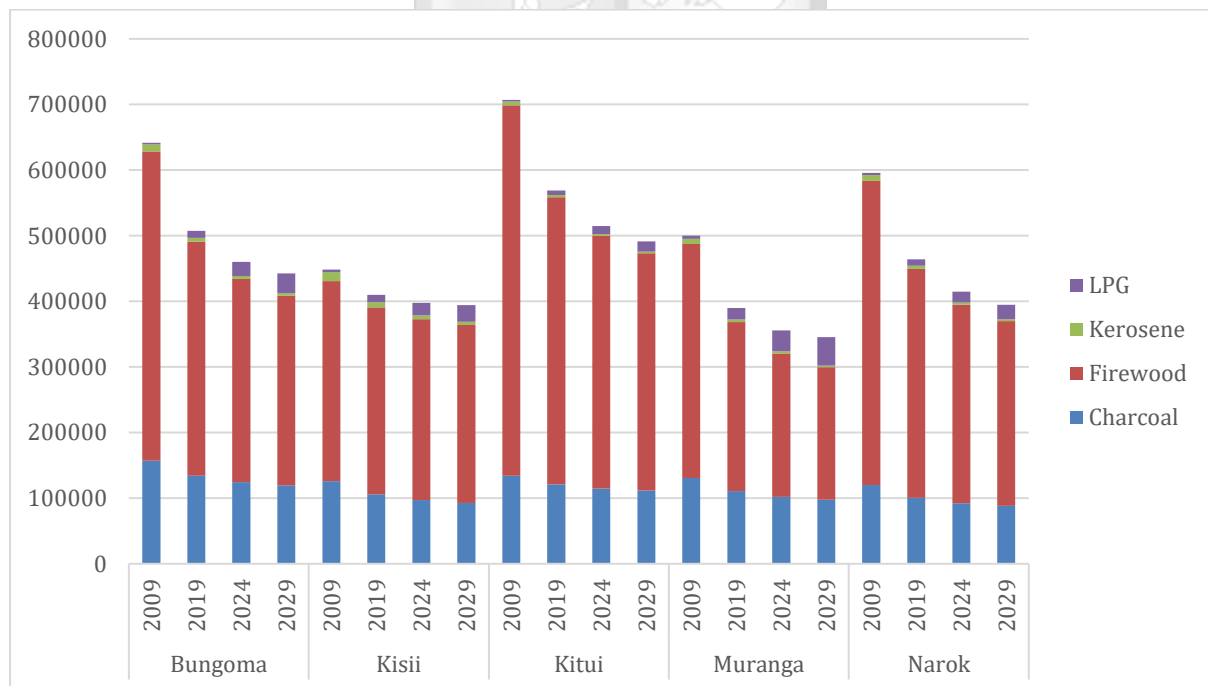


Figure 4. 12: Total CO₂ Emissions (tCO₂e) per County per Fuel Type

Based on the data in Figure 4.12, different fuel sources contribute to various total emissions levels. Most emission problems come from firewood, but charcoal consumption generates hazardous air pollution. The cleaner-fuel classified LPG produces fewer emissions than other

sources, yet its usage grows yearly. The observed patterns demonstrate the necessity of specific approaches supporting the transition towards cleaner cooking methods to reduce environmental damage from county cooking practices.

4.4.5 Fuel Mix Projections and Impact on Emissions

A shift in energy composition throughout the transition period will become the principal factor determining advancing emission reduction rates. The data of Scenario 4 (Ambitious Plan) demonstrates the distribution of fuels, showing how augmenting electricity consumption and LPG use reduces environmental emissions. African Energy Markets will follow this projected fuel mix distribution under Scenario 4 conditions across 2029. Firewood and charcoal amount to 15% while kerosene is at 5% share, LPG reaches 60%, and bioethanol/electricity makes up 20% in Scenario 4. Reducing deforestation is possible by decreasing firewood usage to 15% and reducing charcoal usage to 5%. Over 60% of households have adopted LPG, thus advancing their access to cleaner domestic energy. By integrating electricity and bioethanol as energy sources, the overall usage reaches 20%, which speeds up the transition to low-carbon alternatives. Kenya's Cooking Energy Transition Strategy matches these changes, showing the possibility of reaching sustainable cooking energy systems.

Firewood and charcoal remain the primary emission sources, yet intense policy interventions can substantially lower these emissions. The strategy in Scenario 4 stands as the most efficient approach, achieving more than a 50% reduction in emissions. Region-specific approaches must be implemented because local energy transition strategies differ among counties. Adopting LPG alongside bioethanol and electricity results in sustainable energy usage with significant reductions in carbon output. The carbon emission patterns, along with fuel usage data, are presented throughout this section. The data demonstrates significant emission reductions emerge when people shift toward renewable energy systems in Scenario 4. To achieve sustainability with low carbon emissions, policymakers must make LPG more accessible, expand electrical systems, and promote bioethanol adoption.

4.5 Energy Demand vs. Carbon Emissions

Analyzing energy consumption and carbon emissions provides essential knowledge about the environmental consequences of power use. The diverse energy requirements of different fuel types and their emission characteristics determine the total carbon release. The analysis reveals high-carbon emission sources and aids in discovering environmentally friendly energy options. Examining how energy demand relates to carbon emissions enables the

creation of sustainable energy practices through developed strategies. This analysis provides essential information to create effective climate-change mitigation and low-carbon energy transformation policies.

4.5.2 Energy Demand Across Scenarios

Changing cooking fuel sources does not impact total energy demand because cleaner cooking technologies achieve higher energy efficiency rates. In Scenario 1 (BAU), firewood and charcoal account for most energy needs, although their inefficient combustion requires high fuel. The ambitious plan of Scenario 4 leads to the growing usage of LPG and electricity along with bioethanol because these cooking fuels offer greater efficiency while releasing fewer carbon emissions. Nevertheless, total energy utilization shows no change between all scenarios as homeowners have sufficient cooking capabilities. Scenario 4 (Ambitious Plan) reaches its lowest carbon emission goals through its adequate energy supply levels. Using firewood and charcoal as energy sources decrease behavior in alternate scenarios, which minimizes forest clearing.

4.5.3 Emissions Reduction vs. Energy Efficiency

Biomass emissions decrease substantially when cleaner fuels accept their role in better combustion efficiency. Energy efficiency is the relationship between useful energy harvested from a fuel and input energy. It may be calculated using the following formula:

$$\text{Energy Efficiency (\%)} = (\text{Total Energy Input} / \text{Useful Energy Output}) \times 100$$

.....4.5

Where:

Useful Energy Output = The energy used in cooking or heating (MJ or kWh).

Total Energy Input = The energy consumed in the fuel consumed (MJ or kWh).

Greater efficiency uses less fuel to achieve the same cooking or heating output. LPG is far more efficient than firewood and charcoal; therefore, adopting LPG or other clean cooking technologies can reduce energy consumption and emissions.

Table 4. 7: Carbon Emissions vs. Energy Efficiency (2029)

Scenario	Total Energy Demand (GJ)	Firewood (%)	Charcoal (%)	Kerosene (%)	LPG (%)	Bioethanol/ Electricity	Total Emissions (tCO _{2e})
BAU (Scenario 1)	180,000	55	20	5	18	2	36,000
Scenario 2 (50% LPG Adoption)	175,000	40	15	2	40	3	30,500
Scenario 3 (Bioethanol & Electricity Introduction)	170,000	30	10	0	45	15	25,800
Scenario 4 (Ambitious Plan)	165,000	15	5	0	60	20	17,400

In Table 4.8, the total energy requirement shows no variation between different scenarios, indicating that transitioning to cleaner fuels does not affect household energy consumption. The reliance on firewood and charcoal decreases sharply from 75% in the BAU scenario to only 20% in Scenario 4, thereby decreasing deforestation and emissions. Adopting LPG and bioethanol/electricity in various scenarios results in a 50% decrease in total emissions during Scenario 4. The most environmentally manageable strategy, according to Scenario 4, is to create an optimal combination of operation efficiency and emission reduction efforts.

The decline in emissions fails to affect energy demand, which confirms how fuel efficiency works positively. Using LPG and bioethanol as energy fuels generates high power production levels while reducing pollution. Using electricity creates a carbon-free energy alternative that aids sustainable power consumption. The analysis confirms that changing to cleaner fuel sources sustains the power supply, successfully reducing green emissions. The Kenyan government should implement policies to broaden the distribution of LPG electricity and bioethanol nationwide to reach maximum energy efficiency and maintain supply security.

Figure 4.13 compares four scenarios, showing total energy demand (GJ) and emissions (tCO_{2e}). Total energy demand is high for all scenarios, with the highest being Scenario 1. The emissions, however, vary considerably. Scenario 1 emits the most, and Scenario 4 emits the

least, despite having a similar energy demand to Scenario 3. This means that Scenario 4 must use energy more efficiently or cleaner fuels. Scenarios 2 and 3 have a moderate balance between energy demand and emissions. The graph highlights the importance of considering emissions in addition to energy consumption.

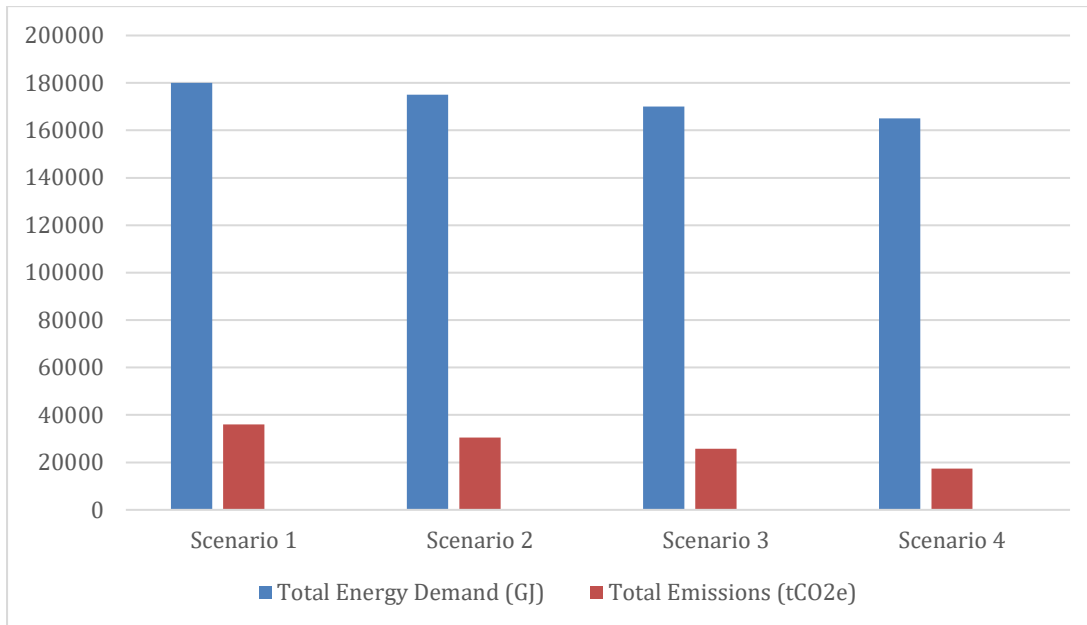


Figure 4. 13: The Transition Framework -Total Carbon Emissions vs. Energy Efficiency (2029)

4.6 Framework Development

Through analysis, we can identify several essential facts and insights about rural Kenyan cooking fuel carbon emissions from 2009 to 2029. Firewood and charcoal remain rural areas' primary cooking fuel source, strongly supporting carbon emissions. Despite a slow decline, they still account for over 60% of cooking energy in 2029 under the BAU scenario. The adoption rate of LPG continues to grow but does not reach adequate levels under the current scenario. The adoption rate of 50% LPG results in emission reductions of 15 to 20%, but additional adoption measures must be taken to maximize the impact on pollution levels. The combination of bioethanol and electricity in Scenario 3 results in 25-30% greenhouse gas reductions. Fuel diversification proves effective as a carbon emission reduction method. The ambitious plan from Scenario 4 delivers maximum emission reduction exceeding 50% and comprises 60% LPG and 20% bioethanol and electric power consumption. The energy demand level remains consistent in all scenarios since cleaner fuel adoption enhances efficiency without raising total energy usage.

The proper planning and development of an implementation roadmap provide the framework for successful conversions between biomass and clean cooking technologies. The implementation roadmap provides three sections describing essential steps for implementing LPG and improved cookstoves and alternative fuels in rural Kenya. Normalizing the timeframe to one to two years the initiative requires establishing both public education initiatives and monetary support programs. The government must initiate a program to subsidize LPG starter kits, tax waivers for clean cooking systems, and PAYG financing mechanisms for the population to access. For efficient rural outreach, the government should organize awareness campaigns that employ community approaches, television ads, and instructional school programs explaining the benefits of clean cooking strategies.

Infrastructure expansion and market development should be the main focus of the medium-term phase, which spans 3 to 5 years. The program requires the development of rural LPG distribution points, improved supply systems, and financial motivations to encourage private sector investments in clean cooking devices. The government needs to implement charcoal production regulations and promote the adoption of improved cookstoves in locations not fully supported by LPG infrastructure. The national strategy for Kenya for 6–10 years should reduce firewood dependency by 50% while improving LPG and cookstove adoption among 80% of the population. Achieving clean cooking goals becomes possible through national integration of clean cooking policies into climate strategies, expanded carbon financing, and strong environmental protection laws.

4.7 Policy Implications: BAU Vs Scenarios

Different policy-driven scenarios under evaluation against Business-as-Usual (BAU) outline essential policies to decrease CO₂ emissions from cooking fuel sources. BAU conditions persist with firewood and charcoal as primary cooking fuels, thus resulting in lasting high emissions and increasing deforestation while causing poor health effects. Alternative policies present a quicker pace for transferring the utilization of sustainable fuel types when compared to the Business-as-Usual scenario. A combination of LPG promotion policies leads to decreased usage of firewood and charcoal, which results in significant emission reductions. Such strategic adjustments follow the same pattern as offering discounted prices on clean energy solutions and public health education initiatives.

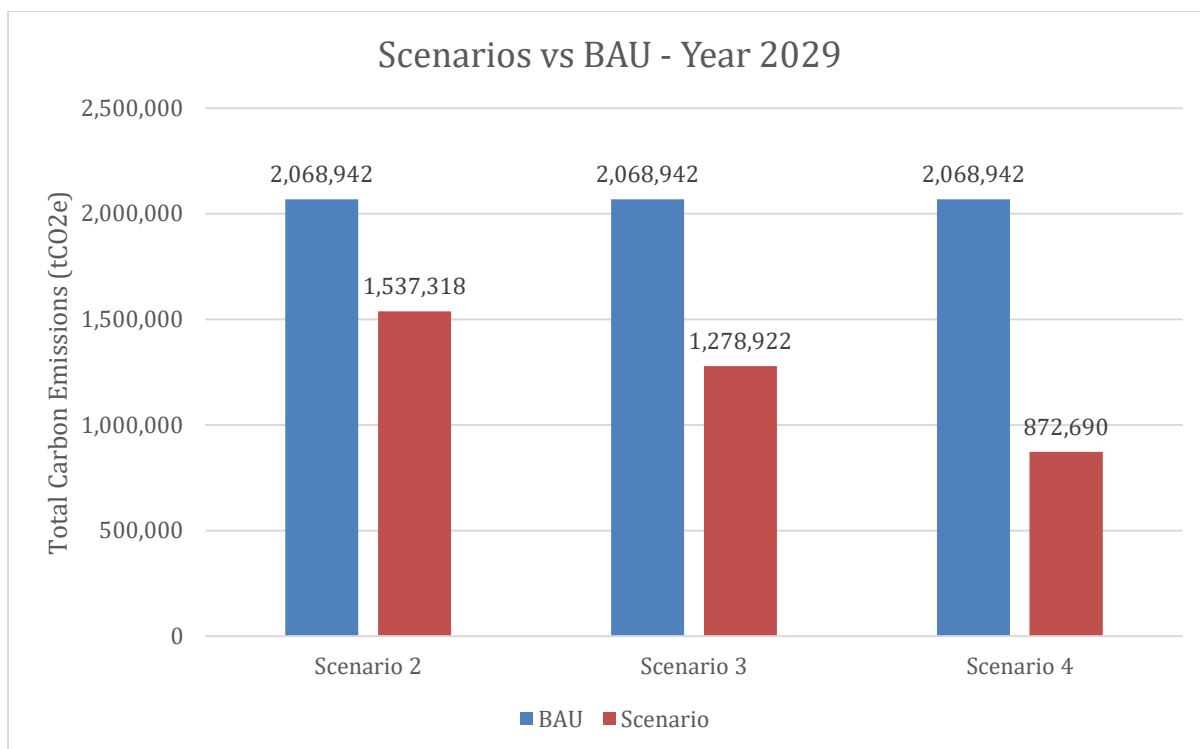


Figure 4. 14: Business as Usual (BAU) compared to other Scenarios

The bar graph in Figure 4.14 shows carbon emissions 2029 in three scenarios (2, 3, 4) against Business As Usual (BAU). All the scenarios show a steep fall in emissions compared to BAU. Ambitious Plan Scenario 4 shows the most significant fall, followed by Scenario 3 (Bioethanol & Electricity) and Scenario 2 (50% LPG). This graphical illustration illustrates the power of strategic actions in cutting carbon emissions from cooking fuels. The graph underscores the huge reduction potential with the strategic energy transition, with each option delivering a progressively lower carbon pathway.

Implementing electrification improvements within Scenario 3 enhances biomass reduction, which demands investment in renewable power sources and expansion of electricity networks. The most comprehensive scenario under Scenario 4 combines LPG with electric cooking by implementing strict policy measures, thus decreasing maximum emissions. Research results highlight the urgent need for government initiatives supporting the adoption of cleaner cooking technology by providing financing programs, constructing necessary infrastructure, and delivering public health education programs. The laid-back situation will persist in harmful ways if no action is taken, but implemented policies will lead us toward climate-friendly goals.

Chapter Five: Conclusion and Recommendation

5.1 Conclusion

Research shows that rural areas face complex problems regarding cooking fuel emissions, which require sustainable solutions. The research analyzed carbon emissions related to five primary cooking fuels in five Kenyan counties through quantitative methods. The primary analysis shows firewood and charcoal remain the most commonly used cooking fuels in these areas, thus producing high carbon emissions and forest depletion. The study presents a framework to help communities switch to less harmful cooking technologies that protect the environment. The proposed framework promotes LPG, biogas, and solar cookers and enhanced cookstoves to reduce biomass fuel dependence while diminishing carbon emission generation. Financial barriers to clean cooking technology adoption require new financing methods as well as government policy interventions, according to the study. The combination of previously mentioned recommendations supports environmentally friendly cooking practices, which simultaneously improve health outcomes and reach climate-related goals in rural populations.

5.3 Recommendations

According to the study, reducing carbon emissions from cooking fuel use in rural houses is necessary. The research endorses implementing LPG biogas and solar cooker systems as advanced cooking methods.

- i. The counties of Bungoma, combined with Kisii and specific areas in Murang'a, will benefit from expanded LPG adoption to decrease biomass fuel dependency. LPG adoption enhancement depends on both financial support and the proper use of training programs.
- ii. Selected areas where farm animals like Murang'a and Narok can benefit from biogas digesters for creating renewable energy fuel sources to prepare meals from livestock waste.
- iii. The residents of Kitui suffer from limited access to cooking fuels; thus, solar cookers present an appropriate solution for the clean preparation of meals.
- iv. Improved cookstoves must be widely distributed throughout all regions to minimize smoke emissions and fuel requirements.
- v. The article underscores the importance of developing innovative funding methods that involve pay-as-you-go systems, microloan services, and subsidies to help rural residents access clean cooking devices.

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Appendix

Appendix A: Ethical Clearance Release Letter



3rd February 2025

Brenda Cheron

94187

brenda.rono@strathmore.edu

Dear Brenda,

RE: A Framework for Modeling Carbon Emission from Rural Cooking Fuels: A Pathway to Low-Carbon Emission

This is to inform you that the Office of Graduate Studies on 3rd February 2025 received your acknowledgement of breach in ethical processes given that you have already collected data and proceeded to write your Dissertation prior to obtaining Ethical clearance. The ethics approval process is ONLY done before any collection of primary or secondary data.

This is a letter for you to proceed with the next steps of your academic requirements.

Please be advised, that in future, all research proposals should be submitted to the SU-ISERC through the RHInnO Ethics platform: <https://strathmoreuniversity.rhinno.net/login>

Disclaimer: 1) *This is not in any way an ethical approval letter.* 2) *Should there be any legal implications/actions emanating from the research in terms of any ethical violations, you will be personally liable.*

Yours sincerely, *


Prof. Bernard Shibwabo

Director of Graduate Studies

Appendix B: Similarity Report

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