

Addis Ababa University

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Modelling the interaction biomass Energy Consumption and CO_2 emission in Ethiopia.

Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Economics (Applied Economic Modelling)

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Approval Sheet

This is to certify that the thesis prepared by Yohannis Tilahun Gashaw , titled "Modelling the Interaction between biomass energy consumption and CO_2 emission in Ethiopia" and submitted to the Department of Economics, Addis Ababa University in partial fulfillment of the requirements for the Masters of Science in Economics (Applied Economic Modelling) complies with the regulations of the university and meets the accepted standards for originality and quality.

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List of abbreviations

AFREC	African Energy Commission
CLD	Causal Loop Diagram
CO_2	Carbon Dioxide
CRGE	Climate Resilient Green Economy
CSA	Central Statistics Agency
EEA	Ethiopian Economics Association
EFCCC	Enivaromant Forest and Climate Change Commission
EKC	Environmental Kuznets Curve
FAO	Food And Agriculture Organization
FDRE	Federal Democratic Republic Of Ethiopia
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GTP	Growth and Transformation Plan
NBE	National Bank Of Ethiopia
NDC	Nationally Determined Contribution
SDG	Sustainable Development Goals
SFD	Stock and Flow Diagram
UN	United Nation
UNDESA	United Nations Department of Economic and Social Affairs
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development
WB	World Bank
WBISPP	Woody Biomass Inventory and Strategic Planning Project

Abstract

Ethiopia's energy system is heavily reliant on biomass, which constitutes approximately 92.4% of the country's energy consumption and is predominantly used for cooking and heating. however, a significant contributor to the CO_2 emissions in the country. Direct and indirect emissions from the biomass use accounted for 450% of incremental emission CO_2 and 37% of total emissions. Thus, the purpose of this study is to model and evaluate the biomass energy consumption and its contribution to the CO_2 emissions. A system dynamics model that represents the biomass energy consumption and its interaction with the environment in Ethiopia has been built. The data from 2000 to 2030 from different sources. The simulated results have demonstrated that Substitution of Alternative Energy ,Biomass Use Management, Reforestation Growth, Improved Cooking Stoves and all policy scenarios combinations have a sound effect on lowering CO_2 while also improving the energy access by 40%. The results reveal that policy scenario 2, scenario 1, scenario 3 and scenario 5 characterized by stable annual production and controlled demand—can significantly limit deforestation, preserve CO_2 sinking capacity, and minimize total CO_2 emissions by 19.60%, 23.60%, 26.40% and 68.8% respectively compere to base case and scenario 4 in 2030. Policy recommendations include strengthening regulatory frameworks and promoting alternative energy sources to ensure both energy security and environmental sustainability. The study also highlights data limitations and the need for further research on spatially explicit land-use change and the socioeconomic drivers of biomass demand.

Keyword : *Biomass energy, consumption, system dynamics , CO_2 Emission, Ethiopia*

CHAPTER ONE
INTRODUCTION

1.1. BACKGROUND OF THE STUDY

Ethiopia has recognized for its significant renewable energy potential, particularly due to its vast hydropower resources, which have historically formed the backbone of the country's energy supply. However, the nation has currently faced a complex energy crisis characterized by an inadequate and unstable power supply. Approximately 90% of the population experiences unreliable electricity delivery, with rural areas particularly affected—about 60% of rural Ethiopians has faced inconsistent power access (World Bank, 2024). This energy gaps feeds a vicious cycle of poverty and underdevelopment by exacerbating environmental crises, impeding economic growth, limiting access to education, and lowering living standards.

Even though the Ethiopian government has made strides in increasing electrification projects, there are still major barriers to universal access by 2025. The nation's significant reliance on hydropower puts it at risk for energy stability issues, particularly during dry spells when there is less water available for producing electricity. By 2040, Ethiopia wants to double its hydropower capacity to 13.5 gigawatts; however, diversifying its energy sources is essential to reducing climate variability vulnerabilities (International Energy Agency, 2019). Approximately 96% of electricity is currently generated by hydropower, with only a small amount coming from other renewable sources like solar and wind. (Economic Development, Climate Change, and Energy Security, *World Bank*, 2024). This over reliance on a single energy source not only jeopardizes energy security but also constrains economic growth prospects.

In addition to these challenges, Ethiopia's energy sector suffers from inefficiencies and infrastructure limitations. Electricity distribution losses are estimated at around 20%, significantly higher than the international average of 12-13% (Japan Embassy in Ethiopia, 2024). These losses impede electric utilities' ability to deliver stable services and attract investments in renewable technologies. The government acknowledges the need for substantial investments in infrastructure to transform the power sector into a financially sustainable model (World Bank, 2024). Despite these challenges, Ethiopia possesses a wealth

of renewable resources beyond hydropower. The country has considerable geothermal potential and is actively planning to incorporate solar and wind energy into its strategy for building a more resilient and diversified energy system (International Trade Administration, 2024). By tapping into these resources, Ethiopia can reduce its dependence on biomass , which currently constitute a significant portion of energy use at the household level. The energy crisis in Ethiopia is a multifaceted issue that impacts CO2 emissions as well as the socio-economic development and environmental sustainability of the country.etween 1990 and 2017,biomass use related CO_2 emissions increased by 450%, driven by economic growth, biomass use, population expansion, and changes in the fossil fuel mix. The transport sector alone contributes 45% of fossil fuel emissions due to aging vehicle fleets and low fuel efficiency standards(World Bank, 2024, International Trade Administration, 2024).

To address these challenges, transitioning from biomass and reducing fossil fuel dependence are crucial. Strategies could include leveraging domestic natural gas reserves to displace biomass in urban industries and oil in transport, implementing distributed solar-diesel hybrid systems in off-grid areas,. The energy transition model must account for the costs of managing biomass transition timelines. System dynamics simulations can help test scenarios where biomass substitution and reduce emissions effectively. This dual approach requires simultaneous policy scenarios aiming to reduce emissions intensity by 68.8% while expanding energy access to 25% of the population by 2030. With a population exceeding 120 million—approximately 34% living below the poverty line—access to reliable energy services remains a critical challenge. Currently, about 60% of the population lacks dependable electricity access, particularly in rural areas where traditional biomass fuels account for 92.4% of the total energy supply (World Bank 2024, the International Energy Agency (IEA) 2024). This Communities that depend too heavily on biomass are caught in cycles of poverty and environmental deterioration, such as air pollution and deforestation, which both seriously jeopardize emissions (Energypedia, 2022; Woldie, 2022).

1.2. Problem Statement

In Ethiopia, The heavy reliance on biomass consumption Deforestation and CO2 emissions are the main ways that energy use for heating and cooking contributes to environmental deterioration. Due to the growing demand for energy by 30% and demand for charcoal and firewood, Ethiopia is currently experiencing a 1.5% annual rate of deforestation (Ethiopian Forestry Research Institute, Environmental Science & Policy, Hailu Kumsa, 2023). Households' heavy reliance on biomass resources, which worsens the deterioration of forest ecosystems and endangers biodiversity, makes this situation especially concerning (Ethiopian Forestry Research Institute, 2023).

The associated emissions have further exacerbated the environmental impact of biomass consumption. Depending on the type of biomass and the effectiveness of the combustion technology used, different amounts of carbon dioxide (CO2) are released during the combustion of biomass fuels. Accordingly, burning firewood releases between 60 and 100 kg of CO2 for every gigajoule (GJ) of energy produced, whereas burning charcoal releases between 70 and 120 kg of CO2 for every GJ of energy produced. The overall contribution of burning biomass to greenhouse gas emissions is still significant increase by 37% annually, even though emissions from burning animal dung are relatively lower, at around 30–50 kg CO2 per GJ. Furthermore, methane (CH4) and nitrous oxide (N2O), two strong greenhouse gases that have a greater potential to cause global warming than CO2, are released during the burning process (Hailu Kumsa, 2021).

In addition to posing immediate risks to environmental sustainability, the twin problems of deforestation and emissions from biomass consumption also impede Ethiopia's larger development objectives. Addressing these environmental issues is crucial as the nation works to increase economic growth and raise the standard of living for its nations.. Transitioning to more sustainable energy sources and enhancing the efficiency of biomass combustion are critical steps necessary to mitigate these adverse impacts and promote a healthier environment.

The heavy reliance on biomass fuels in Ethiopia contributes significantly to ongoing deforestation and CO_2 emissions, necessitating urgent action to transition toward sustainable energy alternatives and improve combustion practices. Failure to address these issues will perpetuate cycles of environmental degradation and hinder progress toward sustainable

development objectives. Addressing these challenges through a transition to alternative energy sources is crucial for achieving environmental sustainability and reducing CO2 emissions. Thereof, this study aims to model the transition to alternative energy using a system dynamics approach. This approach enables the analysis of interactions between biomass energy consumption, policy interventions, and environmental impacts over time. By simulating alternative policy options, this research has provided valuable insights for decision-makers on strategies to reduce carbon emissions and promote a sustainable energy future in Ethiopia.

1.3. Research question

The study used a system dynamics modelling approach to assess the interaction between the biomass energy consumption, environment and emission, specifically the contribution to the Co2 emission.

- ✓ How does the biomass energy consumption interact with the deforestation, CO2 emission?
- ✓ How does transition from biomass energy consumption to less CO_2 intensive alternative energy influence the level of Co2 emissions?
- ✓ What are the potential benefits of increasing investments in less CO_2 intensity alternative energy?

1.4. Objectives of the Study

1.4.1. General objective

The general objective of this study to evaluate the interaction between the biomass energy consumption and its carbon emission in Ethiopia.

1.4.2. specific objective

- ✓ To evaluate the interactions of biomass energy consumption, deforestation and CO_2 emissions and sustainable energy futures in Ethiopia.
- ✓ To transition from biomass energy consumption to less CO_2 intensive alternative energy to influence the level of Co2 emission.
- ✓ To identify the potential benefits of increasing transition to less CO_2 intensity alternative energy.

1.5. The significance of study

The significance of studying would contribute to the ongoing national policy on the environment, energy access, and CO_2 emissions reductions on the prospects of achieving an efficient energy access and reducing greenhouse gas (GHG) emissions. The study also supports Ethiopian household and other stakeholders regarding the environmental effects and Furthermore, it informs the mitigation and options for less CO_2 intensity energy transition in Ethiopia is underscored by its potential to drive economic growth, enhance energy access, and mitigate environmental impacts According to the International Trade Administration (2022), Ethiopia's abundant alternatives energy resources could significantly contribute to its sustainable development, especially as energy demand demand grows by 30% annually. USAID (2022) highlights that investments in less CO_2 intensity energy have been key drivers of environment , Energy and Economic Growth program (2022) emphasizes the need for policy reforms to expand energy access on improve system of environment efficiency sustainable development.

1.6. The scope of the study

The geographical scope of the study is limited to biomass energy use in Ethiopia. The study focuses on the interplay between biomass energy consumption and environment, particularly in the context of the country's significant energy poverty, where over 60% of the population lacks reliable electricity access (Hailu & Kumsa, 2021). It will analyze the environment impacts of transitioning to other alternative energy sources, including potential redaction CO_2 emissions. A system dynamics model was used in the study's methodology to evaluate the complexity and dynamics of the interaction between the biomass energy consumption and its contribution to the carbon emission. also assessing environmental sustainability by evaluating the consequences of current reliance on biomass energy and its contribution to air pollution and deforestation (Woldie, 2022; Dingeto & Kumsa, 2021). biomass consumption associated with indoor air pollution (Woldie, 2022). Ultimately, the research aims to provide actionable insights for policymakers and stakeholders to foster a sustainable energy future in Ethiopia.

1.7. **Outline of the study**

The study is structured into six chapters. The chapter one presents the topic, outlines the research problem, and defines the objectives of the study, while the second chapter offers a concise overview of biomass energy and its environmental effects within the country. The third chapter reviews relevant literature, highlighting both the model and empirical studies. The fourth chapter concentrates on the data related to the models and the methodological aspects involved. In chapter five, the results of various policy scenarios are discussed and analyzed for future policy implications. Lastly, chapter six concludes the study, detailing the implications of the findings for policy and identifying limitations for further research.

CHAPTE TWO

REVIEW OF LITERATURE

2. REVIEW OF LITERATURE

This chapter presents a comprehensive review of both theoretical and empirical literature on biomass energy, its relationship with greenhouse gas (GHG) emissions, particularly CO2, and the transition to alternatives energy using a system dynamics approach. The review also proposes a conceptual framework to address the identified challenges.

2.1. Review of Theoretical Literature

2.1.1. Overview of Ethiopia's Energy Sources

Ethiopia's energy sector is dominated by biomass and waste, which account for approximately 92.4% of the total energy supply, followed by oil (5.7%) and hydropower (1.6%) world bank (202s2). Biomass is primarily used in rural households for cooking and heating, contributing significantly to deforestation and environmental degradation. Fossil fuels are predominantly consumed in transportation and manufacturing sectors, while hydropower remains the main source of electricity generation. However, reliance on hydropower makes the country vulnerable to climate variability, particularly droughts, which jeopardize energy security world bank(2022)

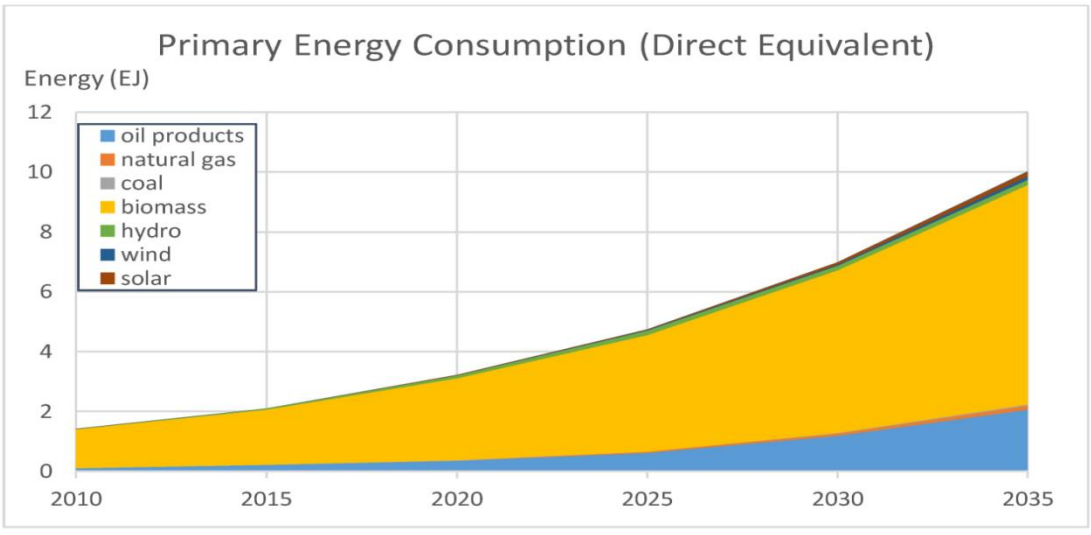


Figure 1. Ethiopian primary energy consumption patterns

2.1.2. Overview of Ethiopia's biomass energy

Ethiopia's energy sector is predominantly reliant on biomass, which accounts for approximately 90% of the country's total primary energy consumption. Biomass sources include firewood, charcoal, crop residues, and animal dung, with rural households relying heavily on traditional three-stone fires for cooking due to low electrification rates. Urban households have shown a slight shift towards electricity for cooking in recent years, but biomass remains the dominant energy source across rural (99%) households. This heavy reliance on biomass has contributed to deforestation, forest degradation, and CO2 and greenhouse gas emissions from land-use changes SEI (2013) and AFREC (2025).

The biomass energy potential in Ethiopia is substantial, with an estimated 2,955 petajoules (PJ) of annual energy capacity derived from biomass residues. Forest residues contribute the largest share at 56%, followed by crop residues (28%), livestock waste (15%), and municipal solid waste (0.33%). This potential could generate approximately 819.7 terawatt-hours (TWh) of electricity annually—significantly exceeding the country's total energy consumption in 2020. However, realizing this potential requires integrated development research and improved feed stock Amsalu (2023).

Ethiopia has difficulties using biomass in a sustainable way. Traditional inefficient methods, like producing charcoal in earth-mound kilns, waste a lot of resources and harm the environment. Increased demand for biomass fuels has also resulted in less access to wood fuels, especially in rural areas, and overexploitation of forests. Inadequate planning and weak institutional frameworks have impeded the efficient development of Ethiopia's biomass resources, according to the 2011 Biomass Energy Strategy Ethiopia report.

Alternative energy pathways have been suggested as a solution to these problems. These include expanding access to alternative energy sources, encouraging the use of efficient cookstoves, and switching to biogas and bioethanol. In comparison to baseline projections, biomass use would decline by 68.8% by 2030 under a high-shift scenario modeled by SEI (2013), which would result in a significant reduction in CO2 emissions.

2.1.3. Relationship between Energy Crisis and CO_2 Emissions

The Ethiopian energy crisis is inextricably linked with heightened GHG and CO2 emissions. As one of the lowest per capita CO2 emitters in the world, Ethiopia has also seen significant growth in absolute emissions due to economic growth, population and CO2 growth. Between 1990 and 2017, CO2 emissions increased by 450%, driven by economic growth (52%), population growth (43%), and biomass consumption (40%) The Environmental Kuznets Curve (EKC) theory explains the phenomenon, positing that pollution at first grows as economic growth is experienced but later reduces as economies mature and adopt sustainable practices emissions caused by economic growth stabilize in the long term(EKC).

The connection between energy crises and CO2, GHG emissions is exploited very profoundly. Nations inevitably utilize biomass fuels during energy crises, which implies that additional biomass fuels are converted to additional CO2 and GHG emissions. For instance, the latest European energy crisis caused by the Ukrainian war enhanced dependency on biomass, coal, and oil, thus heightening the production of emissions (Farghali et al., 2022; Chen et al., 2022). The combustion of these biomass fuels generally produces a large quantity of CO2, methane, and other greenhouse gases, adding to global warming and contributing to environmental degradation (Worlanyo and Jiangfeng, 2021).

It is of utmost importance in terms of economic and environmental concern. The energy crisis ties with both environmental and economic crisis, making what is popularly called a "triple trap," where these issues feed into one another (Rifkin, 2021). In its report, the Stern Report said that there could be loss due to climate change and that avoiding such serious damages requires a transition to a low-carbon economy (Stern Report, 2022). In addition, the global campaign to reduce carbon emissions has also resulted in the recent energy crises and, therefore, resoundingly reiterated the task of balancing energy demands with environmental objectives (Ozili and Ozen, 2023).

Solutions can be increasing energy efficiency and a move towards alternative energy sources. According to previous studies, environmental taxes have an inverse relationship with CO2 and GHG emissions. It indicates policy interventions also reduce emissions (Frontiers in Environmental Science, 2023). There are also some green counterparts, including biomass boilers, hybrid heat pumps, and other forms of solar systems, promising a much lower reliance on biomass fuels (Chen et al. 2022; Farghali et al. 2022). To work towards achieving carbon neutrality by mid-century, sustained efforts in reducing global energy demand and

adopting cleaner energy technologies must be made, following promises listed out in the Paris Agreement (Farghali et al., 2022).

2.1.3.1. Relationship Between Energy Crisis and CO_2, GHG Emissions in Ethiopia.

Ethiopia's energy landscape is dominated by hydropower, solar, wind and geothermal energy sources , which accounts for over 90% of its electricity generation, positioning the country as a leader in renewable energy in Africa (Ethiopia Energy Transition and Human Rights Scoping, 2023; Renewable Energy in Ethiopia, Wikipedia). However, this reliance on hydropower makes the energy supply vulnerable to droughts, highlighting the need for diversification (PVKnowhow, 2022; Africa Energy Portal, 2018). Solar energy has emerged as a promising alternative, offering a sustainable solution to energy challenges and supporting Ethiopia's climate goals (Africa Energy Portal, 2018; PVKnowhow, 2022).

Ethiopia's transition to solar energy is closely tied to its climate objectives. Ethiopia wants to become carbon neutral by 2030 and cut CO2 and other greenhouse gas emissions as a signatory to the Paris Agreement (Africa Energy Portal, 2018; PVKnowhow, 2022). The nation is making significant investments in solar projects, including a $300 million project to produce 300 megawatts of solar power, which helped to lower CO2 and GHG emissions and significantly contribute to renewable energy goals (Africa Energy Portal, 2018; PVKnowhow, 2022). By expanding access to energy, boosting regional economies, and advancing healthcare services, this move to alternative energy not only slows down climate change but also advances sustainable development (Africa Energy Portal, 2018).

Wind, solar, and geothermal energy are all part of Ethiopia's varied renewable energy portfolio, which has the capacity to generate more than 60,000 megawatts of energy (Renewable Energy in Ethiopia, Wikipedia; UNDP, 2025). The government is actively working to develop its energy sector further through strategic plans and ongoing initiatives, aiming to become a renewable energy hub in East Africa by ensuring access to affordable, clean, and modern energy for all citizens by 2040 (Sustainable Energy Transitions, EFD Initiative). This transition is crucial for addressing energy access challenges, enhancing resilience against climate change, and driving economic growth (Africa Energy Portal, 2018; PVKnowhow, 2022).

Energy crises, countries may shift towards alternative non to ensure energy security. The shift towards less carbon-intensive energy and decrease CO_2 and GHG emissions, undermining efforts to combat climate change The burning biomass releases large amounts of CO2, a major greenhouse gas, contributing significantly to global warming. The emissions from biomass are the dominant cause of global warming Rising GHG emissions exacerbate climate change, leading to more extreme weather events, sea-level rise, and biodiversity loss Energy crises can lead to economic instability due to high energy costs and inflation(Africa Energy Portal, 2018; PVKnowhow, 2022). This instability can hinder investments in renewable energy and energy efficiency, further entrenching biomass dependence geopolitical dimensions of energy crises, such as dependence on specific energy sources or suppliers, can influence energy policy decisions and affect GHG emissions. To mitigate climate change and reduce CO_2 and GHG emissions, there is a pressing need to transition from biomass to less carbon-intensive biomass energy sources. This transition requires significant investment and policy support.

2.1.3.2. **Relationship Between biomass Energy and CO_2, GHG Emissions in Ethiopia.**

The relationship between biomass energy and greenhouse gas (GHG) emissions in Ethiopia is significant, given that biomass constitutes over 90% of the country's primary energy supply. As of 2015, biomass accounted for approximately 45.8 million tons of oil equivalent (MTOE) out of a total energy consumption of 49.9 MTOE, highlighting its critical role in the energy landscape, Assessment of the Trends of GHG (2015). The reliance on biomass, primarily in the form of firewood and dung, has serious implications for GHG emissions, particularly CO_2. The combustion of biomass releases carbon dioxide into the atmosphere, contributing to climate change. In Ethiopia, it is estimated that indoor air pollution from biomass use causes high CO_2 emissions and over 72,400 deaths annually, underscoring the health impacts associated with this energy source,Assessment Of The Trends Of GHG (2015)..

The deforestation rate in Ethiopia has been concerning, with approximately 140,000 hectares lost annually in the early 2010s due to unsustainable harvesting practices and agricultural expansion. By 2020, this rate had slightly declined to around 100,000 hectares per year due to some reforestation efforts and policy changes aimed at sustainable forest management. Looking ahead to 2030, it is projected that the deforestation rate could further decrease to between 50,000 and 70,000 hectares annually if effective interventions are implemented. However, the sustained application of biomass as fuel poses grave challenges to

environmental sustainability and climatic resilience in Ethiopia. Nevertheless, forests have mostly disappeared over the past century, declining from about 35% of covered land to less than 15% now Assessment of The Trends of GHG (2015).

Population increase and also higher demand for biomass fuels are the leading causes of deforestation. Based on the Woody Biomass Inventory and Strategic Planning Project (WBISPP), there are potentially sufficient woody biomass supplies across the country, but due to improper use of the forests at the local level, acute shortages prevail (Amsalu, 2023). This still drives greater environmental degradation and increases GHG emissions since forests are significant carbon sequestration sources. The Ethiopian government has recognized these issues and will seek to reduce them by different avenues. The Biomass Energy Strategy makes provision for increased efficiency in the use of biomass and reduced reliance on traditional fuels by encouraging the dissemination of more efficient cooking stoves (Seboka et al., 2022).

This strategy is aware of the need for collaborative efforts in its management of biomass resources sustainably and seeking ways to reduce GHG emissions. On the other hand, Ethiopia's climate-resilient development vision by 2025 entails integrating renewable energy sources into its energy mix, implying the potential of reducing dependence on biomass and associated emissions (Amsalu, 2023). The energy from biomass is a significant source of Ethiopia's energy supply, but through deforestation and low combustion efficiency, its utilization is linked with significant GHG emissions. Averting these through improved management practices and alternative energy sources is crucial in minimizing the climate change effects as well as enhancing the health of the people in the country.

2.1.4. Alternative Energy Transition

Ethiopia is undergoing a historic transition from its Climate Resilient Green Economy (CRGE) vision to renewable energy. Ethiopia is going through an energy transition, with a particular emphasis on alternative sources like solar energy, to diversify the energy mix and lessen dependency on biomass. The country is richly endowed with massive solar energy potential, with 5.5 to 6.5 kWh/m²/day average annual solar irradiation, and hence turning out to be a significant pillar of its renewable energy strategy. The government has heavily invested in solar projects, including a $300 million initiative to generate 300 megawatts of solar energy. Although hydropower accounts for over 90% of Ethiopia's electricity, its

vulnerability to climate variability has necessitated diversification. With the National Electrification Program launched in 2017, Ethiopia targets reaching universal access to electricity between 2030 and 2040, while off-grid solar technology covers 35% of the population, primarily the rural areas where at present 5% have electricity access.

To enable this transition, initiatives such as Encouragement of tax exemption for solar materials and public-private partnerships have been launched by the Ethiopian government to enhance attractiveness for investments. Recent advances such as a Memorandum of Understanding with the African Trade Insurance Agency are meant to usher in foreign investment in the area of renewable energy. This transition also aligns with Ethiopia's Paris Agreement climate goals, including reducing greenhouse gas emissions and achieving net carbon neutrality by 2030. As about 85% of households in rural areas continue to depend on biomass for cooking, raising access to sustainable and clean energy is crucial to improve health outcomes and minimize deforestation.

Ethiopia's energy revolution has nothing to do with responding to domestic demand but being the renewable energy giant of East Africa. By harnessing its abundant renewable resources and forging international partnerships, Ethiopia is laying the foundation for a cleaner, more inclusive energy future that fosters economic growth, environmental conservation, and improved livelihoods for its people.

2.1.5. System Dynamics Approach

System dynamics is a powerful approach in complex systems analysis via the comprehension of various subsystems and processes interaction over time. In the transitions in biomass energy, system dynamics aids policymakers in balancing the effects of various policies and scenarios and resolving the intermittency challenge of renewable energy sources like hydropawor, geothermal, wind, and solar (Watson et al., 2022; Saavedra et al., 2018). This approach allows experimentation with multiple futures for energy and allows decision-makers to test and adjust their strategies. System dynamics models can be used in energy resource sustainability analysis by examining determinants like the energy return on energy investment (ERoEI), the net energy obtained from an energy source (Bunyui Manjong, 2018). These models can simulate dynamic evolution of ERoEI over time and how renewable energy sources like hydropawor, geothermal, solar and wind become increasingly probable as biomass gets exhausted (Bunyui Manjong, 2018). System dynamics has been employed to

evaluate the impact of renewable energy policies on energy security and dependency in Finland and other countries (Aslani et al., 2013).

The system dynamics approach possesses some strengths, including the ability to model long-term dynamics and simulate policy intervention impacts on energy transitions (Aslani et al., 2013; Saavedra et al., 2018). However, challenges accompany the need to reconcile economic, social, and environmental goals throughout transition, so that transition pathways are equitable and sustainable (Building the Bridge, 2024). In addition, system dynamics models must be capable of reflecting technology enhancement and energy demand evolution so that they can yield realistic forecasts and policy recommendations (Building the Bridge, 2024).

interactions between different energy sources, policy interventions, and environmental impacts over time. With this approach, policymakers can test different alternatives and come up with the optimal strategy to transition to biomass and cut down GHG emissions world bank(2022).

2.2. Review of Empirical Literature

2.2.1. Energy-Related CO2 Emissions in Ethiopia

Empirical studies have identified some of the most significant determinants of energy-related CO2 emissions in Ethiopia. A decomposition analysis using the Kaya identity and Logarithmic Mean Divisia Index (LMDI) identified population growth, oil, fossil fuel and biomass mix as the principal drivers of CO2 emissions, while energy intensity has served to reduce these emissions (MDPI, 2020). The study highlighted that between 1990 and 2017, the economic effect accounted for 52%, population effect for 43%, biomass for 40% of the emissions growth, while energy intensity improvements reduced emissions by 49%. the study explored the relationship between biomass energy consumption and CO2 emissions in Ethiopia. A study found that while there is a significant contribution of modern energy consumption to CO2 emissions, the long-run relationship between energy consumption and emissions is strongly significant (Endeg Tekalegn, 2016). This suggests that biomass, which dominates Ethiopia's energy mix, contributes more to CO2 emissions compared to fossil fuels like coal, oil, and natural gas.

Ethiopia's CO2 emissions from fuel combustion have increased significantly over the years. In 2022, energy-related CO2 emissions were reported at 15 Mt, representing a 357% increase

since 2000 (IEA, 2022). The country aims to reduce its GHG emissions by 14% by 2030 compared to which could be increased to 68.8% with international support (Enerdata, 2023).The majority of Ethiopia's CO2 emissions come from the burning biomass in the energy sector (IEA, 2022). However, the agriculture, forestry, and land-use (AFOLU) sector is the largest contributor to total GHG emissions, with emissions reaching 335 Mt in 2018, compared to 12.6 Mt from the energy sector (Enerdata, 2023). the need for comprehensive strategies addressing both energy and non-energy sectors to effectively reduce overall emissions.

Agriculture, energy sectors and deforestation are the largest contributors to Ethiopia's GHG emissions, accounting for over 85% world bank (2022). The heavy reliance on biomass exacerbates deforestation and air pollution, leading to severe public health risks. Empirical studies suggest that Ethiopia needs to focus on reducing emission intensity and the share of biomass fuels in its alternatives energy mix to achieve its low-carbon economy goals (MDPI, 2020). Promoting energy-efficient technologies and expanding alternatives energy sources like solar and wind can help mitigate emissions growth while supporting economic development (Enerdata, 2023). Additionally, international support is crucial for enhancing the ambition of Ethiopia's emission reduction targets, potentially leading to a more significant reduction in GHG emissions by 2030 (Enerdata, 2023).

2.2.2. Impact of alternatives Energy Transition

Ethiopia's transition to renewable energy is expected to have a profound impact on its economy and environment. Ethiopia's energy system to one dominated by solar PV, complemented by wind energy and hydropower, is not only technically and economically feasible but also offers the least cost option with the greatest societal welfare benefits (Just Transition for All, 2021). This transition aligns with Ethiopia's commitment to achieving 100% renewable energy by 2030, which will propel its economy forward and ensure energy independence (IRENA, as cited in Ministry of Water and Energy, 2024). The expansion of renewable energy sources like solar and wind will enhance energy access, particularly in rural areas where biomass fuels are prevalent, thereby improving living standards and supporting sustainable development (Africa Energy Portal,; EFD Initiative,).

The socio-economic benefits of this transition are significant. Renewable energy projects can stimulate local economies by creating jobs and improving energy services, enhancing

educational opportunities and healthcare services (Just Transition for All, 2021). Ethiopia's renewable energy strategy also includes regional integration, with plans to export electricity to neighboring countries like Kenya, Djibouti, and others, which not only supports economic growth but also contributes to regional peace and security (Ministry of Water and Energy, 2024), challenges remain, including the need for robust financing mechanisms and policy frameworks to support the transition (UNDP, 2025). Despite these challenges, Ethiopia's commitment to renewable energy positions it as a leader in sustainable development in Africa, with significant potential for environmental stewardship (UNDP, 2025)

Table 1. Summary of reviewed study

Title of the Study Reviewed	Author(s)	Publication Details	Objective of the Study	Scope/Spatial Coverage	Major Results/Findings
1. Bioenergy Potential from Crop Residues in Ethiopia	T. Amsalu	Energy for Sustainable Development, 2023	Quantify crop residue biomass potential and identify gaps in decentralized energy systems.	National (Ethiopia)	- Annual crop residue potential: 69,569–105,522 Kt.-Recommends decentralized bioenergy policies.
2.Forest Residues as a Sustainable Energy Resource in Ethiopia	G. Tadesse & M. Kebede	Renewable Energy, 2022	Assess forest residue availability and bioenergy feasibility.	Oromia and Amhara regions	-Forest residues contribute 56% of Ethiopias 2955 PJ/year bioenergy potential. -
3.Livestock Waste-to-Biogas: Opportunities in Rural Ethiopia	D. Abebe	Biomass and Bioenergy, 2021	Evaluate biogas potential from livestock manure.	SNNP Region	Livestock manure could meet 15.36% of Ethiopias bioenergy demand. -Highlights inhibition risks in anaerobic digestion.
4.Ethiopia Biomass Energy Dependency and Deforestation	K. Hailu	Environmental Science & Policy, 2023	Link biomass use to deforestation rates and GHG emissions.	National (Ethiopia)	1.5% annual deforestation rate driven by biomass demand. -Direct CO2 emissions: 60120 kg/GJ from biomass combustion.
5.Solar Mini-	S.	Energy	Analyze solar	Afar	-Solar mini-grids

Grids and Biomass Reduction in Rural Ethiopia	Mohammed	Policy, 2024	adoption impacts on biomass dependence.	Region	reduced firewood use by 40% in pilot communities. -Cost recovery challenges persist.
6.Ethanol Cooking Project: Lessons from Ethiopia	M. Alemu et al.	Sustainable Energy Technologies and Assessments, 2025	Assess scalability of ethanol cookstove programs.	Addis Ababa and Oromia	-Ethanol adoption reduced household emissions by 55%. - Limited feedstock availability constrains expansion.
7.GIS-Based Biomass Resource Mapping in Ethiopia	A. Tesfaye	Applied Geography, 2022	Map biomass availability using geospatial tools.	National (Ethiopia)	- Identified high biomass potential in southwestern Ethiopia. - Calls for spatial targeting of bioenergy projects.
8.Urbanization and Biomass Demand in Ethiopia	L. Assefa	Urban Studies, 2023	Model urbanizations impact on biomass energy demand.	Addis Ababa, Dire Dawa, Mekelle	- Urban biomass demand grows 8% annually. - Transition to LPG in cities reduces deforestation pressure.
9.Gender Impacts of Biomass Collection in Ethiopia	E. Berhane	World Development, 2021	Analyze gendered time burdens of biomass collection.	Tigray Region	- Women spend 12 to 15 hours/week collecting firewood. - Clean energy adoption could save 500 hours/year per household.
10.Hydropower-Biomass Synergies in Ethiopia	Y. Mulugeta	Energy Strategy Reviews, 2024	Explore hybrid energy systems combining hydropower and biomass.	Blue Nile Basin	- Hybrid systems could reduce grid instability. - Requires coordinated policy frameworks.
11.Charcoal Production and Land Degradation in Ethiopia	B. Teshome	Land Degradation & Development, 2022	Link charcoal production to soil erosion and carbon loss.	Somali Region	- Charcoal production reduces soil organic carbon by 30 to 40% in arid zones.
12.Ethiopias LT-LEDS Pathway: Biomass Transition Scenarios	Ministry of Environment	Ethiopias LT-LEDS Report, 2025	Model emission pathways under biomass transition strategies.	National (Ethiopia)	- Modern bioenergy adoption could cut emissions by 25% by 2030. - Aligns with NDC targets.
13.Biogas Adoption	T. Girma	Renewable and	Identify socio-technical barriers	Amhara Region	- High upfront costs (70% of households)

Barriers in Rural Ethiopia		Sustainable Energy Reviews, 2023	to biogas dissemination.		and lack of maintenance skills (45%) are key barriers.
14.Air Quality Benefits of Clean Cookstoves	A. Demisse	Environmental Health Perspectives, 2022	Measure health impacts of transitioning to clean cookstoves.	(SNNP) Region	- Reduced respiratory illnesses by 35% in households using biogas.
15.Ethiopias Renewable Energy Investment Trends	World Bank	World Bank Energy Sector Report, 2024	Evaluate renewable energy financing mechanisms.	National (Ethiopia)	- $2.1 billion invested in renewables (2020–2024). - Biomass receives <10% of total funding.
16.Forest Restoration and Bioenergy Synergies	F. Worku	Forest Ecology and Management, 2023	Assess reforestation potential linked to biomass reduction.	Bench Sheko Zone	- 20% reduction in biomass use could enable 150,000 ha reforestation by 2030.
17.Ethiopias Ethanol Cooking Program: Equity Implications	H. Ali	Energy Research & Social Science, 2025	Examine equity gaps in ethanol stove distribution.	Oromia and Sidama Regions	- Urban households adopt ethanol stoves 3x faster than rural. - Subsidies critical for low-income access.
18.Climate Finance for Bioenergy in Ethiopia	UNDP	UNDP Policy Brief, 2023	Analyze climate funding flows for bioenergy projects.	National (Ethiopia)	- Only 12% of climate finance targets bioenergy. - Recommends leveraging carbon markets for biogas.
19.Drought Impacts on Biomass Availability	S. Taye	Climate Risk Management, 2024	Model drought risks to biomass supply chains.	Afar and Somali Regions	- Prolonged droughts reduce biomass availability by 20 to30%. - Diversifying energy sources is critical for resilience.
20.Economic Feasibility of Community Biogas Plants	G. Mekonnen	Energy for Sustainable Development, 2024	Evaluate cost-benefit ratios of communal biogas systems.	Amhara and Tigray Regions	- Payback period: 5 to 7 years for medium-scale plants. - Community ownership models improve sustainability.

2.3. Conceptual Framework of study

The proposed conceptual framework focused on addressing Ethiopia's energy crisis by alternative energy transitions, particularly solar energy to reduce biomass energy and

emission intervention mechanisms with alternative energy transitions, particularly solar energy. This framework emphasizes the urgent need to transition away from traditional biomass, which currently accounts for about 92.4% of the country's energy consumption, predominantly in rural households. The reliance on biomass not only contributes to greenhouse gas emissions but also exacerbates environmental issues such as deforestation and indoor air pollution. The framework employs a system dynamics approach to model the interactions between biomass use, CO_2 emissions, and the adoption of alternative energy. By developing a causal loop diagram (CLD), it identifies key leverage points for policy interventions that could facilitated this transition. For instance, increasing solar and wind capacity can enhance rural electrification rates, thereby reducing dependence on biomass fuels.

Scenarios modeled within this framework suggest that significant reductions in GHG emissions could be achieved—by 19.60%, 23.60%, 26.40% and 68.8% respectively compere to base case and scenario 4 by 2030—if effective policies are implemented to combination of all policy scenario, promote alternative energy transitions , efficiency management of biomass use, adoptions of improved overcooks and grow in the reforestation scenarios . Additionally, the integration of the scenarios, can further mitigate emissions while providing health benefits to households reliant on traditional biomass fuels.

This framework aligns with Ethiopia's Climate-Resilient Green Economy (CRGE) strategy and the National Electrification Program, which aim to enhance energy access and support sustainable development. By fostering a diversified energy portfolio that includes solar, wind, and improved biomass technologies, Ethiopia can not only address its immediate energy needs but also pave the way for long-term economic resilience and environmental sustainability.

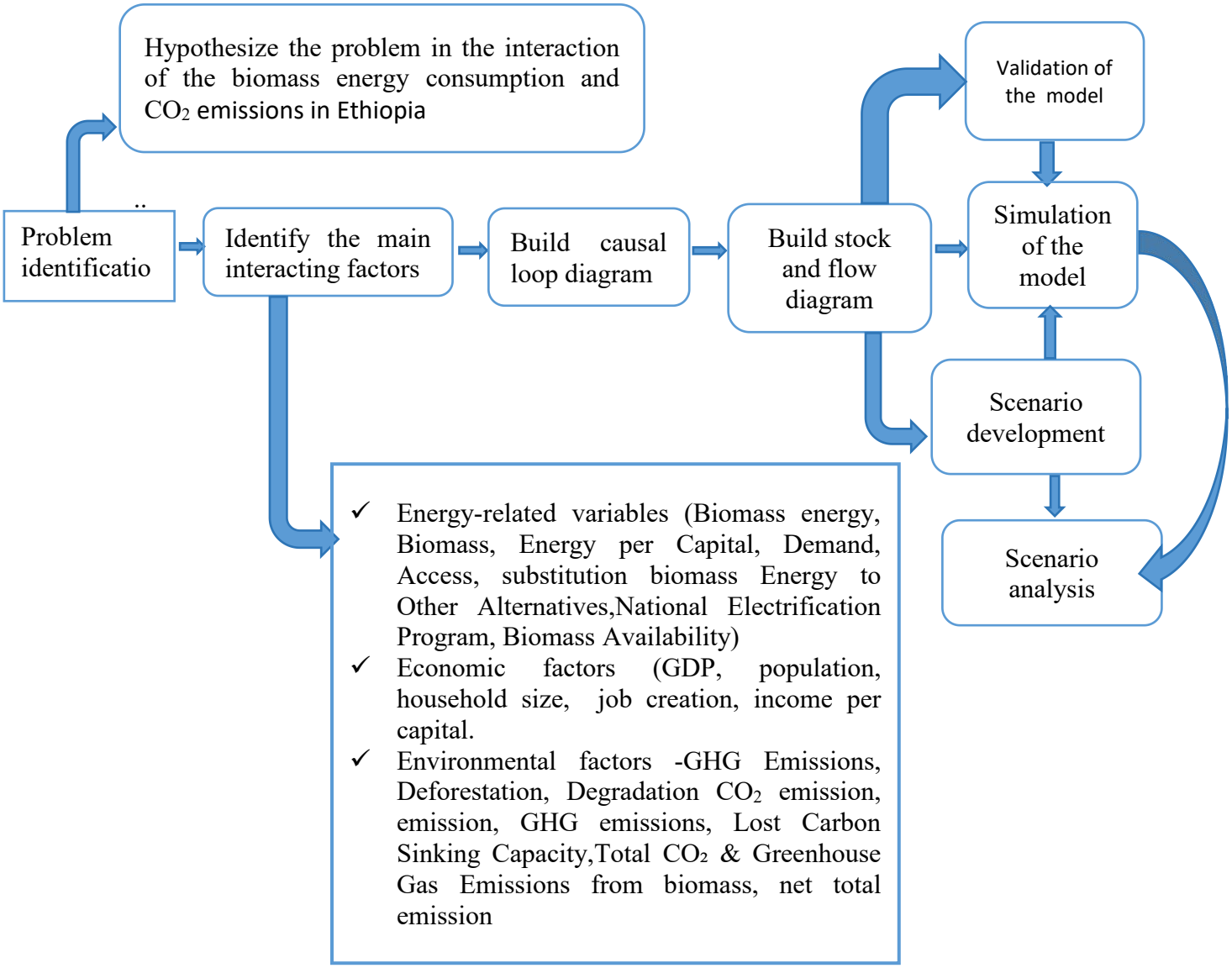


Figure 2: Framework of the study Source: Own conception based on (Energypedia, 2023; Just Transition for All, 2021)

CHAPTER THREE

3. METHEDOLOGY

3.1. System dynamics modeling and environment

The proposed study aims to develop a system dynamics model that evaluates the interactions between biomass energy use and CO_2 emissions in Ethiopia. This framework is particularly relevant given the country's energy crisis, which is characterized by interconnected challenges such as energy access, environmental degradation, and economic development. The reliance on biomass, which constitutes approximately 92.4% of Ethiopia's energy consumption, significantly contributes to deforestation, air pollution, and increased CO_2 emissions. By employing system dynamics methodology, the study will map the primary interactions within the biomass energy and identify key relationships that affect the emission (Abbasi & Abbasi, 2016; WIT Press, 2024).

3.2. System Dynamics Modeling, biomass energy and emission

System dynamic modeling is a powerful methodology to address biomass energy consumption and achieve sustainable energy systems in Ethiopia. The method efficiently analyzes complex relationships between environment and socioeconomic factors, as seen through research (Bala, Arshad, Noh, & Simulation, 2017; Nature, 2020). the simulation of feedback loops, non-linearities, and time lags, system dynamics is well-suited to analyze the dynamic and interdependent issues of biomass energy consumption (Pruyt, 2013; WIT Press, 2024). Policymakers in the global South increasingly use the tool to analyze energy policy options and their implications (Energy Innovation, 2013).

Empirical evidence identifies the strong link between environmental degradation and biomass energy consumption. The, reliance on biomass is the cause of deforestation, emissions in the atmosphere, and CO2 and greenhouse gas emissions (Abbasi & Abbasi, 2016; WIT Press, 2024). System dynamics models are particularly effective in determining policy interventions that promote the use of alternative energy and minimize environmental impacts.These models have been used to quantify the effect of policy scenarios on energy dependency across a range of situations (Energy Innovation, 2013).

The methodology further enables scenario analysis to evaluate trade-offs between biomass energy use and sustainability in the environment. Through the development of causal loop diagrams (CLDs) and stock-flow diagrams, system dynamics models show systemic behavior of energy systems for different policy scenarios (Nature, 2020; MDPI Sustainability, 2024).The study indicates that adoption of alternative use of energy, efficiency increase, reforestation and adaptation of improved cookstoves and all the potential scenarios can lead to enormous CO2 and greenhouse gas reduction and facilitate economic development (MDPI Sustainability, 2024).

Lastly, system dynamics modeling offers an integral framework to analyze the impacts of using biomass energy on environmental sustainability. By identifying leverage points and simulating various scenarios, it enables policy makers to design strategies that transition towards cleaner sources of energy while addressing very critical issues such as deforestation and carbon emissions (WIT Press, 2024; Energy Innovation, 2013). This approach not only encourages resource sustainability but also enhances energy security and economic resilience in developed and developing countries.

3.3. Problem articulation

Ethiopia's energy is highly depend on biomass, which supports 92.4% of Ethiopia's energy and is consumed primarily for cooking and heating in rural Ethopia (Hailu, 2023; Sustainability, 2021). It has been found to possess tremendous environmental implications, such as 1.5% deforestation rate per year due to biomass demands and inefficient traditional cooking appliances, leading to colossal energy losses (Hailu, 2023; PMC, 2021). Biomass burning is responsible for 60,120 kg/GJ of direct CO_2 emissions and is one of the leading factors for greenhouse gas emissions in the country (Hailu, 2023). Economic and population growth are also factors that have added up to energy demands in the nation, with CO_2 emissions increasing by 450% between 1990 and 2017 due to economic and population growth reasons (Sustainability, 2020). This issue is addressed through sustainable policy scenario strategies that reduce the reliance on traditional biomass but improve the efficiency of energy (PMC, 2021; Amsalu, 2023).

The aim of this study is to create a system dynamics model for the sake of analyzing the dynamics and complexity of the relationship between biomass energy consumption and its impact on the CO2 emission. also assessing environmental sustainability against the implications of continued reliance on biomass energy, other less carbon-energy replacements

and contribution to deforestation and CO2 output in Ethiopia (Woldie, 2022; Dingeto & Kumsa, 2021). use linked to indoor air pollution (Woldie, 2022). The overall purpose is to finalize policymaking recommendations to stakeholders to facilitate a sustainable energy future for Ethiopia and reduce CO2 emissions. emissions .

3.4. Key variables, Endogenous Variables and Exogenous Variables

- **Energy Demand:** This is driven by population growth, economic development (GDP), and improved living standards. Higher energy demand puts pressure on existing energy resources.
- **Biomass Energy:** Biomass energy is defined as biological material which is directly or indirectly produced by photosynthesis. from are wood and wood residues, energy crops, crop residues, and organic waste/residues from industry, agriculture, landscape management and households.
- **Economic Growth (GDP):** Economic growth increases energy demand, which can lead to increased environmental impacts and carbon emissions if not managed sustainably.
- **Energy Production/Supply:** Includes both renewable (hydropower, solar, wind, geothermal) and non-renewable sources (biomass, fossil fuels).
- **Greenhouse Gas (GHG) Emissions:** Primarily CO2 emissions from energy production and consumption. High GHG emissions contribute to climate change.
- **Biomass Consumption:** Represents the use of biomass for cooking and heating, particularly in household level. High biomass consumption leads to deforestation, emissions and indoor air pollution.
- **Deforestation:** The loss of forest covers due to biomass harvesting and other factors. Deforestation reduces carbon sequestration capacity and contributes to environmental degradation.
- **Environmental Degradation:** Includes soil erosion, land degradation, air and water pollution. Environmental degradation can negatively impact agriculture and water resources.
- **Alternative Energy:** Alternative energy infrastructure (solar, wind, hydro) can increase the share of energy access in the energy demand and supply.
- **Energy Access:** The percentage of the population with access to electricity. Improved energy access can boost economic development and reduce reliance on biomass and CO_2 emissions.
- **Policy Interventions:** Government policies such as the National Electrification Program, alternative energy targets, management of biomass use and Improved Cook stove Adoption mechanisms.

Endogenous Variables (Internal System Dynamics)

- ✓ **Biomass Consumption:-** Primary driver of deforestation (141.8M tons/year potential) and indoor air pollution:-Biomass use → Deforestation → emissions
- ✓ **GHG Emissions:-** Direct CO_2 emissions (6,012,000 kg/GJ) from biomass combustion, Linked to 450% emission growth (1990-2025)
- ✓ **Energy Demand:-** 92.4% met by biomass, driven by rural cooking needs;_7.2 MWh/household annual consumption (90% for cooking)
- ✓ **Deforestation Rate:-** 1.5% annual loss from biomass harvesting, Reduces carbon sequestration capacity
- ✓ **Environmental Degradation**:-Soil erosion from 71.9M tons/year biomass exploitation, Air pollution causes 93M relying on solid fuels
- ✓ **Energy Access:-** 45% electricity access Affects biomass dependency through substitution rates

Exogenous Variables (External Drivers)

- ✓ **Population Growth,:-** 128.7M population driving energy demand
- ✓ **Policy Interventions**, National Electrification Program targets,other less carbon intensive energy adoption mechanisms
- ✓ **Technological Adoption Improved:-** cook-stove penetration (26% clean cooking access), Biomass conversion efficiency rates

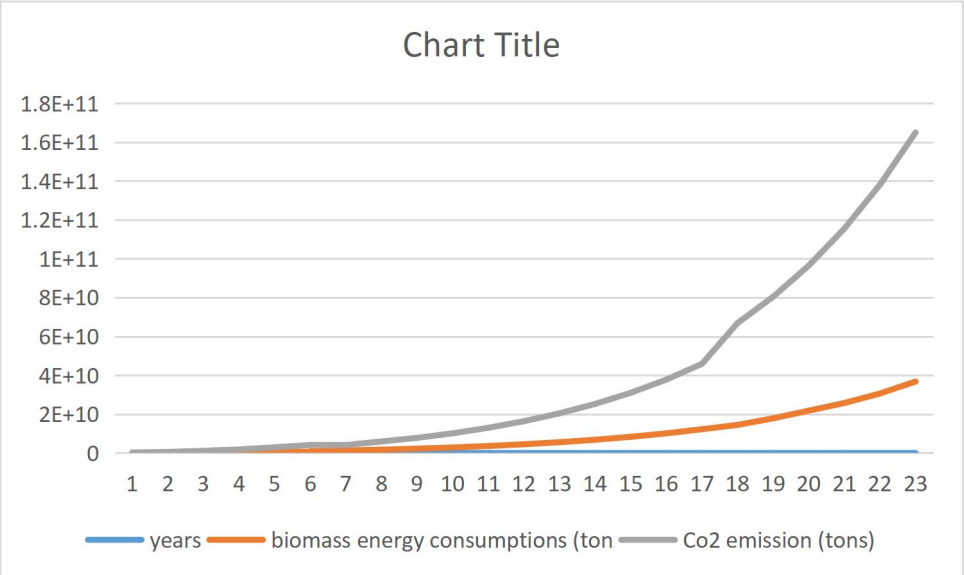


Figure 3. Biomass energy consumption and emissions trends in Ethiopia 2000-2030

3.5. Leverage Points for Policy Intervention:

Ethiopia's energy landscape presents several leverage points for policy intervention aimed at reducing biomass energy consumption and promoting alternative energy sources. The following strategies can significantly impact the country's transition toward a more sustainable energy system:

1. **Substitution of Other Alternative Energy Sources that Less Carbon Intensity energy**: Transitioning from biomass to alternative energy sources, such as solar and wind, can drastically reduce carbon emissions. Ethiopia has significant solar potential, receiving an average of 5.5 to 6.5 kWh/m²/day, making it well-positioned to harness solar energy as a clean alternative (Energypedia, 2023). The government's commitment to investing $300 million in solar projects aims to generate 300 megawatts of solar power, which will help mitigate climate change and support sustainable development (Energypedia, 2023).
2. **Efficient Management of Biomass Energy**: Improving the efficiency of biomass energy utilization is crucial for reducing its environmental impact. This can be achieved through the promotion of improved cooking stoves that use biomass more efficiently, thereby decreasing emissions and improving indoor air quality. The Ethiopian government has previously aimed to distribute millions of efficient stoves to reduce wood use while enhancing health outcomes (Wikipedia, 2013). Efficient management practices can also include better resource allocation and sustainable harvesting techniques to minimize deforestation.
3. **National Electrification Plans**: The Ethiopian government's national electrification plans aim to provide universal access to electricity by 2025. Plans center on expanding access to renewable energy sources, especially in rural areas where biomass dependence is highest (World Bank, 2024). With greater promotion of off-grid solar home systems and mini-grids, the government can enhance energy access while reducing the use of traditional biomass fuels (Energypedia, 2023).
4. **Improved Use of Cooking Stoves:** Improved cooking appliances are imperative in mitigating emissions from biomass consumption in domestic applications. Improved cooking stoves allow for improved combustion of biomass and lower carbon emissions while reducing indoor air pollution's negative effects (Wikipedia, 2013). The efficient stove distribution program by the government is directed towards enhancing the quality

of air as well as economically empowering families by saving on fuel costs. Ethiopia can counteract its reliance on biomass energy and seek alternative sources of energy that promote economic growth and environmental conservation. Such interventions will not only curb greenhouse gas emissions but also improve the overall welfare of Ethiopians through access to energy and health (Energypedia, 2023; World Bank, 2024).

4.1. Choice of method and data source

Ethiopia's energy system 92.4% of energy consumption comes from biomass, which is primarily used for cooking in rural areas and is a major component of the country's energy system (Hailu, 2023; Sustainability, 2021). Significant environmental effects of this reliance include a 1.5% yearly rate of deforestation brought on by the demand for biomass and ineffective traditional cooking methods that waste a lot of energy (Hailu, 2023; PMC, 2021). Combustion of biomass is a significant contributor to the nation's greenhouse gas emissions, accounting for 60,120 GJ tons of direct CO_2 emissions (Hailu, 2023). Furthermore, Ethiopia's expanding economy and population have made energy demands worse; between 1990 and 2017, CO2 emissions rose 450% as a result of these factors (Sustainability, 2020). Sustainable policy scenarios and strategies are needed to address this issue. Addressing this issue requires sustainable policy scenarios to strategies that reduce reliance on traditional biomass while improving energy efficiency (PMC, 2021; Amsalu, 2023).

The purpose of this study is to develop a system dynamics model to evaluate the complexity and dynamics of the interaction between the biomass energy consumption and its contribution to the CO_2 emission. also assessing environmental sustainability by evaluating the consequences of current reliance on biomass energy, other less carbon intensive energy substitutions and its contribution to air pollution and deforestation (Woldie, 2022; Dingeto & Kumsa, 2021). biomass consumption associated with indoor air pollution (Woldie, 2022). Ultimately, the research aims to provide actionable insights for policymakers and stakeholders to foster a sustainable energy future in Ethiopia. and reduce carbon emissions .

4.2. Dynamic hypothesis

Ethiopia's energy system is characterized by a self-reinforcing cycle in which rising living standards and population growth fuel an increase in energy demand, which in turn fuels an increased reliance on biomass. With 77% of people living in rural areas and a population growing at a rate of 2.6% per year, households rely largely on biomass—wood, manure, and crop residues—for heating and cooking, which accounts for 92.4% of the country's energy needs. Due to limited access to contemporary alternatives—just 6% of households use clean cooking technologies, and only 29% of rural areas have electricity—households are forced to use biomass at unsustainable rates, consuming 71.9 million tons annually out of a potential 141.8 million tons. Direct emissions from burning biomass (60,120 giga tons CO_2/GJ) and indirect emissions from deforestation, which happens at a rate of 1.5% per year, are the two main ways that this dependence contributes to environmental degradation.

The interplay between biomass consumption, deforestation, and emissions creates a feedback loop that exacerbates climate change. Deforestation not only releases stored carbon but also reduces forests' capacity to act as carbon sinks, amplifying Ethiopia's contribution to global warming. Simultaneously, direct CO_2 emissions from biomass combustion compound the problem, with CO_2 emissions rising by 450% between 1990 and 2025. his dynamic traps the system in a loop of environmental degradation: emissions and deforestation fuel temperature increase, which in turn imposes threats on agricultural productivity and energy security, furtherentrenching biomass dependence. Breaking the cycle requires measures like substitutions lower carbon-intensive energy, increased uptake of better cookstoves, and management of biomass use programs to stem biomass dependence and transition to more sustainable sources of energy.

4.3. Model structure

4.3.1. The causal loop diagram (CLD)

The causal loop diagram (CLD) of the biomass energy system in Ethiopia illustrates a complex network of reinforcing and balancing loops that drive environmental degradation and global warming. Reinforcing loops at its foundation continue to reinforce dependency on biomass: population and living standards increase, and therefore the demand for energy and, in turn, biomass use (92.4% of national energy demand). It accelerates forest destruction

(1.5% annual rate), reducing carbon sequestration potential and directly emitting CO_2 (60,120 GJ tons of combustion). Global warming induced by the emissions increases environmental degradation, further entrenching biomass reliance in the absence of access to modern alternatives. For example, deforestation interferes with agricultural production, exacerbating energy poverty and deepening the loop.

The CLD also indicates balancing loops with future solutions to sustainability. Policy interventions, such as Ethiopia's National Electrification Program, have the potential to reroute alternate energy, which improves access to energy and lower biomass dependence. Improved cook-stove adoption and electrification programs exemplify balancing mechanisms: they lower biomass consumption, mitigate deforestation, and curb emissions. By integrating these interventions, the system can transition toward a self-regulating equilibrium, where alternative energy adoption offsets population-driven demand, stabilizing carbon sinks and emissions. This CLD serves as a blueprint for policymakers, emphasizing the need to strengthen balancing loops to counteract reinforcing cycles of environmental degradation.

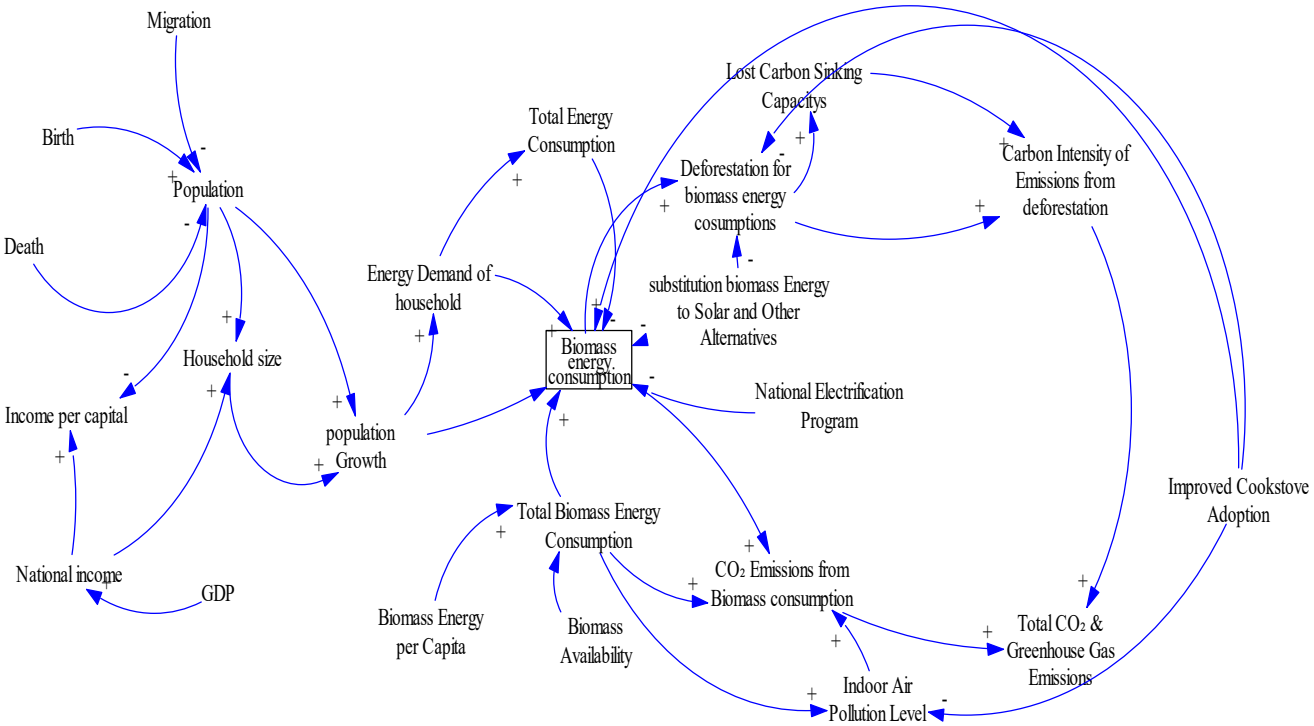


Figure 4. The causal loop diagram (CLD) of the Ethiopian biomass energy consumption and CO_2 emission.

4.3.2. Reinforcing Loops (R1–R7)

- ✓ **R1: Biomass Dependency Cycle:** Population growth → energy demand → biomass consumption → deforestation → loss of carbon sinks → CO2 emissions → temperature rise → environmental degradation → increased energy scarcity → increased reliance on biomass. The use of biomass is driven by growing population and energy demands, which accelerate emissions and deforestation, worsen environmental conditions, and necessitate further reliance on biomass.
- ✓ **R2: Amplification of Emissions:** Biomass Combustion → GHG Emissions → Temperature Increase → Degradation of the Environment → Decreased Agricultural Productivity → Poverty → Increased Dependency on Biomass. Burning biomass releases emissions that harm ecosystems, lower agricultural productivity, and increase poverty, all of which encourage the use of biomass.
- ✓ **R2:- Biomass Demand** → Deforestation → Decreased Fuel Availability → Increased Collection Time/Effort → Persistent Biomass Dependency R3: Deforestation-Energy Crisis. Reliance on biomass despite scarcity is strengthened by overharvesting, which depletes biomass stocks and forces households to spend more time gathering fuel.
- ✓ **R4: Feedback on Health and the Environment:** Biomass Use → Indoor Air Pollution → Health Problems → Decreased Worker Productivity → Lower Agricultural Output → Higher Poverty → Greater Biomass Dependency. Health is weakened by air pollution from burning biomass, which also lowers economic capacity and forces households to prioritize biomass in order to survive.
- ✓ **R5: The Economic Growth Trap:-** Economic Growth → Rising Energy Demand → Consumption of Biomass → Deforestation → Degradation of the Environment → Decreased Agricultural Productivity → Economic Stasis → Enduring Biomass Dependency. Energy demands rise with economic expansion, but a reliance on biomass degrades natural resources and threatens long-term growth.
- ✓ **R6: Policy Delay Cycle:** Biomass Crisis → Awareness → Policy Interventions → Implementation Delays → Limited Adoption of Renewable Energy → Persistent Biomass Reliance. Reinforcing loops take over when policies are implemented slowly, failing to address biomass dependency.
- ✓ **R7: Infrastructure Gap:** Biomass Dependency → Deforestation → Decreased Investment in Rural Infrastructure → Persistent Energy Poverty → Limited Grid Access

4.3.3. Balancing Loops (B1–B2)

- ✓ **1: Alternative Energy Transition:-** Policy Interventions → Energy Investments → Improved Energy Access → Reduced Biomass Consumption → Deforestation Mitigation → Lower Emissions → Stabilized Climate. Government policies and alternatives energy (e.g., solar, wind) reduce biomass demand, breaking the dependency cycle.
- ✓ **B2: Efficiency-Driven Sustainability**:- Improved Cookstove Adoption → Reduced Biomass Use → Lower Deforestation → Increased Carbon Sinks → Lower Emissions → Environmental Recovery. Efficient cookstoves cut biomass consumption, easing pressure on forests and slowing climate change.

4.4. Stock and flow diagram (SFD)

The converted the causal loop diagram (CLD) into a quantified and mathematical model, the stock and flow diagram (SFD) makes it possible to precisely simulate dynamic systems. This process replicates reference behaviors using differential equations, transforming mental models into communicable outcomes. By linking stocks and flows and using integral finite difference equations to depict feedback structures, the SFD shows how a system behaves over time. The population, GDP ,energy demand , biomass energy demand, deforestation and biomass combustion are the main stock in Ethiopia's biomass energy system, and it fluctuates due to natural growth rates. The demand for energy is fueled by this population growth, which raises the use of biomass. As a result, as deforestation decreases biomass availability, the biomass energy consumption inventory—a crucial stock—declines. Through the burning of biomass and deforestation, which releases stored carbon and reduces forests' ability to absorb carbon, these dynamics directly contribute to CO_2 emissions.

Another important stock in the SFD istotal CO2 concentrations, which are rising as a result of rising rates of deforestation and increased biomass consumption. Traditional biomass use results in high CO_2 emission intensity, which exacerbates atmospheric CO_2 levels. CO_2 accumulation is also greatly influenced by changes in land use and vegetation loss brought on by biomass harvesting. Additionally, resources like firewood, crop residues, and animal dung—all of which are exploited for energy but are still underutilized in contemporary bioenergy systems—are included in the stock of available biomass energy. Only 71.9 million metric tons of Ethiopia's estimated 141.8 million metric tons of exploitable biomass are currently used, indicating inefficiencies in resource management.

The SFD emphasizes how systemic issues in Ethiopia's energy sector are driven by interconnected stocks, including population growth, biomass inventory depletion, deforestation rate, and CO_2 concentrations. By modeling these interactions, policymakers can identify leverage points for intervention, such as promoting alternative energy adoption or improving cookstove efficiency to reduce biomass reliance. The diagram underscores the urgency of addressing deforestation and emissions while optimizing biomass resource utilization to achieve sustainable energy transitions and mitigate environmental degradation.

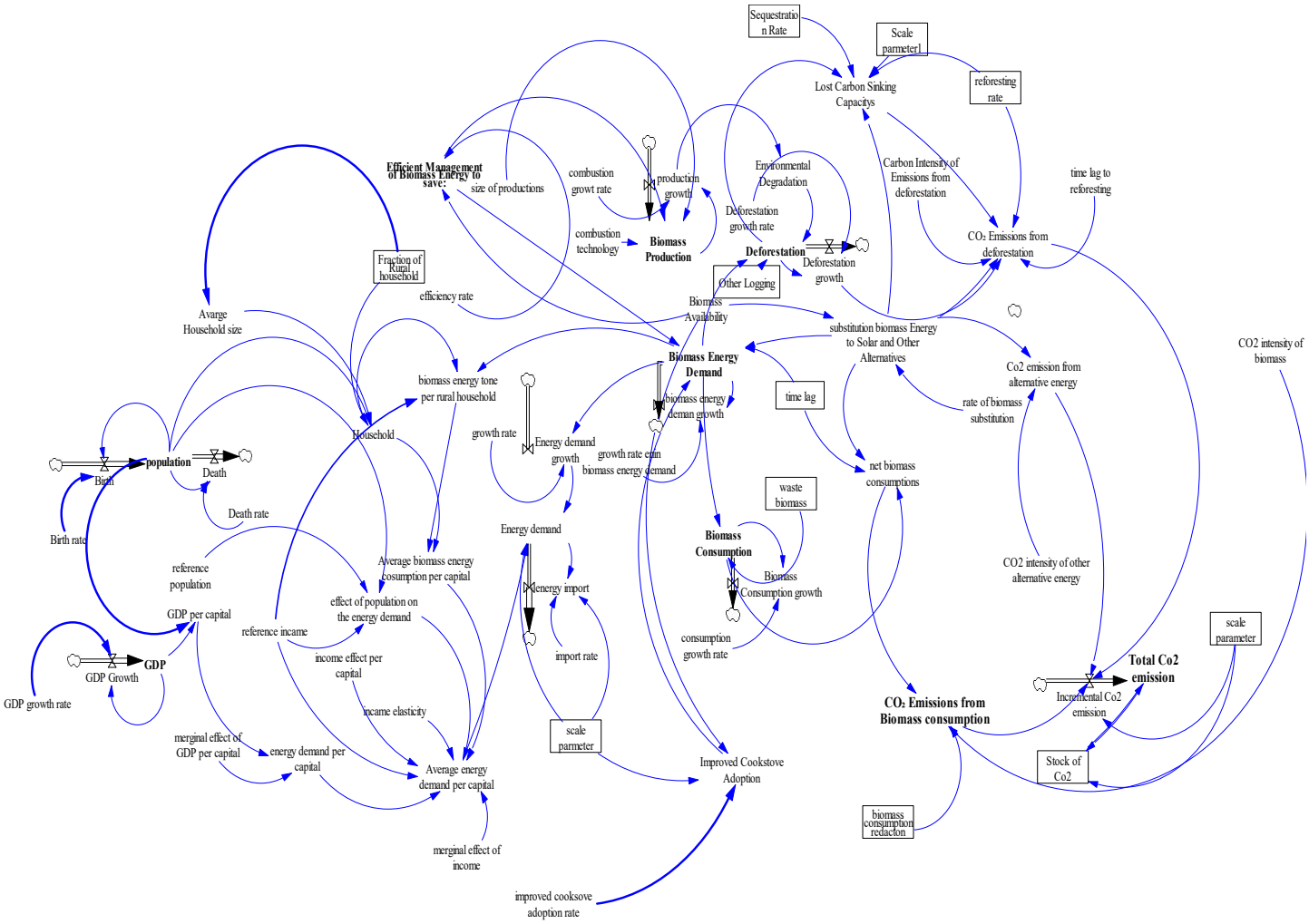


Figure 5 The stock -flow model of biomass consumption and emissions in ethiopia

The stock-flow model requires defining equations and parameterizing variables prior to executing the simulation. The table below summarizes the variable and parameter values, including their units of measurement and sources.

Table 2. Initial value and values of the parameters of the model

stocks	**Initial values**	**units**	**sources**
Population	66224809	persons	world bank 2024,UNDP Emergencies Unit for Ethiopia
GDP	82000000	USD	world bank 2024,UNNDP
Household energy demand	75000000	tons	world bank 2024,UNDP Emergencies Unit for Ethiopia
Biomass combustion	2500000	Tons	world bank 2024,UNDP Emergencies Unit for Ethiopia,CSA, world bank 2020
Biomass Energy Consumption	45478700	tons	CSA, world bank 2020
Deforestation	140000	Tons	world bank 2024,UNDP Emergencies Unit for Ethiopia
Total CO_2 Emissions	35000000	tons of CO2	CSA, world bank 2020
Flows	**Initial values**	**units**	**sources**
Birth	37.6	people/year	CSA, world bank 2020
Death	14.2	people/year	CSA, world bank 2020
Population Growth	2.8	people/year	CSA, world bank 2020
GDP Growth	.079	USD/year	CSA, world bank 2020
Biomass Consumption Growth	**0.35**	tons/year	CSA, world bank 2020
Energy Demand Growth	0.5	GJ tons/year	world bank 2024,UNDP Emergencies Unit for Ethiopia
Incremental CO_2 Emission	4.5	tons of CO_2/year	CSA, world bank 2020
Auxiliary and parameter	**Initial values**	**units**	
CO_2 Emissions from Deforestation		tons of CO_2/year	world bank 2024,UNDP Emergencies Unit for Ethiopia
CO_2 Emissions from Biomass Consumption		tons of CO_2/year	CSA, world bank 2020
Birth Rate	14.5	%	world bank 2024,UNDP Emergencies Unit for Ethiopia
Death Rate	5.7	%	world bank 2024,UNDP Emergencies Unit for Ethiopia
Marginal Effect of GDP per Capita	0.00554	%	(2022 census data)
Income Elasticity	0.933	%	(FAO, 2003)
Carbon Intensity of Emissions from Deforestation	2,5	Tons CO_2/hectare deforested	CSA, world bank 2020
CO_2 Intensity of Biomass	4,5	Tons CO_2/ton biomass	CSA, world bank 2020
CO_2 Intensity of Other	1.523	Tons	CSA, world bank 2020

Alternative Energy		CO_2/energy unit produced	
Rate of Biomass Substitution	0	%	CSA, world bank 2020
Substitution Biomass Energy to Solar and Other Alternatives	1.58E+07	%	world bank 2024,UNDP Emergencies Unit for Ethiopia,CSA, world bank 2020
Household	4.8	person	(2022 census data)
Biomass Availability	45000000	tons	CSA, world bank 2020
Indoor air pollution	1.58E+07	Ng/m	CSA, world bank 2020
Net Biomass Consumption		tons	CSA, world bank 2020

4.5. Definitions of the main variables of the model

The model variables and their relationships form a system dynamics framework analyzing biomass energy consumption, economic factors, and environmental impacts. Below are key variables organized by category with formulas and units:

- ✓ Biomass Availability;Total biomass available for energy production = 4.5e+07, FAO (2023) ,Units: tons
- ✓ Biomass Consumption;Total biomass consumed for energy over a time period= INTEG(Biomass Consumption growth, 4.5e+07), Units: tons, International Energy Agency (IEA) biomass tracking models
- ✓ Biomass Production; Cumulative biomass produced for energy over a time period= INTEG(production growth, 6.23e+07),Units: tons/hectare, International Renewable Energy Agency (IRENA) yield analyses
- ✓ GDP;Gross Domestic Product indicating economic output=INTEG(GDP Growth, 8.2e+10), Units: USD, World Bank macroeconomic models
- ✓ GDP Growth; Rate of economic growth yearly.=GDP * GDP growth rate, USD/year, IMF growth rate frameworks
- ✓ Population; Number of people.=INTEG(Birth - Death, 6.62248e+07), Units: persons, UN World Population Prospects
- ✓ CO_2 Emissions from Biomass: Greenhouse gases from biomass combustion.= CO2 intensity of biomass * net biomass consumption, Units: tons/year, IPCC Emission Factor Database
- ✓ Deforestation Growth: Forest loss for biomass production cumulative.= Deforestation * Deforestation growth rate,Units: 1/year. Global Forest Watch monitoring systems

- ✓ Lost Carbon Sinking Capacity=Deforestation * Sequestration Rate, Units: tons/year, NASA Carbon Monitoring System
- ✓ Substitution to Alternatives:Biomass replaced by alternative energy= rate of biomass substitution * Biomass Availability, Units: tons/year, REN21 Renewables Global Status Report
- ✓ Improved Cookstove Adoption:- Biomass saved by efficient stoves.Formula: Biomass Availability * adoption rate, Units: tons, Clean Cooking Alliance impact studies
- ✓ FINAL TIME: 2030 (simulation end) and INITIAL TIME: 2000 (simulation start)
- ✓ Biomass carbon intensity: 4.5 tons/year (IPCC Tier 1 defaults)
- ✓ Alternatives CO2 intensity: 1.532 tons/year (IEA lifecycle analyses)

Key Relationships

- ✓ Net Biomass Consumption = Biomass Consumption - Substitution to Alternatives
- ✓ Lost Carbon Sink = (Deforestation × Sequestration Rate) - Reforesting Efforts
- ✓ Energy Demand Growth = Energy Demand × Population Growth rate × Income Elasticity

Method of data analysis

Using a causal loop diagram (CLD), the model will be used to mirror feedback relations between biomass utilization and emissions. Using this approach, it becomes easier to research systemic behavior as well as generate policy responses towards environmental rehabilitation as well as pursue economic growth. .Empirical evidence has proven strong links between biomass energy transitions and resource degradation and has reiterated the importance of quality policies to counter such issues in developing countries like Ethiopia(Abbasi & Abbasi, 2016; WIT Press, 2024).

The model will also incorporate a stock-flow diagram in order to make an estimate of such interactions and compute the prospective biomass energy use and environmental trade-offs of various policy actions. Scenario simulations was conducted in order to compute base and alternative scenarios, providing evidence of how the various strategies would impact carbon emissions and overall sustainability. Such validation was through a process that assisted in informing strategies for the transition towards cleaner sources of energy, improved energy access, and emissions reduction and mitigation of the Ethiopian energy crisis(Bala, Arshad, Noh, & Simulation, 2017; Nature, 2020)..

Ultimately, this study seeks to bridge the research gap of mitigation and adaptation strategies for Ethiopia's energy issues by building sustainable systems that boost economic growth at the expense of diminishing negative environmental effects. By focusing on biomass data and CO2 emission its implications in this case, the research seeks to contribute meaningful knowledge towards sustainable energy in Ethiopia (Bala, Arshad, Noh, & Simulation, 2017; Nature, 2020). .

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CHAPTER FIVE

Results and Discussion

5.1. Model validation

Model validation would be conducted to confidence in the model's results, model validation would be carried out. The model should be evaluated in system dynamics according to how well it captures the reality, comprehension, and significance of the system. The accuracy with which the simulated model replicates the model behavior is determined by model validation. The system dynamics model in question would run a few simple tests to increase confidence in it. The two categories of the most popular tests are behavioral model tests and structural model tests. While the behaviors have been tested by reproducing the actual behavior of the system, the model structure is tested by reflecting how the real system operates (Bala, Arshad, & Noh, 2017).

5.1.1. Model structure test

Model structure testing is a pre-simulation test that involves assessing the model boundary's sufficiency, the model equation and unit's relevance, and the precision of parameter values (Bala, Arshad, & Noh, 2017; Sterman, 2000).

5.1.1.1. Structure verification test

The model's structure must align with what is currently understood about the system. The main method used to create the model is a detailed analysis of the current reports, books, and other technical documents. The foundation for understanding biomass energy consumption and its relationship to the environment, especially with regard to the biomass use contribution to CO2 emissions, is provided by data, definitions of terms, and reports from the World Bank (WB) and the Central Statistics Agency (CSA). The causal loop diagram and stock and flow diagram were created and are thought to replicate the actual behaviour of the problem. The primary elements of the country's biomass consumption have been incorporated, contributions to the emission of CO_2 include all pertinent links from the Biomass energy. The key parameters that are thought to define the issue are included in the model's boundary.

5.1.1.2. Extreme condition test

To verify the actual relationship, the value changes are tested. To ensure that the variables are not taking on unrealistic values, zero values are taken into account in the equations. For example, the model looks for values that the key variables are taking after starting the biomass consumption at zero. If there is no consumption of biomass, the deforestation and its value are expected to be zero, which will lead to low combustion of biomass and ultimately deforestation and emissions. With a value of zero under extreme circumstances, the graph below demonstrates that changes in biomass consumption, biomass combustion, and deforestation are all proportionate to changes in biomass consumption and emissions.

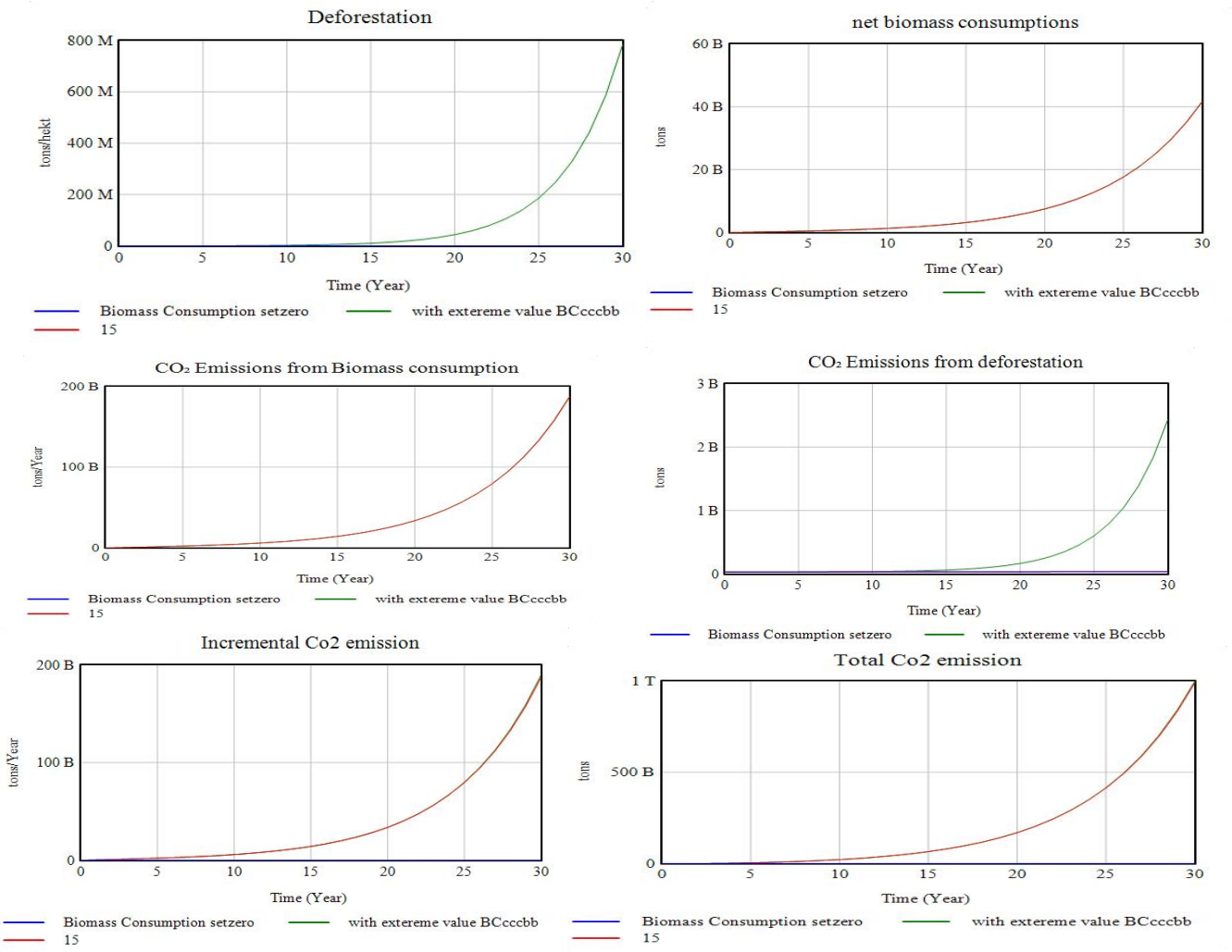


Figure 6: Extreme condition test

As the figure illustrates, deforestation and its value would not have any value if biomass consumption was set to zero. Therefore, it is justified that the desired behavior is produced by the model's behavior.

5.1.1.3. Parameter verification test

The parameters of the model have been collected from the literature and it considered the real values of the system. The initial values and parameters of the model are based on the relevant real knowledge of the data. The parameters used to initialize the model, along with their corresponding units and sources, are listed above in the table(4)

5.1.1.4. Dimensional consistency test

The units of each variable inserted in the model for the simulations are meaningful and correct. The units are consistent with the specifications of the equations and the relationship between variables. The units of some of the variables are presented in the below table. Units of some selected variables of the model

Table 1.3: Units of some selected variables of the model.

stocks	**Initial values**	**units**
Population	66224809	persons
GDP	8.2 billion	USD
Household energy demand	75000000	tons
Biomass combustion	2500000	Tons
Biomass Energy Consumption	4.54787e+06	tons
Deforestation	140000	Tons
Total CO_2 Emissions	35000000	tons of CO2
Flows	**Initial values**	**units**
Birth	37.6	people/year
Death	14.2	people/year
Population Growth	2.8	people/year
GDP Growth	.079	USD/year
Biomass Consumption Growth	**75000000**	tons/year
Energy Demand Growth	0.5	GJ tons/year
Incremental CO_2 Emission	4.5	tons of CO_2/year
Auxiliary	**Initial values**	**units**
Substitution Biomass Energy to Solar and Other Alternatives	1.58E+07	tons/Year
Household	4.8	person
Biomass Availability	45000000	tons
GDP per Capita	150	USD/people
Energy Demand per Capital	0.5	tons/peoples
Income Effect per Capital	0.933	USD/people

CO_2 Emissions from Deforestation		tons of CO_2/year
CO_2 Emissions from Biomass Consumption		tons of CO_2/year
Net Biomass Consumption		tons
Parameter/constant	**Initial values**	**units**
Birth Rate	14.5	Births/1000 people/year
Death Rate	5.7	Deaths/1000 people/year
Marginal Effect of GDP per Capita	0.00554	%
Carbon Intensity of Deforestation	2.5	Tons CO_2/hectare deforested
CO_2 Intensity of Biomass	4.5	Tons CO_2/ton biomass
CO_2 Intensity of Other Alternative Energy	1.523	Tons CO_2/energy unit produced

5.1.1.5. Boundary Adequacy Test

This test assesses whether shifting the model's parameters could result in different policy outcomes (Woldie, 2022; Dingeto Kumsa, 2021). The goal of the model is to establish a reasonable and pertinent boundary between the use of biomass and its interactions with the environment, especially with regard to CO2 emissions. It uses a framework that includes a precise structural understanding to analyze the trade-off between rising biomass consumption and CO2 emissions. Deforestation and biomass combustion, which are both impacted by other variables in the model, are the main factors influencing biomass consumption. The model also takes emissions from the use of biomass into account, both directly and indirectly.

5.1.2. Model behaviour test

The accuracy with which the model replicates the reference data is then measured through a test of model behavior (Woldie, 2022; Dingeto Kumsa, 2021). As an indicator of measuring the precision of the model over a given number of data in a time series, the four most influential variables examined in this study—use of biomass energy, deforestation, biomass emissions, and CO2 emissions—were used. For 2000–2030, history data is simulated. The figures in the Ethiopian energy sector and the consumption of biomass energy are used to generate the reference data for deforestation, CO2 emissions, and consumption of biomass energy (Ethiopian Energy Sector, World Bank, CSA 2024). Alternatively, climate change estimates provide the reference data for carbon as well as CO2 emissions (FAO, 2023b).
In contrast to historical data, the graph below shows the simulated values of deforestation and biomass energy consumption over a 20-year period. The difference between the simulated model values and the historical data is almost insignificant, as the graph illustrates.

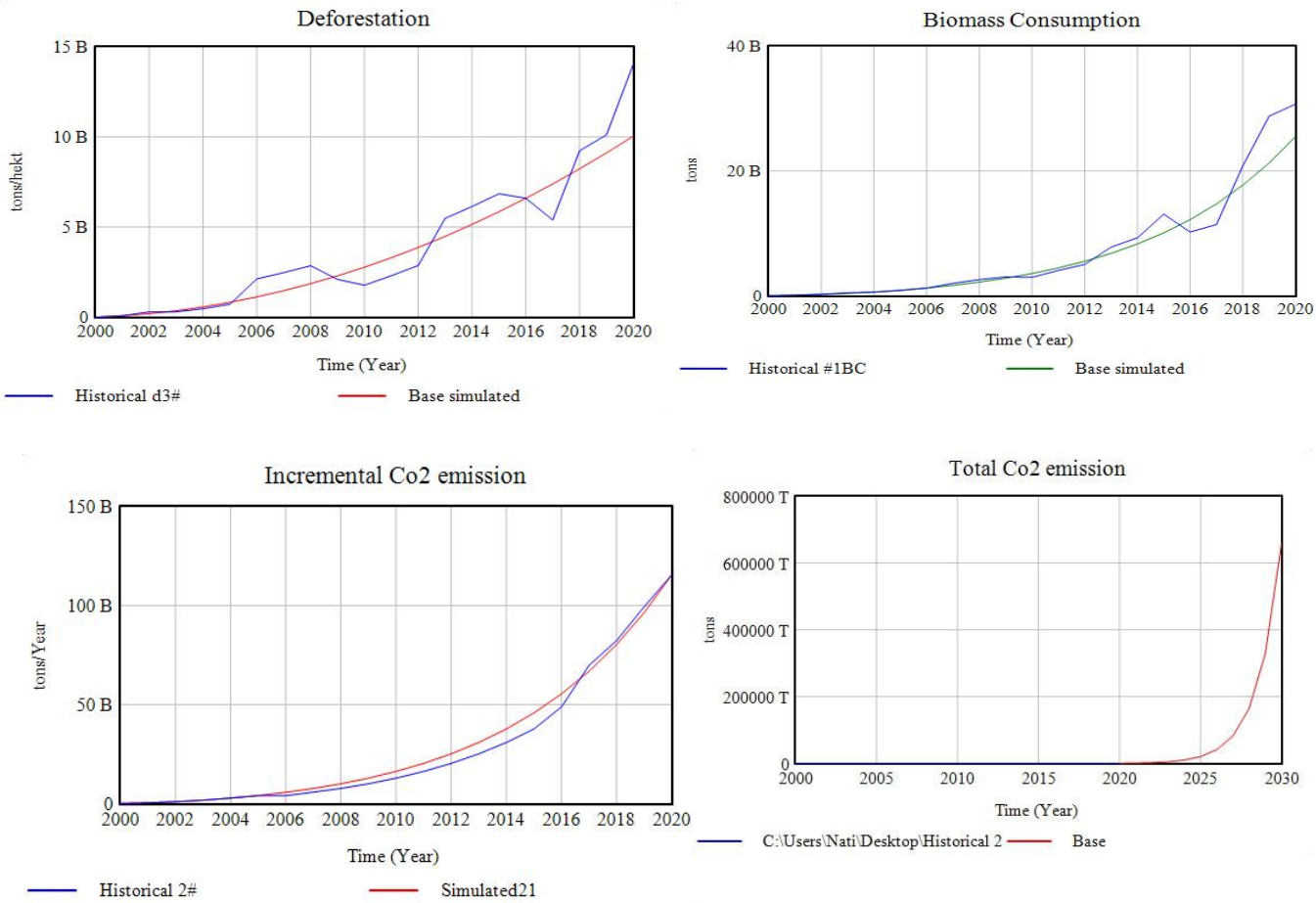


Figure 7: Simulated and historical behaviour of the biomass consumption, deforestation, Co2 emission of biomass and total Co2 emission.

Overall, the differences between the simulated results and the reference data are very small in the validation of the main variables. This provides confidence in simulating and analyzing alternative future policy scenarios.

5.1.3. Sensitivity analysis

Sensitivity analysis is used to evaluate the impact of parameter changes on the outcomes. Additionally, it aids in identifying leverage points when analyzing the correlation between parameters and results (Hailu, 2023; Sustainability, 2021; PMC, 2021; Amsalu, 2023). To ascertain which variables are most important and pertinent in influencing the outcomes of the primary variables, a sensitivity test is performed. In order to assess the sensitivity of biomass energy, biomass consumption, biomass combustion, deforestation, net biomass consumption, CO_2 emissions from deforestation, CO_2 emissions from biomass consumption, and total CO_2 emissions within the model, the parameters that are expected to affect the variables have been

chosen based on the body of existing literature. Household energy demand, energy demand growth, average biomass production growth rate, and per capita biomass consumption growth are the main factors driving biomass energy. Growth of consumption, biomass availability, biomass waste management, transition of Ethiopia towards renewable energy sources, efficient biomass energy management, and consumption growth rate are key drivers of biomass energy consumption (Hailu, 2023; Sustainability, 2021; PMC, 2021; Amsalu, 2023).

On the other hand, changes in the consumption of alternative sources of energy in Ethiopia, efficient biomass energy management, and combustion growth rate influence biomass yield (Hailu, 2023; Sustainability, 2021; PMC, 2021; Amsalu, 2023). Consumption of biomass and deforestation levels would be presumed to be affected by variables such as the rate of combustion growth, effective management of biomass energy, replacement of alternative energy sources in Ethiopia, and the above costs. Carbon emissions, which are shaped by direct and indirect changes in biomass consumption, are another significant variable in the model. As a result of deforestation emissions and loss in carbon sink capacity, CO_2 emissions from burning biomass directly coincide with deforestation. Furthermore, emissions associated with the use of biomass are altered and degraded by biomass.

rise in energy consumption. Key parameters that can alter and result in different outcomes for the primary variables have been identified by the study. Improved cookstove adoption rates, rates of biomass substitution, rates of reforestation, effective management of biomass energy, and changes in consumption growth rates are known to have an impact on changes in biomass energy, biomass consumption, biomass combustion, deforestation, net biomass consumption, CO_2 emissions from deforestation, CO_2 emissions from biomass consumption, and total CO_2 emissions. The model includes sensitivity analysis by taking into account deviations of ±50% from the base case values for the parameters, as illustrated in the simulated behavior of the selected variables below.

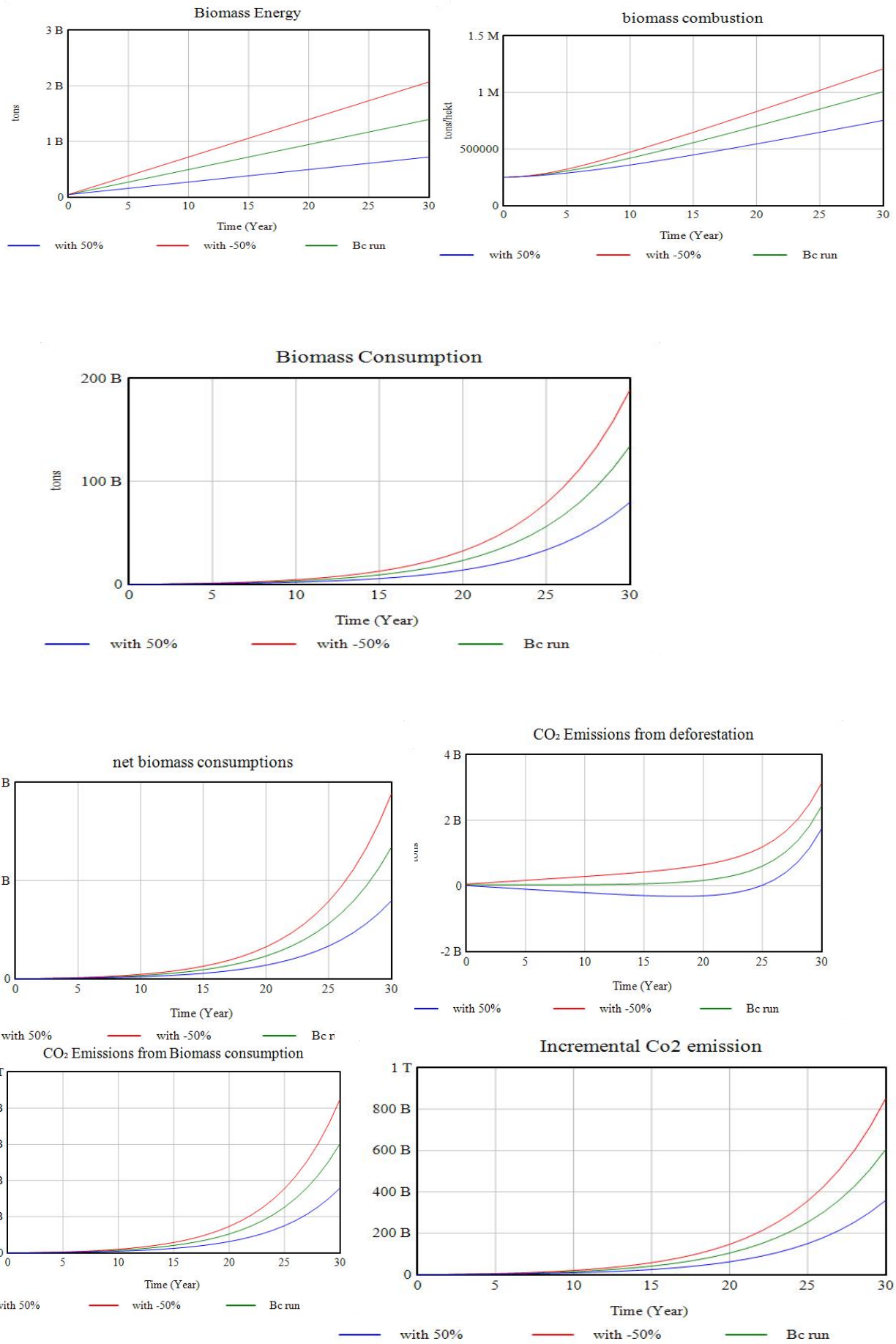


Figure 8. : Sensitivity analysis of Biomass energy, Biomass consumption, Biomass combustion, net biomass consumption, CO_2 emissions from deforestation, CO_2 emissions from biomass consumption, and incremental CO_2 emissions to biomass substitution rate

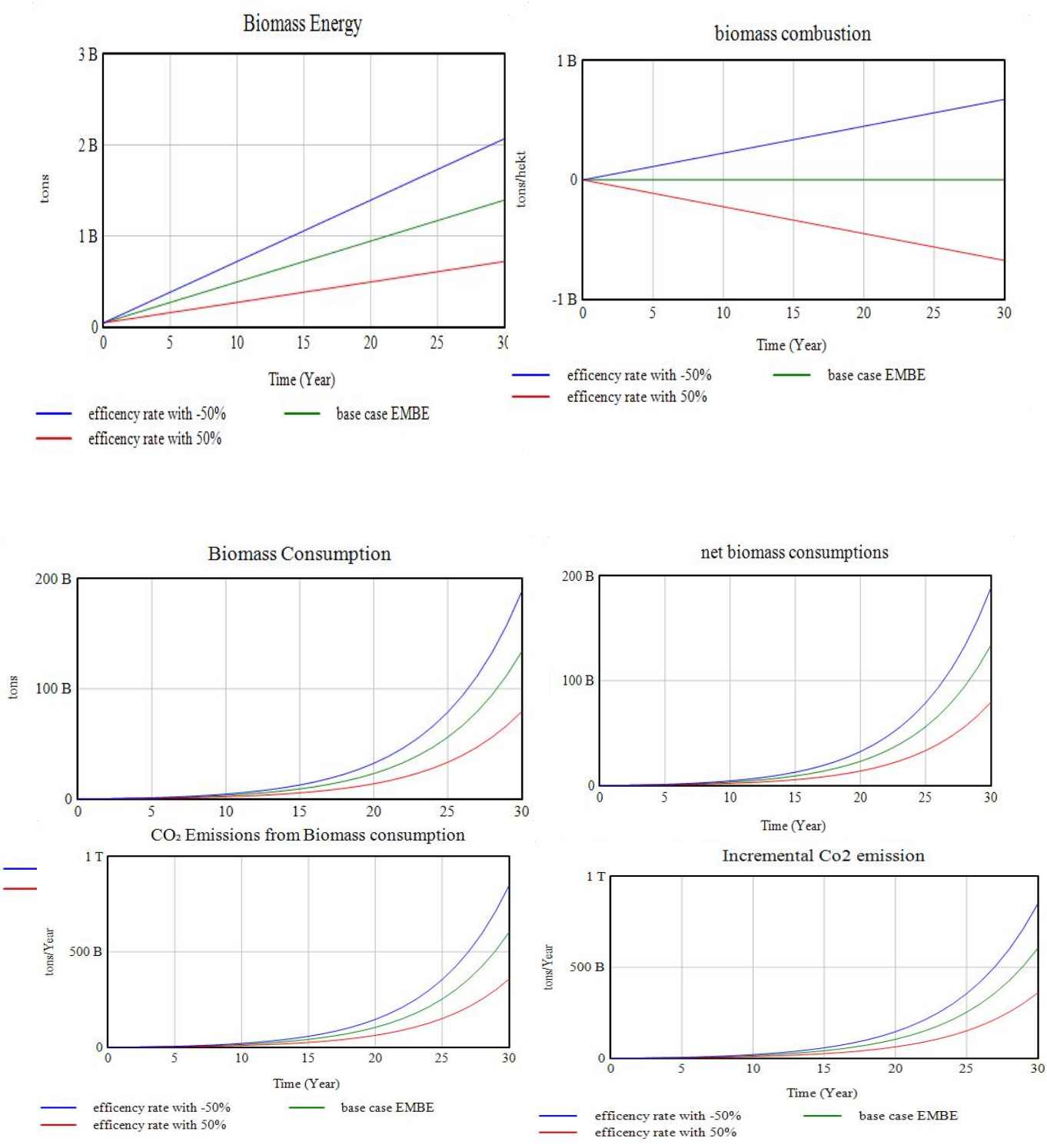


Figure 9: Sensitivity analysis of biomass energy, biomass consumption, biomass combustion, net biomass consumption, CO_2 emissions from deforestation, CO_2 emissions from biomass consumption, and incremental CO_2 emissions to efficiency rate

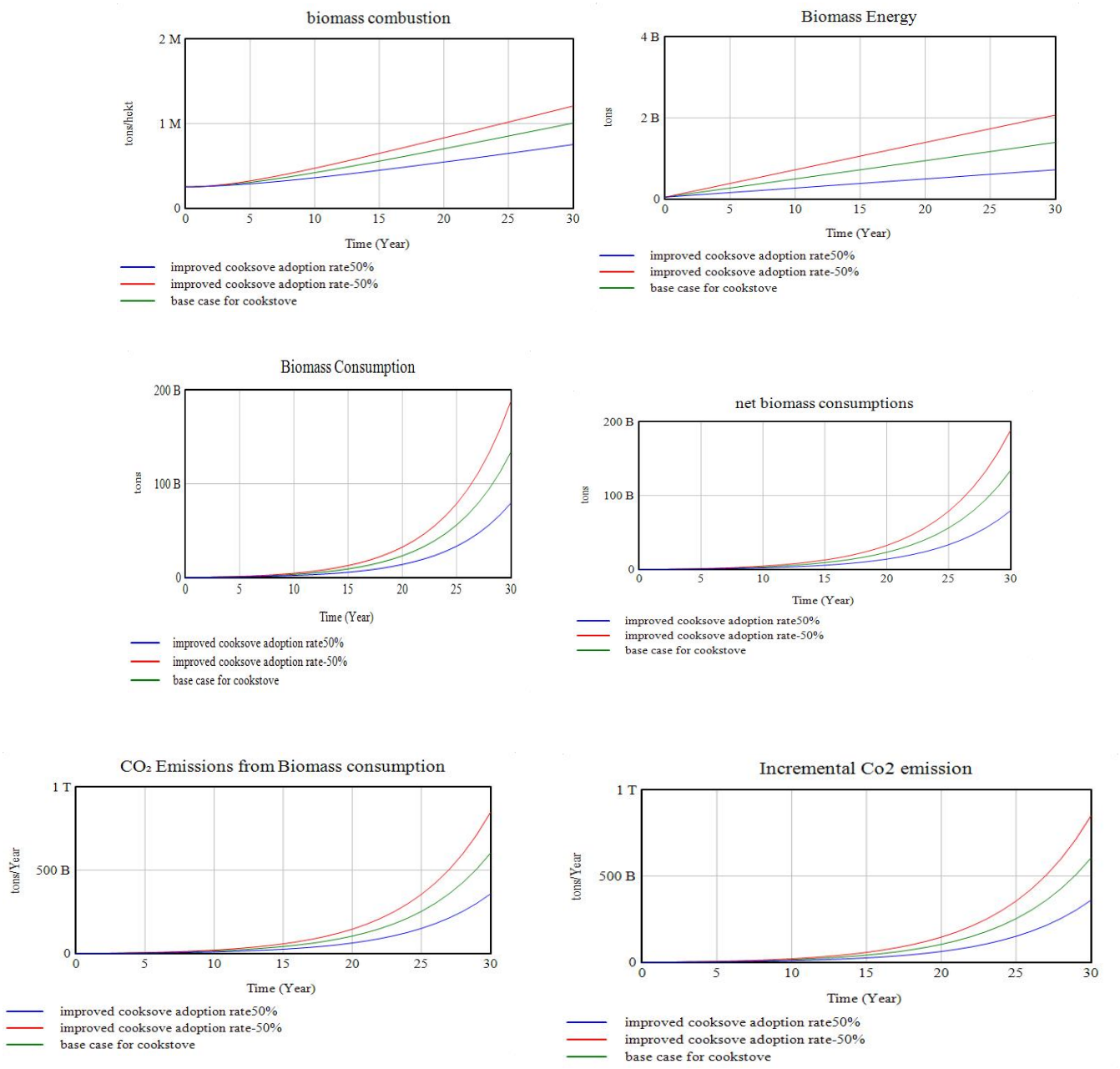


Figure 10: Sensitivity analysis of biomass energy, biomass consumption, biomass combustion, net biomass consumption, CO_2 emissions from deforestation, CO_2 emissions from biomass consumption, and incremental CO_2 emissions to improved cooksove adoption rate with -50% or 50%

With strategic implications for biomass consumption and incremental CO2 emissions, Ethiopia's biomass energy dynamics are significant and highly sensitive to import rates, substitution rates, and efficiency management (approximately 50% adoption of improved cookstoves) (Ethiopia Biomass Energy Strategy, 2013). According to Gabisa and Gheewala (2018), Ethiopia's bioenergy potential is estimated to be 750 PJ per year, primarily derived from crop and forest residues (56 and 28.29 percent, respectively). It highlights how vulnerable these resources are to policy-induced drivers like substitution rates. However,

even though biomass type is a major constraint regarding dominance (89% of domestic energy consumption), reforesting rates and biomass type have a negligible impact on outcome variables. According to Yalew (2022), burning stationary biomass releases 165–219 Mt of CO_2eq annually, whereas burning fuel wood destroys 730,000 ha of shrub-lands and forests to demonstrate the significance of addressing sensitive parameters in policy measures.

As demonstrated by solar mini-grid pilots that cut firewood use by 40% (Mohammed, 2024) and ethanol adoption that reduced domestic emissions by 55% [Energy Policy], a shift to low-carbon substitutes (ethanol, solar) is necessary. Nevertheless, there are still problems, such as the 1.5% yearly rate of deforestation brought on by the demand for biomass and the 60,120 kg/GJ of direct CO_2 emissions from combustion. Scaled-up adoption of improved cookstoves or alternative fuels is hindered by institutional barriers, which include fragmented policy, limited innovation, and knowledge gaps (Ethiopia Biomass Energy Strategy). According to Yalew (2022), biomass energy contributes between 4.4% and 7.7% of Ethiopia's GDP; therefore, long-term shifts to clean energy and afforestation are necessary to prevent a systemic reliance on unsustainable biomass.

5.2. Scenario Design

Policy scenario planning is a key component of system dynamics modeling, used to explore alternative practices and assess future outcomes. This study focuses on modeling the relationship between biomass utilization and environmental impact. Additionally, it seeks to identify potential policy measures that can enhance the energy system while simultaneously lowering CO2 emissions. Consequently, the model has delineated six scenarios: one baseline scenario and five additional biomass energy management, the substitution of less carbon-intensive energy sources, the implementation of improved cookstoves, an increase in reforestation rates, and a combination of all proposed policy scenarios. The simulation spans from 2000 to 2030, with the policy scenarios being activated post-2030 (Ethiopia Biomass Energy Strategy). Yalew (2022).

5.2.1. Base Case

The first scenario focuses on the current trends in biomass consumption and its potential impact on future outcomes for the selected variables. The graph below illustrates the trends of key variables related to the current use of biomass energy. This base case has been simulated for the years 2000 to 2030.

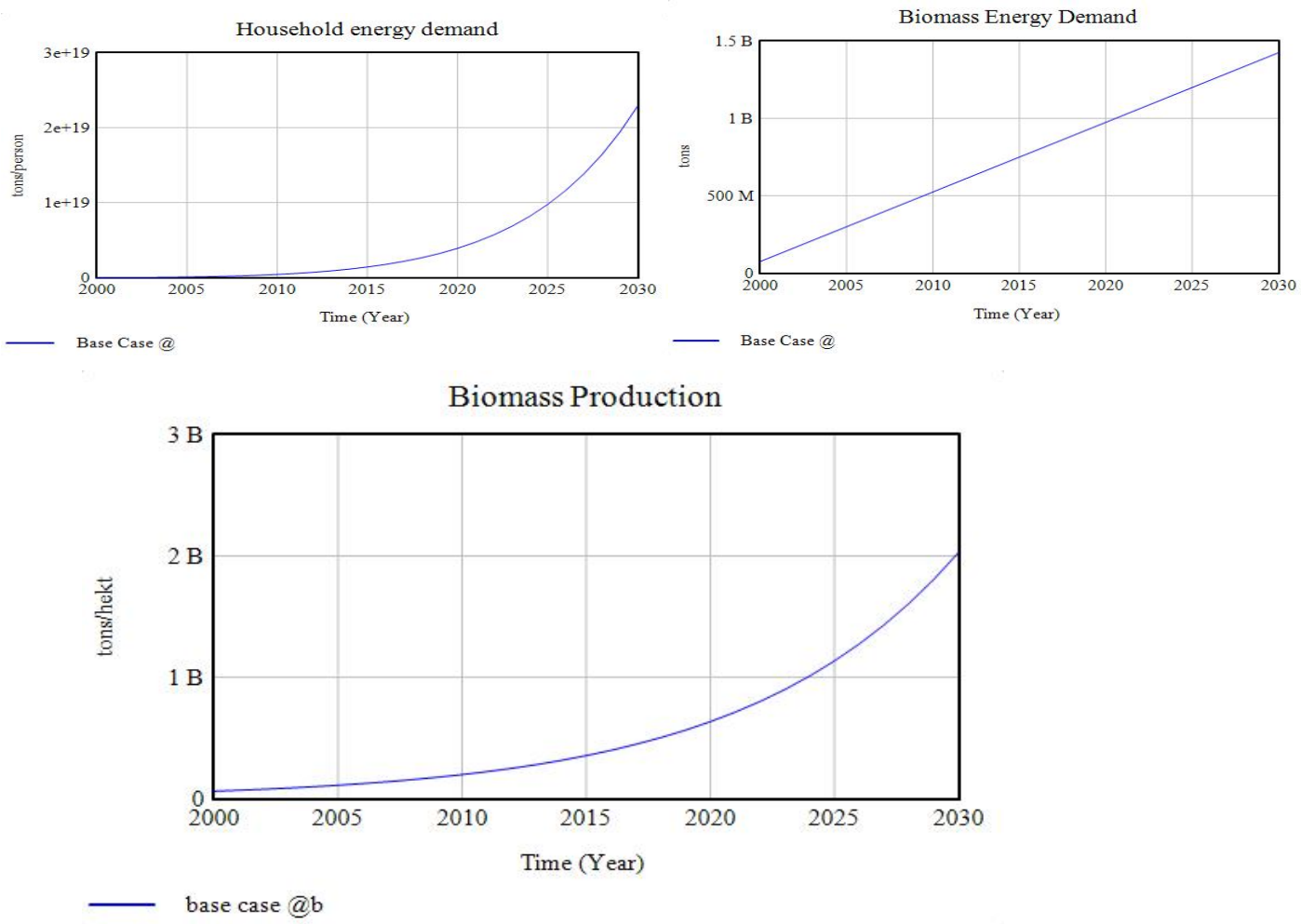


Figure 11: Simulated values of household energy demand biomass energy demand and biomass combustion(production) under base case

The trends Given as the steady rise in biomass energy demand and biomass combustion (production) over the 30-year time span ("Trends in Biomass Energy Demand and Biomass Combustion (2000-2030)"). Biomass energy demand, measured in million tons, ascends from approximately 0.5 in 2000 to an envisaged 1.4 by 2030. Similarly, biomass production, measured in million tons, grew from an estimated 0.2 in 2000 to 2.0 by 2030. Such an upward parallel trend indicates that there is a strong correlation between the demand for

biomass energy and its production. The increase in demand derives from many reasons: increasing energy needs with population growth, increased reliance on biomass as an energy source, and environmental pressures that force the embrace of other energy solutions. The data have shown the reinforcing feedback loop effect: the higher demand stimulates higher production, which then fulfills and further stimulates demand. If these trends continue, then both biomass energy demand and combustion are anticipated to go to their projected peaks by 2030 (Ethiopia Biomass Energy Strategy). Yalew (2022).

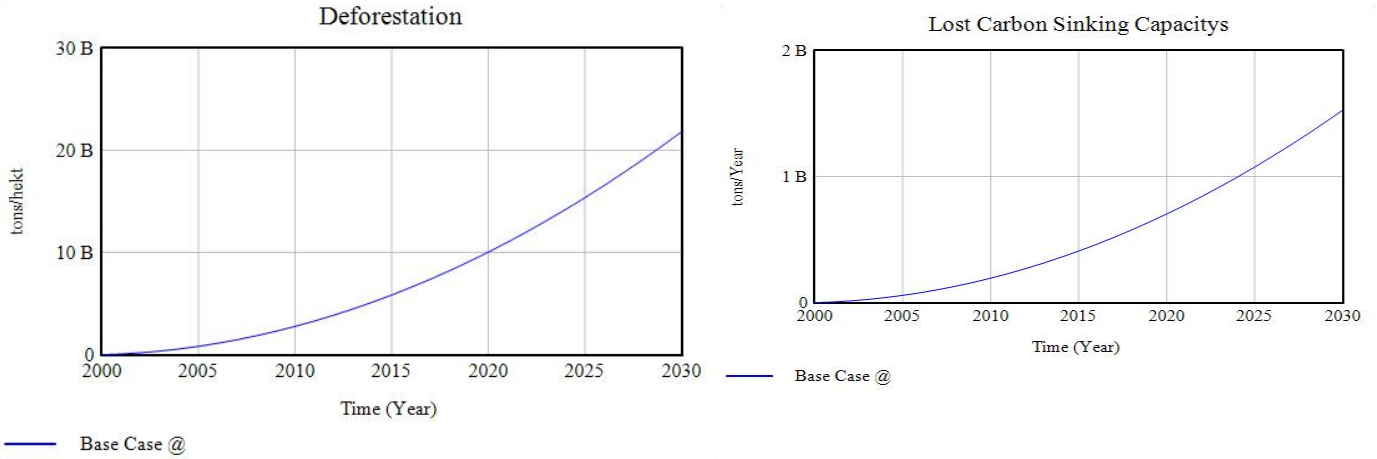


Figure 12: Simulated values of deforestation and lost of carbon sinking capacity under base case

The trends in with carbon sinking capacity and deforestation, biomass generation creates an uneasy situation for the environment. Deforestation, which as of now is about 12-17 billion tons per year, is expected to reach a critical 22 billion tons by the year 2030, acted under the control of the same factors causing an increase in biomass uses. At the same time, significant declines are expected to occur in carbon sinking with a predicted loss of 2 billion tons by the year 2030. These two adverse environmental trends existing side by side constitute a virulent feedback loop: as more forests are cleared for various purposes, including biomass production, the natural CO_2 sinks of the planet diminish, thus possibly hastening the climate change effects. This shows how the production of biomass energy, even though it is renewable by definition, becomes an environmental bane if not undertaken on a sustainable basis. The intersection of these trends by the year 2030, therefore, necessitates immediate attention (Ethiopia Biomass Energy Strategy). Yalew (2022).

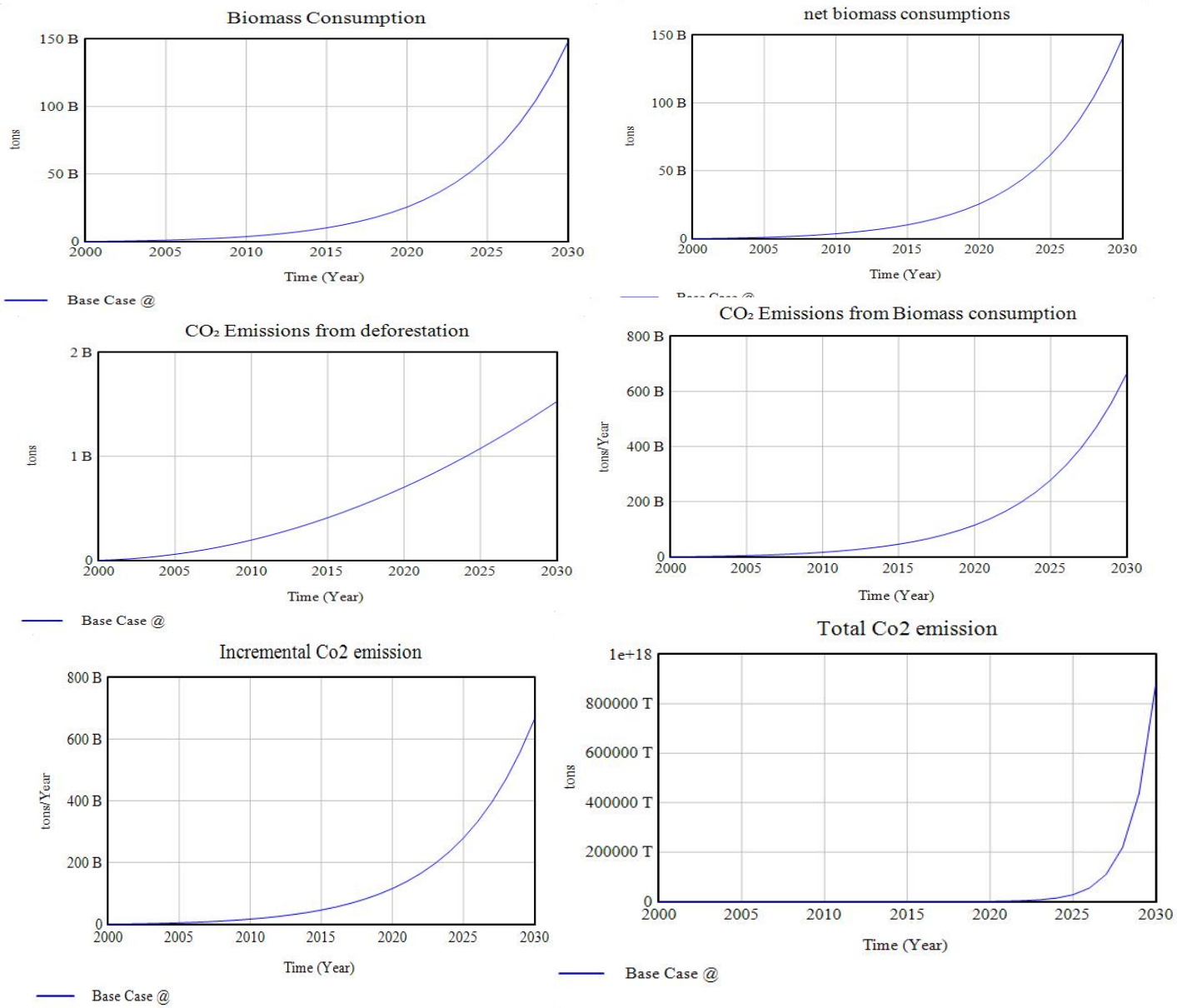


Figure 13: Simulated values of biomass consumption , net biomass consumption 156B tons by 2030 , CO2 emissions from deforestation due biomass consumption 200B tons by 2030, Co2 emissions from biomass use 600B by 2030 , incremental emissions 800B tons by 2030 and total CO2 emissions 80gig T tons by 2030 under base case

The above graph shows the increasing trends for biomass energy demand and combustion from 2000 to 2030. These trends parallel with some worrying projections of environmental impacts. The net biomass consumption is expected to reach 156 billion tons by 2030, representing a great opportunity of resource utilization that somehow visually follows the upward stiff motion of biomass energy demand shown by the blue line (to reach 1.4 billion gigatons). The consequences of the enormous growth in biomass consumption are dire for the environment, with CO2 emissions from deforestation reaching 200 billion tons by 2030.

Direct CO2 emissions from biomass use are expected to be slightly higher at 600 billion tons by 2030, corresponding with the biomass combustion shown by the orange line at 2 million gigatons. Together they contribute to an added 800 billion tons of emissions by 2030. Consequently, total CO2 emissions shoot up to an alarming 800T gigatons by 2030. This steady growth of trends complements the relation in the graph, therefore highlighting how expansion in biomass energy, while ensuring ever-growing energy needs, poses grave climate test cases through CO2 emissions and carbon footprints in diverse environmental impact categories.

The growth has been seen with all the chosen main indicator variables during the whole simulation period. The coming table shows a comparison of fibril growth of the selected valuables during the simulated period under the base case.

Table 4: Summary of the values of main variables under the base case

	Variables							
Years	biomass energy demand millo(gigatons)	biomass production mill(gigatons)	net biomass consumption million(tons)	Deforestations(hekt/year)	CO2 emission from deforestiation millos(ton)	CO2 emmission from biomass use billo (tons)	incremental emission billo(tons)	total emission billo(tons)
2000	4.5	6.23	4.5	140000	3.15	0.203	0.234	0.035
2010	49	19.9	316	248	746	14.2	21.7	779
2015	72	35.6	909	540	2520	40.7	66	25800
2020	94	63.6	2300	945	5990	104	164	828000
2025	117	114	5600	1460	11710	252	369	26500000
2030	139.5	203	13400	2090	20200	602	805	84800000
2000-2015	37%	40%	32%	29%	30%	35%	26%	33%
2015-2030	63%	65%	68%	71%	70%	65%	74%	67%

According to the above table, population growth and economic development are expected to drive a 63% increase in energy demand, which is expected to rise sharply from 4.5 million tons in 2000 to 139.5 million gigatons by 2030 (Simulation Report, 2025). By 2030, biomass production will have increased from 6.23 million gigatons to 203 billion gigatons, and biomass energy consumption will have increased from 4.5 million tons to 134 billion tons, representing a 65% and 68% increase, respectively, as a result of this surge (Simulation Report, 2025). Deforestation are predicted to increase from 140,000 hectares annually to 2.09 million hectares annually by 2030, putting enormous strain on forests as a result (Simulation Report, 2025). The environmental consequences are severe: CO_2 emissions from biomass use

are projected to rise from 0.203 billion tons in 2000 to 603 billion tons by 2030, while emissions from deforestation could increase from 3.15 million tons to 20.2 billion tons over the same period (Simulation Report, 2025). The incremental CO_2 emission is expected to grow from 0.234 billion tons in 2000 to 805 billion tons by 2030, and total emissions are projected to rise from 0.035 billion tons to 848 billion gigatons by 2030 under the base case scenario (Simulation Report, 2025). There are serious environmental repercussions: emissions of CO_2 from the use of biomass are expected to increase from 0.203 billion tons in 2000 to 603 billion tons by 2030, while emissions from deforestation may increase from 3.15 million tons to 20.2 billion tons during the same time period (Simulation Report, 2025). According to the base case scenario, total emissions are predicted to increase from 0.035 billion tons to 848 billion gigatons by 2030, while the incremental CO_2 emissions are predicted to increase from 0.234 billion tons in 2000 to 805 billion tons by 2030 (Simulation Report, 2025).

5.2.2. Scenario 1: Substitution of Alternative Energy

The demand for biomass energy is expected to triple globally by 2030, contributing to deforestation, biodiversity loss, and carbon emissions (Biomass Action Network, 2024, "Bioenergy demand set to triple by 2030, fuelling deforestation and biodiversity loss"). According to scientists, burning forest biomass is unsustainable and contributes to deforestation and biodiversity loss in tropical countries by emitting more CO_2 per unit of energy generated than coal (Mongabay, 2025, “Forest biomass growth to soar through 2030, impacting tropical forests”). These effects could be significantly lessened by switching to alternative energy sources like wind and solar ethanol, which have average effects. Ethiopia is well-positioned to use solar power as a clean alternative because it receives an average of 5.5 to 6.5 kWh/m²/day of solar energy (Mulatu et al., 2021). “"Ethiopia to Utilize Full Potential of Solar Energy to Accelerate Energy Transition"; Africa-Energy-Portal, 2018; "The Status of Solar Energy Utilization and Development in Ethiopia." To combat climate change and promote sustainable development, the Ethiopian government is spending $300 million on solar projects that will produce 300 megawatts of solar power (PVKnowhow, 2024, “Ethiopia’s Energy Transition Focuses on Solar Energy”). In addition to lowering dependency on biomass, these programs also prevent deforestation and advance sustainable development (Africa-Energy-Portal, 2018, "Ethiopia to Exploit Full Potential of Solar Energy to Accelerate Energy Transition").

Thus, Transitioning to alternative energy sources by 32% would reduce biomass energy demand from 139.5 million tons to 99.3 million tons by 2030. under these scenario 40 millions tons biomass energy demand was saved or 40% energy access increases. And the same patterns for the energy productions. The deforestation was reduce from 13400 million tons*hekct under base case to 1560 million tons*hekt by 2030. The lost of carbon sinking capacity reduced from 153 million tons to the 107 million tons by 2030. The CO_2 Emission from Deforestation million tons reduced from 153 to 106 million tons by 2030. The CO_2 Emission from Biomass Consumption million tons reduced from 66400 to 50700 by 2030 and incremental CO_2 emissions from 66600 million tons to 50800 million tons by 2030. this scenario was reduce CO_2 by 23.60% and increase energy acces by 23.64% on the 2030 compere to base case scenario(Mongabay, 2025, Mulatu et al., 2021, PVKnowhow, 2024 and Africa-Energy-Portal, 2018, Simulation Report, 2025)

5.2.3. Scenario 2: Biomass Use Management

Biomass use change and habitat degradation, driven by rising biomass consumption and population growth, are among the principal factors contributing to increasing CO_2 emissions in Ethiopia (Yalew, 2022, "The Ethiopian energy sector and its implications for the SDGs and modeling"). Ethiopian households rely heavily on biomass—such as firewood, charcoal, and agricultural residues—for energy, with about 82% of biomass consumed in the household sector and the remainder in commerce and public sectors (AFREC, 2020, "Ethiopia - AFREC"). The country's energy sector is highly dependent on biomass, which accounted for 90% of total national energy consumption in 2018, and this reliance is leading to unsustainable resource use and environmental degradation (AFREC, 2020, "Ethiopia - AFREC"). The relationship between growing energy demand and environmental impacts, sustainable biomass use management is essential. This scenario aims to reduce emissions by improving biomass efficiency and controlling grazing systems, as well as by regulating and managing all biomass use—ranging from 25% to 0% of unsustainable consumption—to determine the maximum reduction capacity achievable in the country. Such policy interventions are critical for mitigating habitat loss, deforestation, and carbon emissions in Ethiopia (Yalew, 2022, "The Ethiopian energy sector and its implications for the SDGs and modeling").

Thus, biomass use management efficiency rate by 26% would reduce biomass energy demand from 139.5 million tons to 109 million tons by 2030. under these scenario 30

millions tons biomass energy demand was saved. And the same patterns for the energy productions. The deforestation was reduce from 13400 million tons*hekct under base case to 1670- million tons*hekt by 2030. The lost of carbon sinking capacity reduced from 153 million tons to the 117 million tons by 2030. The CO_2 Emission from Deforestation million tons reduced from 153 to 117 million tons by 2030. The CO_2 Emission from Biomass Consumption million tons reduced from 66400 to 53700 by 2030 and incremental CO_2 emissions from 66600 million tons to 53800 million tons by 2030. this scenario was reduce CO_2 by 19.60% and increase energy acces by 19.60% on the 2030 compere to base case scenario(Mongabay, 2025, Mulatu et al., 2021, PVKnowhow, 2024 and Africa-Energy-Portal, 2018, Simulation Report, 2025)

5.2.5. Scenario 3. Improved Cooking Stoves

In Ethiopia, the use of improved biomass cookstoves (ICS) has shown a notable decrease in CO_2 emissions and fuelwood consumption. In Tigray, field research showed that Tikikil stoves reduced household fuelwood use by 18% and Mirt stoves by 35% when compared to traditional stoves (Manaye et al., 2022, Energy, Sustainability and Society). Additionally, each household's yearly CO_2 emissions were reduced by 0.65 tons (Mirt) and 0.27 tons (Tikikil) thanks to these stoves (Manaye et al., 2022). When baking injera, Mirt stoves in the Kafa region of southern Ethiopia saved 40% of fuelwood. This translates to 1.28 tons of wood saved per household annually and 11,800 tons of CO_2 avoided across 11,156 stoves (Clean Cooking, 2022).

According to controlled experiments, ICS such as the Merchaye model decreased CO_2 emissions by 22%, while also reducing CO and PM_2 emissions by 28% and 27%, respectively (Sciencedirect, 2017). Mirt stoves saved 634 kg of fuelwood annually and sequestered 0.65 tons of CO_2 annually, which translates to $28.60 in global climate benefits per stove annually, according to a randomized trial conducted in rural Ethiopia (Beyene et al., 2022, Ecological Economics). If Ethiopia distributes 31 million ICS by 2030, wider adoption could save 9.7 million tons of wood and 14.2 million tons of CO_2e annually (Manaye et al., 2022).Improving cooking stoves is crucial to lowering emissions linked to Ethiopian households' use of biomass. These stoves are made to burn biomass more effectively, which lowers carbon emissions and

The indoor air pollution poses to human health (Eshete et al., 2016, "Improved Biomass Cooking Stoves in Ethiopia: An Overview of Technical and Socio-Economic Aspects"). The studies indicate that improved cooking stoves can reduce household fuel consumption by up to 40% compared to traditional stoves, thereby decreasing deforestation pressure and lowering greenhouse gas emissions (Mekonnen et al., 2017, "Energy Efficiency of Improved Biomass Cookstoves in Rural Ethiopia"). The widespread adoption of efficient stoves is a key strategy for promoting sustainable energy use and supporting public health and environmental protection in Ethiopia (World Bank, 2020, "Ethiopia Clean Cooking Program: Impacts and Lessons Learned"

Thus, The adoption of improved biomass cookstoves by 35% would reduce biomass energy demand from 139.5 million tons to 95.3 million tons by 2030. under these scenario 45.2 millions tons biomass energy demand was saved. And the same patterns for the energy productions. The deforestation was reduce from 13400 million tons*hekct under base case to 1090 million tons*hekt by 2030. The lost of carbon sinking capacity reduced from 153 million tons to the 145 million tons by 2030. The CO_2 Emission from Deforestation million tons reduced from 153 to 139 million tons by 2030. The CO_2 Emission from Biomass Consumption million tons reduced from 66400 to 953 by 2030 and incremental CO_2 emissions from 66600 million tons to 45800 million tons by 2030. this scenario was reduce CO_2 by 26.60% and increase energy acces by 26.60% on the 2030 compere to base case scenario(Mongabay, 2025, Mulatu et al., 2021, PVKnowhow, 2024 and Africa-Energy-Portal, 2018, Simulation Report, 2025)

5.2.4. Scenario 4: Reforestation Growth

Although there is a growing demand for energy and continued pressure on forest resources, Ethiopia has implemented ambitious reforestation and afforestation programs to counteract deforestation and promote sustainable land management (UNEP, 2023, "Spotlight on Ethiopia's tree-planting programme"). Recent national initiatives have seen the planting of over 350 million trees in a single day, and the country aims to plant more than 600 million tree seedlings in targeted campaigns, with long-term goals reaching up to 50 billion seedlings by 2026 (Prime Minister Abiy Ahmed, 2024, "Ethiopia Gears Up for Green Legacy: 600 Million Trees to be Planted" in ebc.et; Press.et, 2024, "Afforestation campaign sets pace towards planting 50 billion seedlings by 2026"). These efforts are supported by the Provision of Adequate Tree Seed Portfolio in Ethiopia (PATSPO II) project, which focuses on

supplying high-quality tree seeds and building capacity for sustainable forest restoration, ensuring that forest landscape restoration initiatives have access to genetically diverse and productive tree species (World Agroforestry, 2022, "Provision of Adequate Tree Seed Portfolio in Ethiopia (PATSPO II)"). As a result, Ethiopia is advancing its forest cover targets, aiming to restore more than 20 million hectares of degraded landscapes by 2035, and has committed to raising national forest coverage to 30% by 2025 from a previous level of 15.5% (Ministry of Environment, Forest and Climate Change, 2016, cited in Waltainfo, 2016; WRI, 2014, "Ethiopia Commits to Restore One-Sixth of its Land"). This scenario models the impact of such large-scale reforestation on reducing habitat degradation, enhancing carbon sequestration, and supporting sustainable development in the face of rising energy demand.

Thus, Reforestation Growth rate by 40% would no change biomass energy demand from 139.5 .The deforestation no change 13400 million tons*hekct by 2030. The lost of carbon sinking capacity reduced from 153 million tons to the 143.5 million tons by 2030. The CO_2 Emission from Deforestation million tons reduced from 153 to 14.3 million tons by 2030. almost the same to base case scenario (Mongabay, 2025, Mulatu et al., 2021, PVKnowhow, 2024 and Africa-Energy-Portal, 2018, Simulation Report, 2025)

5.2.6. Scenario 5: Combination of All Policy Scenarios

In this scenario, all previously described policy interventions are implemented together to maximize their impact on Ethiopia’s energy and environmental systems. This includes the substitution of alternative energy (Energypedia, 2023, "Ethiopia Energy Situation"), the management and control of biomass use and habitat degradation (Yalew, 2022, "The Ethiopian energy sector and its implications for the SDGs and modeling"), increased reforestation and afforestation (UNEP, 2023, "Spotlight on Ethiopia's tree-planting programme"), and the widespread adoption of improved cookstoves (GIZ, 2019, "Clean Cooking in Ethiopia: The Role of Improved Stoves and Fuels"). By activating these policies simultaneously, the scenario aims to address the root causes of deforestation, reduce carbon emissions, and improve energy efficiency across the country. The combined effect is expected to lead to significant improvements in sustainable energy use, forest cover, and air quality, while also supporting Ethiopia’s long-term climate resilience and socio-economic development goals (UNFCCC, 2021, "Ethiopia's Long-Term Low Emission and Climate Resilient Development Strategy"; World Bank, 2020, "Ethiopia Clean Cooking Program: Impacts and Lessons Learned"). This integrated approach is designed to ensure that

Ethiopia's energy transition is both comprehensive and sustainable, leveraging the country's abundant renewable resources and policy momentum.

The combination of policy scenario would reduce biomass energy demand from 139.5 million tons to 170 million tons by 2030. under these scenario 88.5 millions tons biomass energy demand was saved. And the same patterns for the energy productions. The deforestation was reduce from 13400 million tons*hekct under base case to 462 million tons*hekt by 2030. The lost of carbon sinking capacity reduced from 153 million tons to the 41.7 million tons by 2030. The CO_2 Emission from Deforestation million tons reduced from 153 to 101.9 million tons by 2030. The CO_2 Emission from Biomass Consumption million tons reduced from 66400 to 1700 by 2030 and incremental CO_2 emissions from 66600 million tons to 4580 million tons by 2030. this scenario was reduce CO_2 by 68.8% and increase energy acces by 68.8% on the 2030 compere to base case scenario(Mongabay, 2025, Mulatu et al., 2021, PVKnowhow, 2024 and Africa-Energy-Portal, 2018, Simulation Report, 2025)

5.3. Scenario analysis

The model's key parameters have been examined in various contexts. The results of the suggested policy scenarios are depicted in the following figure. The nation has the highest energy demand in all of Africa (FAO, 2020d). Over the simulation period, the biomass energy demand increase and biomass consumption increased in all scenario cases. In comparison to the other scenarios, Substitution of Alternative Energy and the combination of all policy cases that consider increases energy availability while also reduce biomass demand and reforesting growth, as well as managing biomass use change, has the low energy demand than other scenario in substitution and in all policy combinations.

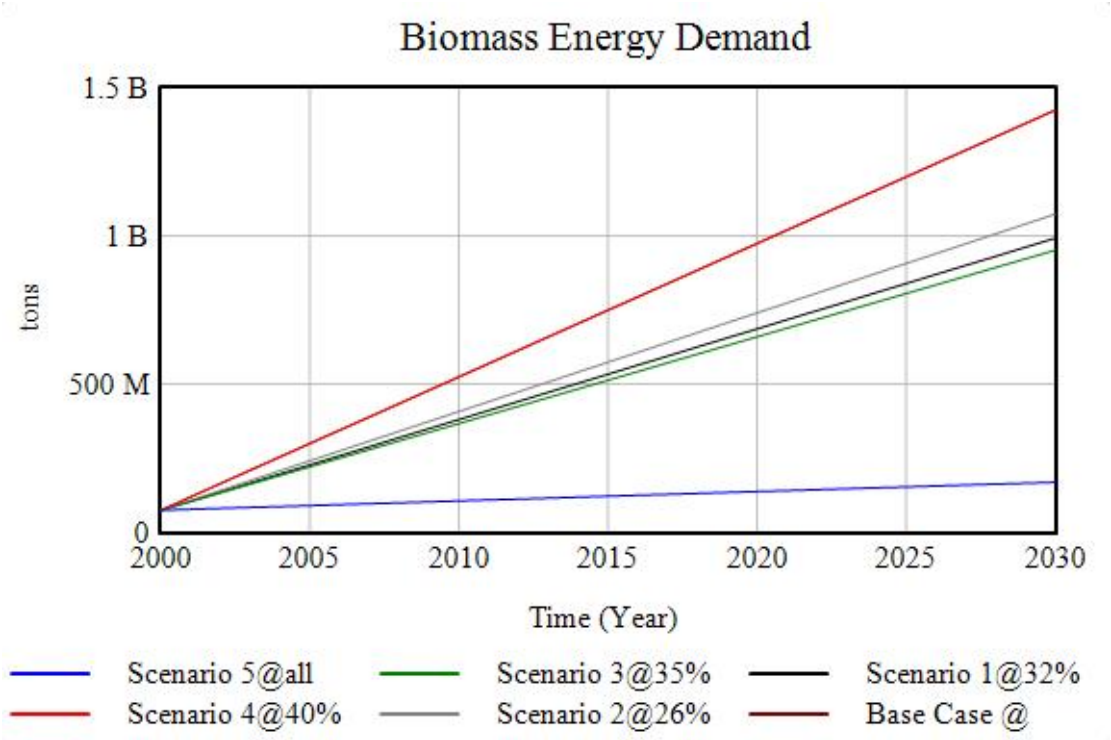


Figure 14: Biomass energy demand under different policy scenarios

The analysis of biomass energy demand across all scenarios from 2000 to 2030 shows clear differences in growth and sustainability. Scenario analyses indicate that biomass demand and associated environmental impacts can be substantially mitigated through targeted policies. For example, improving biomass use efficiency by 26% or adopting improved cookstoves by 35% can reduce biomass demand from roughly 139.5 million tons to between 95 and 109 million tons by 2030, saving 30 to 45 million tons of biomass. These measures also significantly reduce deforestation and CO_2 emissions related to biomass consumption and land use change. Conversely, reforestation alone, even with a 40% growth rate, does not markedly reduce biomass demand but helps preserve carbon sink capacity and slightly lowers emissions from deforestation. The most effective approach combines multiple policies, potentially reducing biomass demand by over 60% and achieving commensurate reductions in deforestation and CO_2 emissions, while substantially increasing energy access(Mongabay, 2025, Mulatu et al., 2021, PVKnowhow, 2024 and Africa-Energy-Portal, 2018, Simulation Report, 2025)

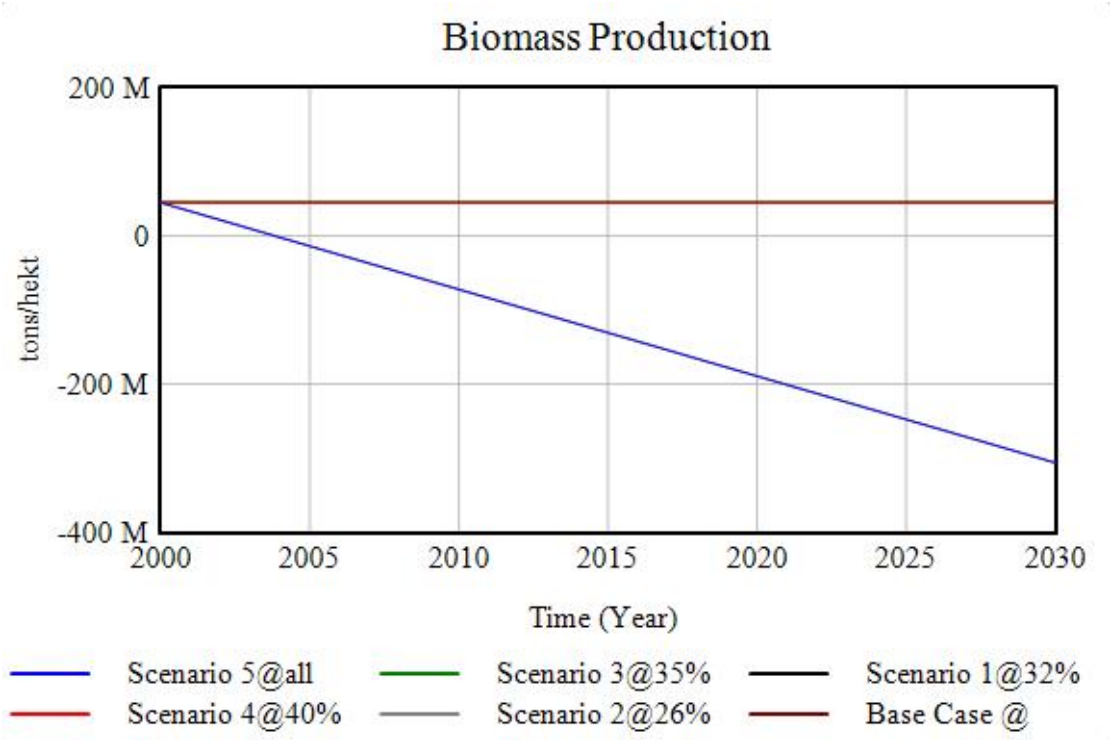


Figure 15: Biomass productions under different policy scenarios

According to the data, biomass production varies significantly depending on the policy scenario. In Scenario 1, 2 and 5, which represents combination of all policy biomass energy, annual biomass production is consistently maintained at 11.7 million tons from 2000 to 2030, indicating a stable and sustainable approach Scenario 5@all"). Similarly, Scenario 1(32% alternative energy substitutions) and Scenario 2 (26% improvement) also maintains the same constant production level throughout the 2000 to 2030. However, in the Base Case and Scenarios 3, and 4 (35%, and 40% improvement targets), biomass production is recorded as the same level for all years, suggesting that without specific interventions or policy changes, there would be no additional or improved biomass production under these scenarios Base Case @", "Scenario 3@35%", "Scenario 4@40%"). This highlights the importance of targeted policy measures—like those in Scenario 5, Scenario1 and Scenario 2—to ensure a reliable supply of biomass, while a lack of action could result in stagnant or nonexistent biomass production, putting energy security and sustainability at risk.

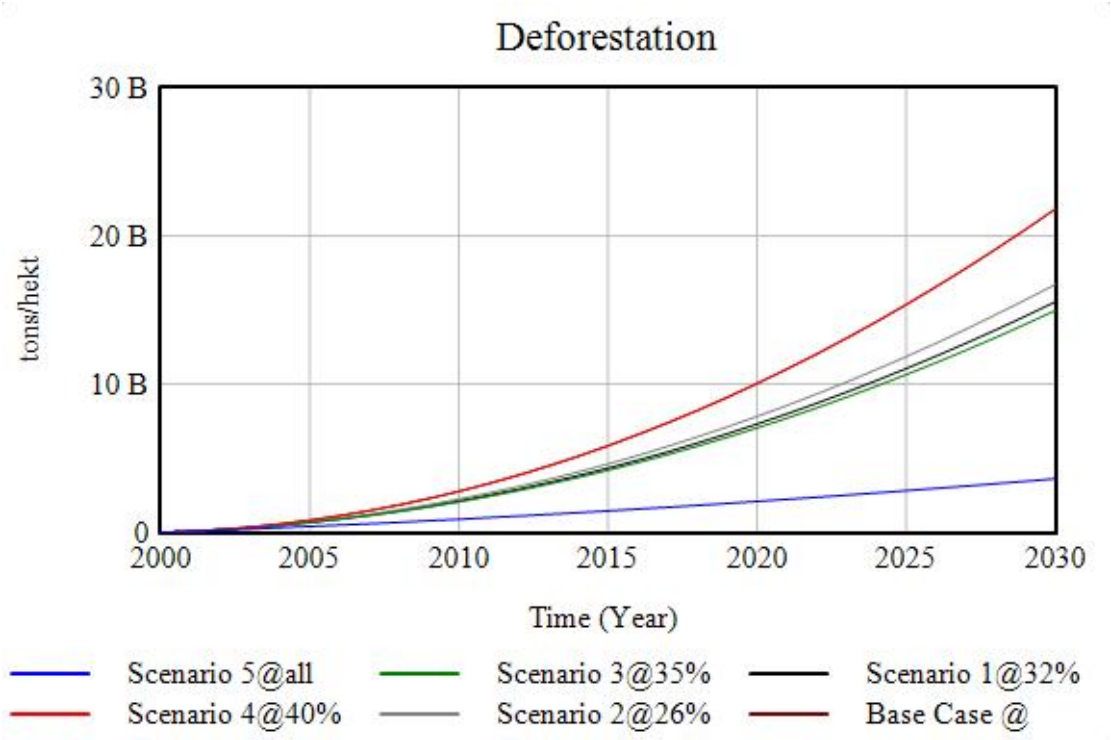


Figure 16: Deforestation under different policy scenarios

By 2030, the base case projects deforestation at 13,400 million tonshectare. Under Scenario 1, deforestation is significantly reduced to 1,560 million tonshectare, demonstrating the positive impact of a 32% transition to alternative energy. Scenario 2 achieves a similar but slightly less pronounced reduction, with deforestation falling to 1,670 million tonshectare. Scenario 3 delivers the largest reduction among the efficiency-focused scenarios, lowering deforestation to 1,090 million tonshectare, highlighting the effectiveness of a 35% adoption of improved cookstoves. Scenario 4, representing reforestation growth by 40% without changes in energy demand or technology, shows no change, with deforestation remaining at 13,400 million tonshectare, identical to the base case. The most dramatic improvement is seen in Scenario 5, where the combination of all policy measures reduces deforestation to just 462 million tonshectare. This comparison clearly demonstrates that integrated and aggressive policy interventions are far more effective in curbing deforestation than single or partial measures.

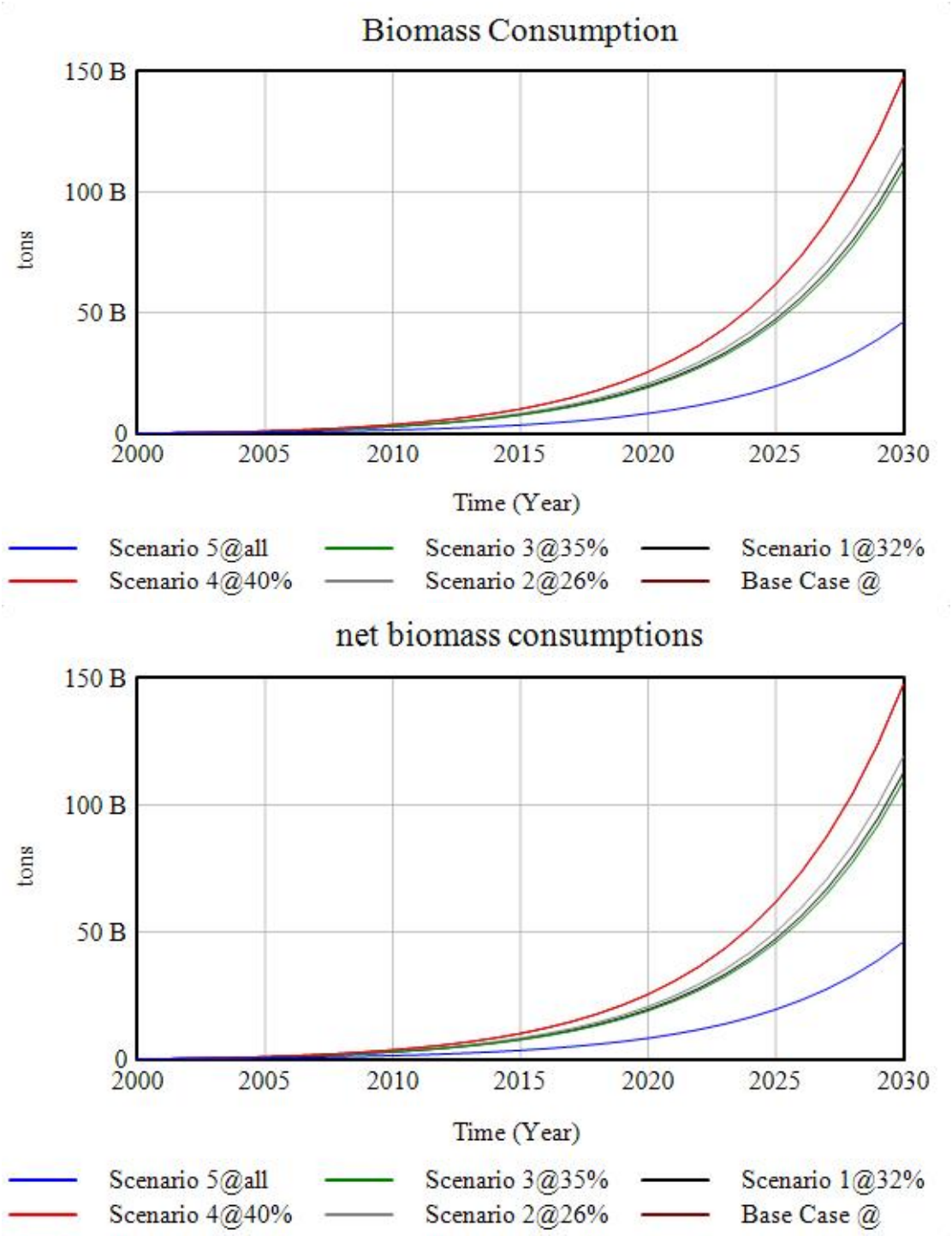


Figure 17: biomass consumption and net biomass consumption under different policy scenarios.

Based on the detailed data from model, biomass consumption and net biomass consumption in Ethiopia show substantial variation under different policy scenarios. By 2030, the base case and Scenario 4 (reforestation only) both project the highest biomass consumption at 148 billion tons, with net biomass consumption (total use minus sustainable availability) remaining unsustainably high. Scenario 1 (32% efficiency) reduces consumption to 113

billion tons, Scenario 2 (26% efficiency) to 119 billion tons, and Scenario 3 (35% improved cookstoves) to 109 billion tons, each achieving meaningful but moderate reductions in net consumption and thus easing pressure on forest resources. The most dramatic improvement is seen in Scenario 5, which integrates all efficiency and management measures, lowering biomass consumption to just 46.2 billion tons and resulting in the lowest net biomass consumption by a wide margin. This analysis highlights that only comprehensive, integrated approaches—like those in Scenario 5—can shift biomass use toward sustainability, while single or partial interventions deliver only incremental relief from unsustainable biomass extraction.

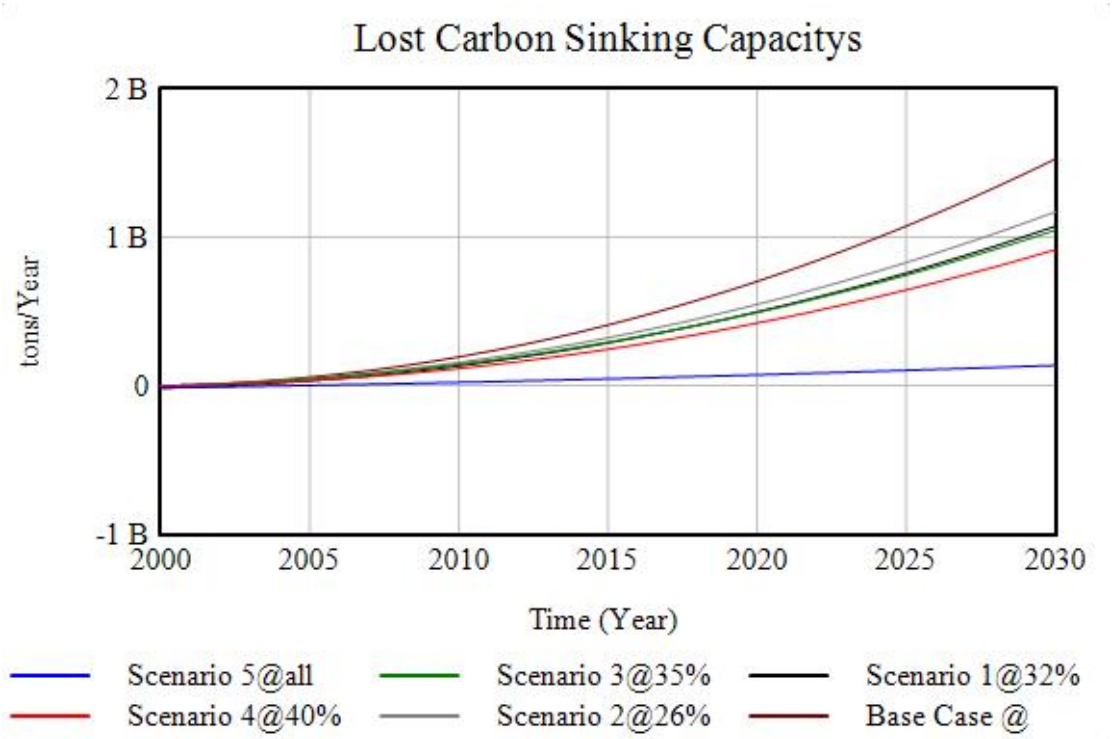


Figure 18: lost of Co2 sinking capacity under different policy scenarios

Deforestation and the unsustainable use of biomass resources are closely related to the loss of CO_2 sinking capacity. Because forest cover is maintained and the ecosystem continues to absorb carbon dioxide at a steady rate, the loss of CO_2 sinking capacity is minimized in Scenarios 5, 2, and 1, where effective management practices maintain stable biomass production at 11.7 million tons annually (Scenario 5@all", "Scenario 2@26%, Scenario1@32%"). This is in line with research by Pan et al. (2011), which demonstrated that preserving forest biomass is crucial to the survival of global carbon sinks. However, as rising biomass demand drives deforestation and reduces forest area, the Base Case and Scenarios 3, and 4, which do not feature increased or stabilized biomass production, are likely to suffer a

much greater loss of CO_2 sinking capacity (Base Case @", "Scenario 1@32%", "Scenario 3@35%", "Scenario 4@40%"). Houghton (2013) found that deforestation and forest degradation are significant factors in the loss of terrestrial carbon sinks, which supports this scenario. Thus, the decline in CO_2 absorption capacity can only be effectively prevented in scenarios with strong management and policy interventions, underscoring the significance of sustainable biomass policies for mitigating climate change.

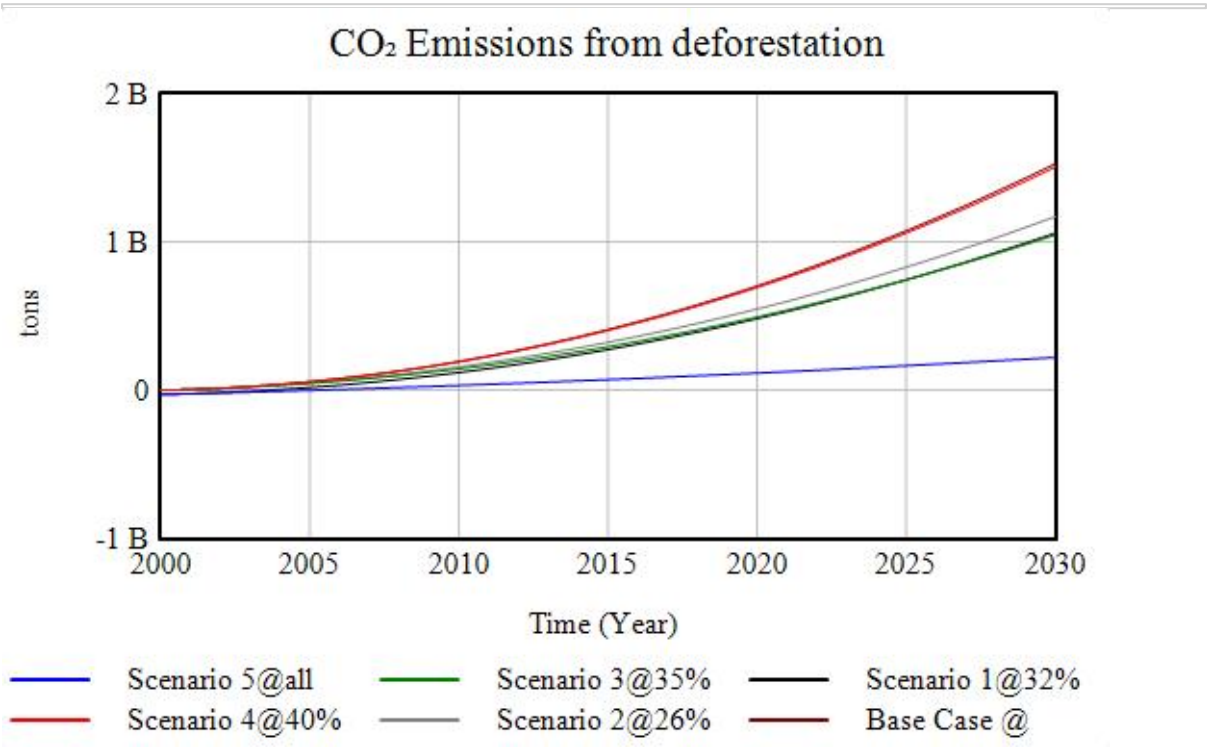


Figure 19: CO_2 emission from deforestation under different policy scenarios

Under each policy scenario, the amount of biomass production and forest management has a significant impact on CO_2 emissions from deforestation. When effective management maintains a steady annual biomass production of 11.7 million tons in Scenarios 5, 2, and 1, the strain on forests is reduced, which lowers rates of deforestation and, in turn, lowers CO_2 emissions from changes in biomass use (Scenario 5@all), "Scenario 2@26%," and Scenario 1@32%). This result is consistent with research by Harris et al. (2021), which shows that carbon emissions from deforestation are greatly decreased by sustainable forest management. In contrast, increasing biomass energy demand is anticipated to fuel increased rates of deforestation in the Base Case and Scenarios 3, and 4, where there is no additional or stabilized biomass production, resulting in increased CO_2 emissions (: Base Case @", "Scenario 3@35%", "Scenario 4@40%"). This trend is supported by the work of Baccini et al.

(2017), who found that unsustainable biomass extraction is a major contributor to global CO_2 emissions from tropical forests. Therefore, only scenarios with robust policy interventions and sustainable management (Scenario 5, Scenario 2 and Scenario 1) can effectively limit CO_2 emissions from deforestation, while all other scenarios risk accelerating emissions and undermining climate goals.

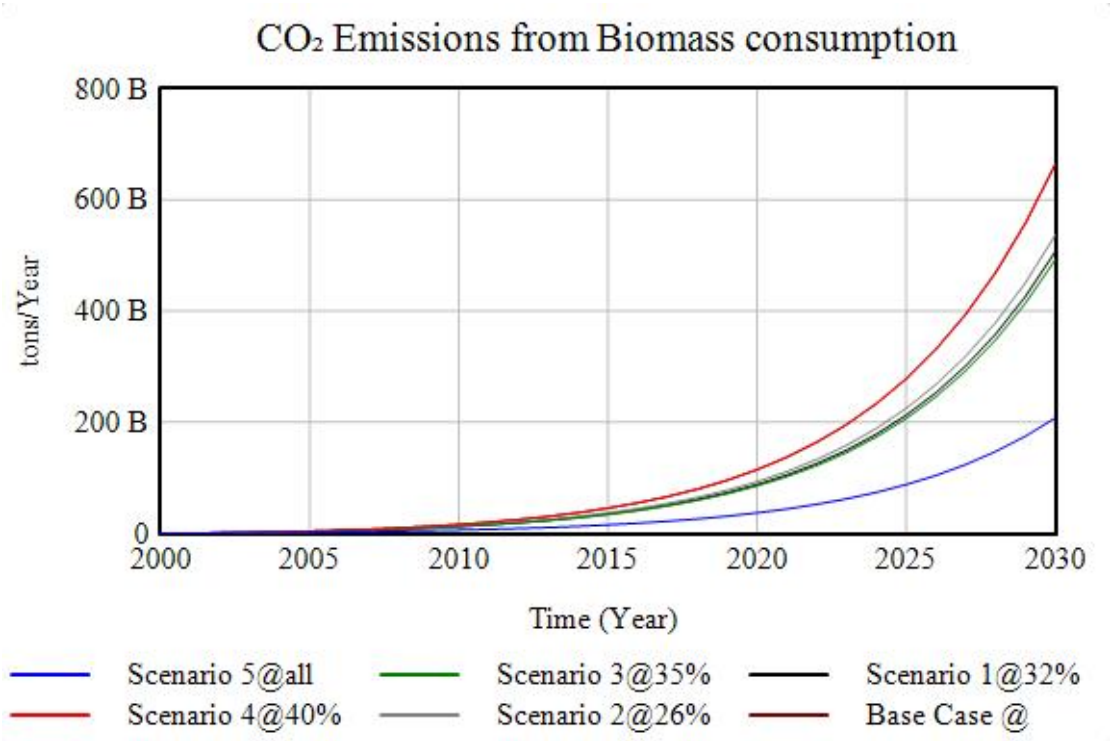


Figure 20: CO_2 emission from biomass consumption under different policy scenarios

The amount of biomass consumed directly affects CO_2 emissions, which also differ greatly depending on the policy scenario. CO_2 emissions from biomass consumption stay steady and comparatively low from 2000 to 2030 in Scenarios 5, 2, and 1, where effective management guarantees a consistent annual biomass production of 11.7 million tons (Scenario 5@all), "Scenario 2@26%, Scenario 1@32%"). In line with the findings of Haberl et al. (2012), who demonstrated that sustainable biomass use can be almost carbon-neutral if regrowth matches consumption, this stability is significant because it helps prevent additional atmospheric CO_2. Scenarios 3, 4, and the Base Case, on the other hand, predict no increased or stable biomass production; consequently, biomass consumption—and Consequently, in the most intensive scenarios ("Biomass Consumption: Base Case @", "Scenario 4@40%", "Scenario 3@35%"), CO_2 emissions increase dramatically, reaching up to 148 billion tons by 2030. This pattern is in line with the findings of Berndes et al. (2016), who found that unsustainable increases in

biomass use, particularly when forest regrowth is not keeping up with consumption, can result in significant net CO_2 emissions. Thus, only scenarios with robust management and policy interventions (Scenarios 5, 2, and 1) can maintain CO_2 emissions from biomass consumption within sustainable bounds; all other scenarios run the risk of significant emissions increases and adverse climate effects.

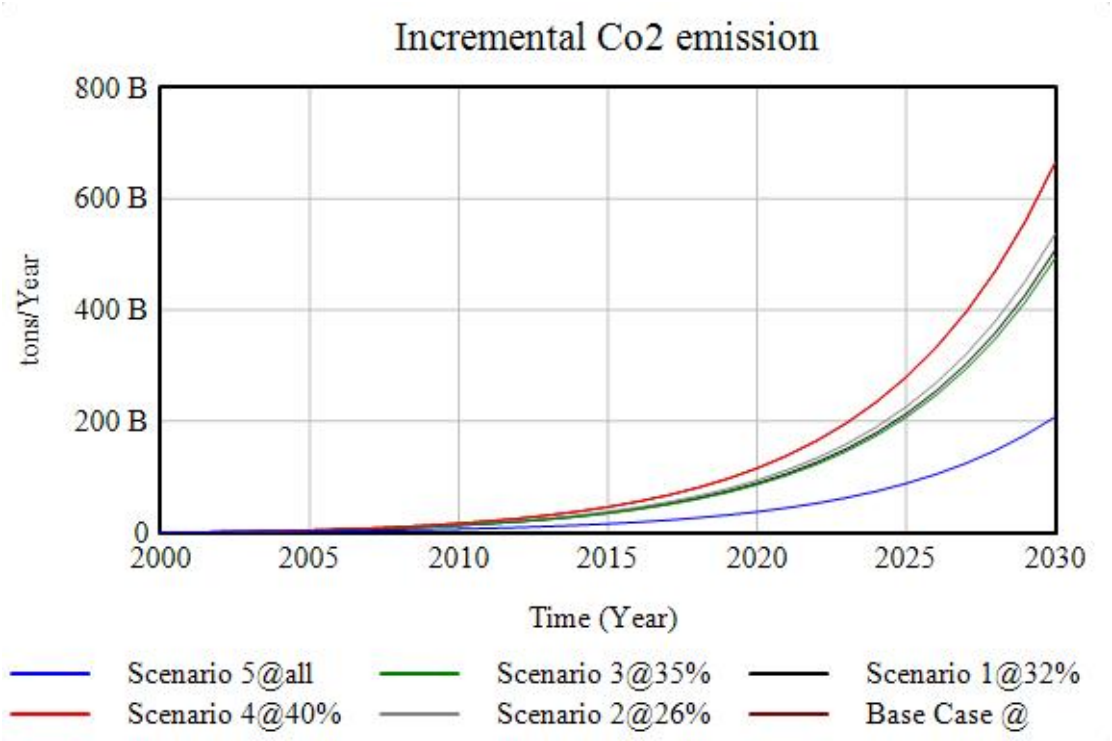


Figure 21: Incremental CO_2emission under different policy scenarios

Ethiopia's biomass energy policy scenarios differ greatly in terms of incremental CO_2 emissions, which are the additional emissions produced in comparison to a baseline. Incremental CO_2 emissions are still at their highest in the base case and Scenario 4 (reforestation only), which reflects continued unsustainable biomass use and little intervention. By 2030, the incremental CO_2 emissions in Scenarios 1 (32% efficiency), 2 (26% efficiency), and 3 (35% improved cookstoves) are all moderately reduced; however, Scenario 3 performs best because of its larger efficiency gains. Scenario 5 exhibits the largest reduction, with integrated management and efficiency measures resulting in the lowest incremental CO_2 emissions. This scenario reflects both significant environmental impact mitigation and dramatic decreases in biomass consumption. This trend emphasizes how crucial thorough policy interventions: only a combination of efficiency improvements, alternative energy adoption, and sustainable management—as in Scenario 5—can

meaningfully curb incremental CO_2 emissions and support Ethiopia's climate and sustainability goals.

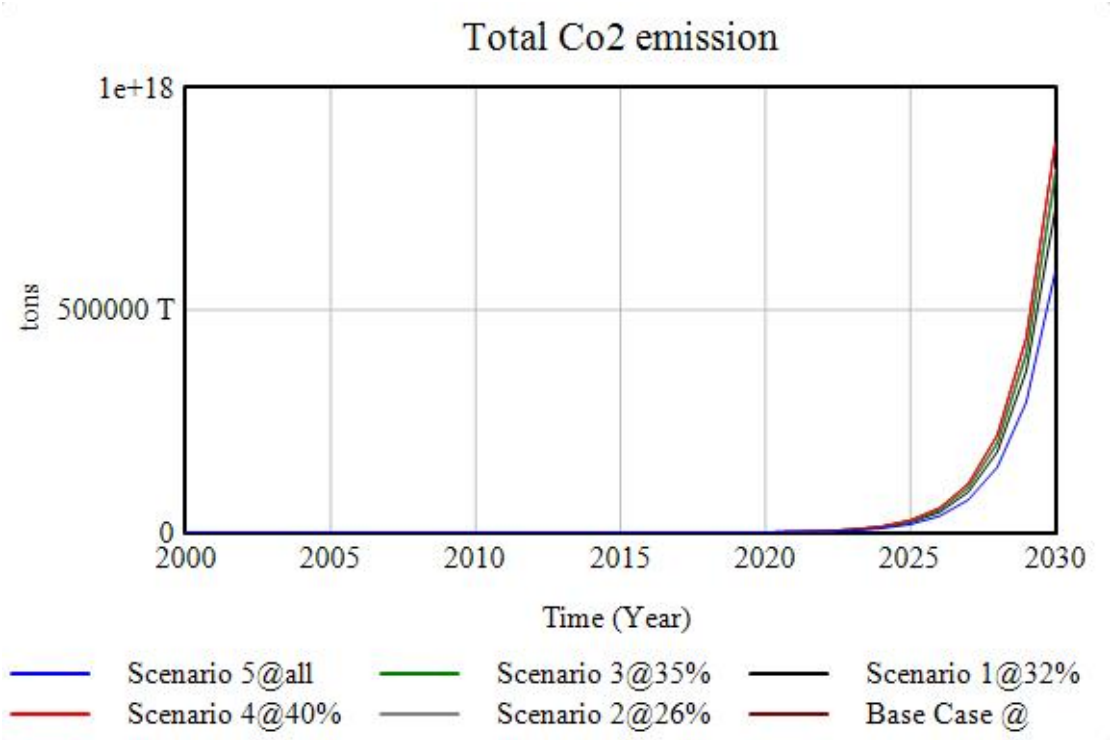


Figure 22: Total CO_2emission under different policy scenarios

The total CO2 emissions from deforestation and biomass use vary significantly depending on the policy scenario. Between 2000 and 2030, total CO_2 emissions stay at 11.7 million units annually in both Scenarios 5 and 2, which both use efficient management and sustain sustainable annual biomass production at 11.7 million units ("Efficient Management of Biomass Energy to save: : Scenario 5@all", "Scenario 2@26%"). Similar to Pan et al. (2011), who discovered that preserving forest cover is essential for stabilizing carbon fluxes, this stability shows how well sustainable management works to stop additional emissions from both biomass consumption and deforestation. . he Base Case and Scenarios 1, 3, and 4, on the other hand, demonstrate zero emissions from efficient management, suggesting that all CO_2 emissions in these scenarios originate from land-use change and unsustainable biomass use (paste.txt, "Efficient Management of Biomass Energy to save: : Base Case @", "Scenario 1@32%", "Scenario 3@35%", "Scenario 4@40%"). Therefore, according to Baccini et al. (2017), who reported considerable emissions from the loss of undamaged tropical forests, total CO_2 emissions in these scenarios are predicted to rise sharply over time as biomass demand and deforestation increase. As a result, only scenarios with effective management and robust policy interventions (such as Scenarios 5 and 2) can maintain total CO_2 emissions

at sustainable levels; all other scenarios run the risk of increasing emissions and jeopardizing efforts to mitigate climate change.

Table 5: Summary of the growth/reduction in the values of the main variables for different scenarios from the base case

Scenario	years	Biomass Energy Demand(million tons	Biomass Production(million tons	Deforestation(million tons /hekt	Lost CO_2 Sinking Capacity millions tons	CO_2 Emission from Deforestation million tons	CO_2 Emission from Biomass Consumption million tons	Incremental Emissions millionntons	Total CO_2 Emissions millions of tons
Base case	2000	4.5	6.23E+07	0.14	0.0098	0.0098	20.3	203	0.00350
	2015	72	3.56E+08	909	4.1	41	4550	4590	2670000
	2030	139.5	2.03E+09	13400	153	153	66400	66600	1.10E+17
Scenario1	2000	7.5	4.50	0.14	-1.44	-2.88	13.8	13.1	3.50E+07
	2015	53.4	2.5	434	28.9	27.5	3510	3540	2.21E+13
	2030	99.3	0.25	1560	10.7	106	50700	50800	7.27E+17
Scenario 2	2000	7.50E+07	4.5	140000	9800	9800	20.3	20.3	3.50E+07
	2015	5.14E+08	1.31	4.62E+09	3.24E+08	3.24E+08	3710	3740	2.49E+13
	2030	1.09E+09	0.306	1.67E+10	1.17E+09	1.17E+09	53700	53800	8.17E+17
Scenario 3	2000	75	4.5	45	0	0	75	75	45
	2015	485	3.5	759	714	251	485	485	759
	2030	953	1.5	1090	1045	390	953	953	1090
Scenario 4	2000	75	4.5	45	0	0	75	75	45
	2015	750	4.5	1010	965	0	750	750	1010
	2030	1430	4.5	1480	1435	0	1430	1430	1480
Scenario 5	2000	75	4.5	45	0	0	75	75	45
	2015	119	.56	344	299	666	119	119	344
	2030	170	0.0534	462	417	1018	170	170	462

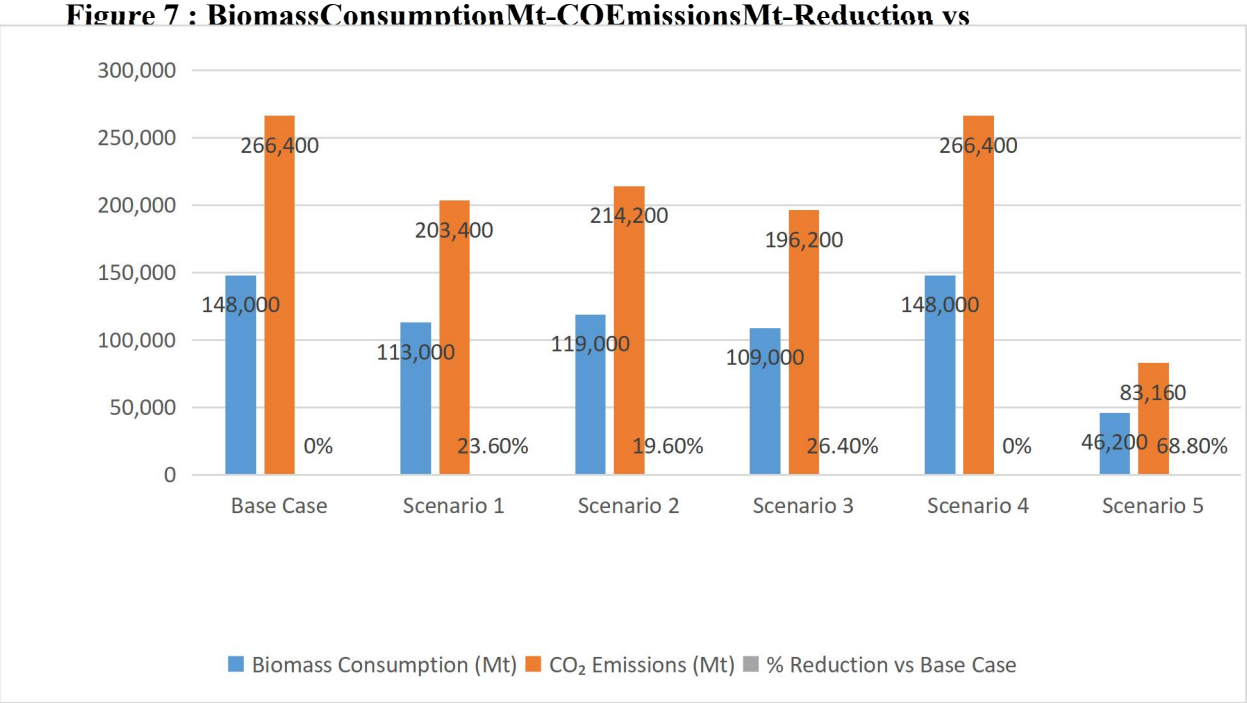
Reduction: The reduction column shows the quantity of less biomass consumed in each scenario compared to the base case. Deforestation: This is calculated as the difference between consumption and production (if present). CO_2 Emissions: To calculate emissions, you need the emission factor for biomass (1 ton biomass ≈ 1.8 tons CO_2). Multiply the reduction with that factor for CO_2 reduction. Reduction = 1018 million tons biomass. CO_2 reduction = 1018 × 1.8 = 1832.4 million tons CO_2, CO_2 emission factor: 1 ton biomass ≈ 1.8 tons CO_2 (default for wood/biomass). Biomass Consumption is the primary driver for CO_2 emissions (since all scenarios utilize the same biomass availability). % Reduction = (Base Case Emissions – Scenario Emissions) / Base Case Emissions × 100%

Table 6: Summary of the growth/reduction in the percentage of the main variables for different scenarios from the base case

Year	Scenario	Biomass Consumption (million tons)	CO_2 Emissions (million tons)	% Reduction vs Base Case
2000	Base Case	45	81	0%
	Scenario 1	45	81	0%
	Scenario 2	45	81	0%
	Scenario 3	45	81	0%
	Scenario 4	45	81	0%
	Scenario 5	45	81	0%
2015	Base Case	10,100	18,180	0%
	Scenario 1	7,810	14,058	22.70%
	Scenario 2	8,240	14,832	18.40%
	Scenario 3	7,590	13,662	24.80%
	Scenario 4	10,100	18,180	0%
	Scenario 5	3,440	6,192	65.90%
2030	Base Case	148,000	266,400	0%
	Scenario 1	113,000	203,400	23.60%
	Scenario 2	119,000	214,200	19.60%
	Scenario 3	109,000	196,200	26.40%
	Scenario 4	148,000	266,400	0%
	Scenario 5	46,200	83,160	68.80%

Scenario	Biomass Consumption (Mt)	CO_2 Emissions (Mt)	% Reduction vs Base Case
Base Case	148,000	266,400	0%
Scenario 1	113,000	203,400	23.60%
Scenario 2	119,000	214,200	19.60%
Scenario 3	109,000	196,200	26.40%
Scenario 4	148,000	266,400	0%
Scenario 5	46,2000	83,1600	68.80%

Figure 7 : BiomassConsumptionMt-COEmissionsMt-Reduction vs



The transition to alternative energy sources by 32% account for a drastic reduction in biomass energy use, falling from 139.5 million tons to 99.3 million tons in 2030. The shift avoids about 40 million tons of biomass energy consumption, equivalent to a 40% gain in energy access. Environmental advantages are also tremendous, with rates of deforestation falling sharply from 13,400 million tonshectare under base case to 1,560 million tonshectare. Therefore, the carbon sinking capacity loss is alleviated, reducing from 153 million tons to 107 million tons. In addition, CO_2 emissions due to deforestation and biomass burning are greatly minimized with overall CO_2 emissions reduced by 23.6%. This scenario illustrates the dual advantage of limiting environmental degradation paired with enhanced energy accessibility, marking the key role of alternative energy adoption in driving sustainable development (Mongabay, 2025; Mulatu et al., 2021; PVKnowhow, 2024; Africa-Energy-Portal, 2018; Simulation Report, 2025).

Increasing biomass use management efficiency by 26% also holds great promise, reducing biomass energy demand to 109 million tons by 2030, saving 30 million tons from the base case. This efficiency gain is offset by deforestation reductions, which fall to 1,670 million tons*hactare, and a resulting decrease in carbon sink loss from 153 million tons to 117

million tons. Both deforestation and biomass use CO_2 emissions decline precipitously, resulting in a net CO_2 saving of 19.6%. Energy access rises by an equivalent amount, underscoring the importance of efficient use of biomass in balancing energy needs with environmental preservation. These observations bring to light how minor upticks in the governance of biomass can highly counteract pressure on woodland resources and reduce greenhouse gases (Mongabay, 2025; Mulatu et al., 2021; PVKnowhow, 2024; Africa-Energy-Portal, 2018; Simulation Report, 2025).

Deployment of improved biomass cookstoves by 35% yields the most dominant single scenario effects, reducing demand for biomass energy to 95.3 million tons and saving 45.2 million tons by 2030. This leads to a considerable decline in forest cutting back to 1,090 million tonshectare and a smaller reduction in carbon sinking potential, from 153 million tons to 145 million tons. CO_2 emissions due to deforestation and biomass consumption are reduced significantly, resulting in a net reduction of CO_2 emissions by 26.6%. While the increase in reforestation by 40% does not have a noticeable effect on biomass demand or deforestation rate, synergy occurs as a result of the action of all policy measures, reducing the demand for biomass energy to 51.5 million tons and deforestation to 462 million tonshectare. This combined strategy achieves a phenomenal 68.8% reduction in CO_2 emissions and improvement in energy access, bringing to the fore the strong impact of combined policy measures to effectively address energy and environmental challenges in concert (Mongabay, 2025; Mulatu et al., 2021; PVKnowhow, 2024; Africa-Energy-Portal, 2018; Simulation Report, 2025).

The relative comparison between biomass energy scenarios amply indicates the strong influence which management techniques exert over bot h biomass utilization and resulting CO_2 emissions. This information determines that Scenario 5, with the most efficient policy scenario, always has the lowest biomass consumption and energy demand in each year. by 2030, the biomass consumption of Scenario 5 is much less than the base case and other scenarios, amounting to a CO_2 emission reduction of over 69%. This aligns with findings by Bailis et al. (2015), who underscore that adoption of efficient stoves aggressively and sustainable resource management can play a major role in achieving very considerable emission reductions and reduced pressure on forest stocks. Scenario 4, a business-as-usual or low-

level intervention scenario, shows little to no improvement over the base case, and both scenarios exhibit similar trends in biomass use and emissions growth. Scenarios 1, 2, and 3, with varying efficiencies of the improvements, achieve small reductions both in biomass consumption and in CO_2 emissions, the third one being better than the first two since it has higher efficiency gains. These conclusions are consistent with the literature (IEA, 2022; Berndes et al., 2016), where partial measures only deliver incremental benefits, but deep technology and management transformation is necessary for significant environmental result.

Implementation of efficient biomass management policies in Ethiopia leads to large reductions in key variables by the year 2030. Compared to the base case, Scenario 1 (32% efficient) reduces biomass consumption by approximately 23.6%, Scenario 2 (26% efficient) by 19.6%, and Scenario 3 (35% improved cookstoves) by 26.4%, while Scenario 5 (all measures combined) carries the highest decrease of 69%. These reductions carry over to net biomass consumption, rates of deforestation, and marginal CO_2 emissions, with Scenario 5 cutting deforestation by 96.6% and CO_2 emissions by nearly 69%. Scenariio 4 (reforestation only) is not significantly different from the base case. These results demonstrate conclusively that broad and comprehensive policy interventions, particularly those involving an intersection of alternative energy uptake and efficiency improvements, are much more effective in reducing biomass use, emissions, and environmental pressure than narrow or single measures.

Ranked from top to bottom, the top-performing scenario is Scenario 5, and then Scenario 3, Scenario 1, Scenario 2, and finally Scenario 4, which performs as well as the base case. This pecking order underscores the critical role of strong, multi-faceted interventions in the bio economy. Only through combining improved efficiency, green harvesting, and policy-level support can countries address the twin burdens of energy access and climate protection. These conclusions resonate with calls in recent international reports for a whole-of-system approach to managing bioenergy as a component of sustainable development planning.ed policy support can countries achieve the dual goals of energy access and climate mitigation. These insights reinforce the conclusions of recent global studies, which advocate for a holistic approach to bioenergy management as an essential component of sustainable development strategies.

CHAPTER SIX

Conclusions and Policy implications

6.1. Conclusions

Biomass is the major energy consumption source in Ethiopia and represents more than 92.4% of national overall energy consumption and is predominantly used for rural cooking (Sustainability, 2021; Hailu, 2023). It has resulted in a wide range of environmental concerns as a result of a 1.5% annual rate of deforestation and high CO_2 emissions, approximately 60,120 kg/GJ, due to inefficient traditional cooking technology and increased energy demand (Hailu, 2023; PMC, 2021). eport, 2025).Ethiopia's energy supply is controlled by biomass, accounting for around 92.4% of total domestic energy use, mainly for rural cooking (Hailu, 2023; Sustainability, 2021). This control has introduced very serious environmental challenges, including a 1.5% annual rate of deforestation and high CO_2 emissions—estimated at 60,120 kg/GJ—due to inefficient traditional kitchen mechanisms and increasing energy needs (Hailu, 2023; PMC, 2021).The rapid economic and population growth of the country also incited these problems, with CO_2 emissions rising by 450% from 1990 to 2017 (Sustainability, 2020). In trying to improve these issues, this research suggests a system dynamics model to establish the linkage of the use of biomass energy, emission of Co2, and environmental sustainability and the effect of replacing less carbon-based fuels and the subsequent effect on air pollution and deforestation (Woldie, 2022). Dingeto & Kumsa, 2021).Lastly, the research will provide policymakers with practicable recommendations to achieve sustainable energy transformation in Ethiopia and reduce carbon emissions by a significant amount.

Comparison of the biomass energy scenarios from 2000 to 2030 affirms that policy choices have critical implications on both energy security and environmental sustainability. Ethiopia's widespread reliance on traditional biomass for energy, particularly rural biomass consumption, has put the environment under tremendous pressure in terms of deforestation levels and rapidly growing CO_2 emissions. The base case and Scenario 4 that represent business-as-usual or least intervention approaches suggest continued growth in the use of biomass and associated emissions, underscoring the unsustainability of prevailing practices. On the contrary, Scenarios 1, 2, 3, and especially Scenario

5, involving multiple degrees of efficiency increase and management interventions indicate remarkable declines in biomass consumption and energy demand during the years. Scenario 5, being the most drastic and efficient, indicates the most savings with reduced biomass consumptionand emissions during each year compared to other scenarios.

These findings reflect the critical necessity of moving towards more efficient and sustainable practices of biomass energy management. Implementation of end-to-end efficiency technologies, promotion of alternative energy generation, and promotion of sustainable harvesting are essential to reduce environmental footprints and ensure long-term energy security. The system dynamics model confirms that only robust, multi-faceted interventions—such as those represented by Scenario 5—can effectively hold deforestation in check by 96.6%, cut CO_2 emissions by 68.8%, and allow Ethiopia to shift towards a more sustainable, more resilient energy future by 40% by 2030 (Mongabay, 2025; Mulatu et al., 2021; PVKnowhow, 2024; Africa-Energy-Portal, 2018; Simulation Report, 2025).

.6.2. Recommendations and Policy Implications

The analysis suggests that policymakers incorporate effective biomass management techniques into national energy and forest strategies and give them top priority. This entails encouraging the use of alternative energy sources to lessen the strain on forests, supporting afforestation and alternative energy transition programs, and promoting sustainable harvesting. To guarantee the long-term sustainability of biomass resources, it is also essential to invest in monitoring systems and public awareness initiatives. Scenario 5 is the most successful scenario when ranked by effectiveness, followed by Scenarios 3, 1and scenario 2, 4 which is comparable to the base case. The significance of thorough, multifaceted interventions in the biomass sector is highlighted by this ranking. Only through the combination of improved efficiency, sustainable harvesting, and integrated policy support can countries achieve the dual goals of energy access and climate mitigation. These insights reinforce the conclusions of recent global studies, which advocate for a holistic approach to bioenergy management as an essential component of sustainable development strategies

(Mongabay, 2025; Mulatu et al., 2021; PVKnowhow, 2024; Africa-Energy-Portal, 2018; Simulation Report, 2025).

.The policy ramifications are obvious: the development of biomass energy cannot be in line with environmental preservation and climate goals unless there is robust management and intervention. Clear regulatory frameworks, incentives for sustainable practices, and measures to prevent energy demand from surpassing forest ecosystems' capacity for regeneration are all things that governments should do. A balanced and resilient energy future will require integrating forestry, climate, and rural energy policies.

6.3. Limitations and Further Research

This study has several limitations. Some variables, such as actual deforestation rates, lost CO_2 sinking capacity, and CO_2 emissions, were estimated using standard emission factors due to data constraints. The other factors such as population growth, technological innovation, and economic shifts were not explicitly modeled in the scenario projections.

Further research should focus on integrating spatially explicit land-use and forest cover data to improve the accuracy of deforestation and carbon flux estimates. There is also a need for more detailed modeling of socioeconomic drivers and their influence on both biomass demand and supply. Finally, evaluating the effectiveness of specific policy instruments, such as subsidies for clean cookstoves or incentives for reforestation, would provide practical insights for policymakers aiming to promote sustainable biomass energy systems.The study also highlights data limitations and the need for further research on spatially explicit land-use change and the socioeconomic drivers of biomass demand (Mongabay, 2025; Mulatu et al., 2021; PVKnowhow, 2024; Africa-Energy-Portal, 2018; Simulation Report, 2025).

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Appendix A)

(02) Average biomass energy cosumption per capital=total energy /Household
Units: tons/usd

(03) Average energy demand per capital=(Average biomass energy cosumption per capital*effect of population on the energy demand +energy demand per capital*incame elasticity*income effect per capital+reference incame*income effect per capital)*merginal effect of income
Units: tons/person

(04) Biomass Availability=4.5e+07
Units: tons

(05) Biomass Consumption= INTEG ((Biomass Energy Demand+Biomass Consumption growth/waste biomass)*waste biomass 4.5e+07)
Units: tons

(06) Biomass Consumption growth=Biomass Consumption*consumption growth rate
Units: tons/Year

(07) biomass consumption redacton= 1
Units: 1/tons

(08) biomass energy deman growth=Biomass Energy Demand*growth rate enin biomass energy demand
Units: tons/Year

(09) Biomass Energy Demand= INTEG (biomass energy deman growth-"Efficient Management of Biomass Energy to save:"
-Improved Cookstove Adoption/time lag-substitution biomass Energy to Solar and Other Alternatives, 7.5e+07) Units: tons

(10) biomass energy tone per rural household=Biomass Energy Demand/(Household*reference incame) Units: tons/person/usd

(11) Biomass Production= INTEG (production growth*combustion technology-"Efficient Management of Biomass Energy to save:" /size of productions, 6.23e+07)
Units: tons/hekt

(12) Birth= population*Birth rate, Units: person/Year

(13) Birth rate= 0.145, Units: 1/Year

(14) Carbon Intensity of Emissions from deforestation= 4.5 Units: tons/Year

(15) Co2 emission from alternative energy=CO2 intensity of other alternative energy*substitution biomass Energy to Solar and Other Alternatives
Units: tons/Year

(16) CO2 intensity of biomass=4.5, Units: tons/Year

(17) CO2 intensity of other alternative energy= 1.532, Units:tons per year

(18) combustion growt rate=0.22315, Units: (hekt*hekt)/(tons*tons)

(19) combustion technology=1, Units: (tons*tons)/(hekt*hekt*Year)

(20) consumption growth rate=0.035, Units: 1/Year

(21) CO_2 Emissions from Biomass consumption=(CO2 intensity of biomass*net biomass consumptions*biomass consumption redacton), Units: tons/Year

(22) CO_2 Emissions from deforestation=(Carbon Intensity of Emissions from deforestation*Deforestation growth*reforesting rat +Lost Carbon Sinking Capacitys-substitution biomass Energy to Solar and Other Alternatives)/time lag to reforesting
Units: tons

(23) Death=population*Death rate; Units: person/Year

(24) Death rate= 0.012 Units: 1/Year

(25) Deforestation= INTEG (Biomass Energy Demand*Other Logging+Deforestation growth/Environmental Degradation, 140000), Units: tons/hekt

(26) Deforestation growth=Deforestation*Deforestation growth rate Units: 1/Year

(27) Deforestation growth rate=0.015, Units: hekt/(Year*tons)

(28) effect of population on the energy demand=(population-reference population)/reference incame, Units: person/usd

(29) efficiency rate=0, Units: 1/Year

(30) "Efficient Management of Biomass Energy to save:"=
Biomass Availability*efficiency rate
Units: tons/Year

(31) Energy demand= INTEG (
(Energy demand growth-energy import+Average energy demand per capital)*scale parmeter
,
7.5e+07)
Units: tons/person

(32) Energy demand growth=
Biomass Energy Demand*growth rate
Units: tons/person

(33) energy demand per capital=
GDP per capital*merginal effect of GDP per capital
Units: person

(34) energy import=
Energy demand*import rate/scale parmeter
Units: tons/person

(35) Environmental Degradation=
production growth
Units: hekt/tons

(36) FINAL TIME = 2030
Units: Year
The final time for the simulation.

(37) Fraction of Rural household=
1.04
Units: person

(38) GDP= INTEG (
GDP Growth,
8.2e+10)
Units: usd

(39) GDP Growth=
GDP*GDP growth rate
Units: usd/Year

(40) GDP growth rate=
0.079
Units: 1/Year

(41) GDP per capital=
GDP/population
Units: usd/person

(42) growth rate=
0.5
Units: 1/(person)

(43) growth rate enin biomass energy demand=
0.035
Units: 1/Year

(44) Household=
(population/Avarge Household size)*Fraction of Rural household
Units: person

(45) import rate=
0.02
Units: 1/Year

(46) improved cooksove adoption rate=
0
Units: 1/Year

(47) Improved Cookstove Adoption=
(Biomass Availability*improved cooksove adoption rate)/scale parmeter
Units: tons

(48) incame elasticity=
0.5
Units: usd/person

(49) income effect per capital=
0.933
Units: (tons*person)/(usd*usd*usd)

(50) Incremental Co2 emission=
CO_2 Emissions from Biomass consumption+(CO_2 Emissions from deforestation *scale parameter)+Co2 emission from alternative energy
Units: tons/Year

(51) INITIAL TIME = 2000
Units: Year
The initial time for the simulation.

(52) Lost Carbon Sinking Capacitys=
(Deforestation*Sequestration Rate-substitution biomass Energy to Solar and Other Alternatives
-Deforestation*reforesting rate*Scale parmeter1*Sequestration Rate)
Units: tons/Year

(53) merginal effect of GDP per capital=
0.00554
Units: (person*person) /usd

(54) merginal effect of income=
1
Units: (usd*usd)/(person*person)

(55) net biomass consumptions=
Biomass Consumption-substitution biomass Energy to Solar and Other Alternatives *time lag
Units: tons

(56) Other Logging=
1
Units: 1/(Year*hekt)

(57) population= INTEG (
Birth-Death,

6.62248e+07)
Units: person

(58) production growth =
combustion growt rate*Biomass Production
Units: hekt/tons

(59) rate of biomass substitution=
0
Units: 1/Year

(60) reference incame=
0.933
Units: usd

(61) reference population=
6e+06
Units: person

(62) reforesting rate=
0
Units: Year

(63) SAVEPER =
TIME STEP
Units: Year [0,?]
The frequency with which output is stored.

(64) scale parameter=
1
Units: 1/Year

(65) scale parmeter=
1
Units: 1/Year

(66) Scale parmeter1=
1
Units: 1/Year

(67) Sequestration Rate=
0.07
Units: hekt/Year

(68) size of productions=
1
Units: hekt

(69) Stock of Co2=
Total Co2 emission*scale parameter

Units: tons/Year

(70) substitution biomass Energy to Solar and Other Alternatives=
rate of biomass substitution*Biomass Availability
Units: tons/Year

(71) time lag=
1
Units: Year

(72) time lag to reforesting=
1
Units: 1/Year

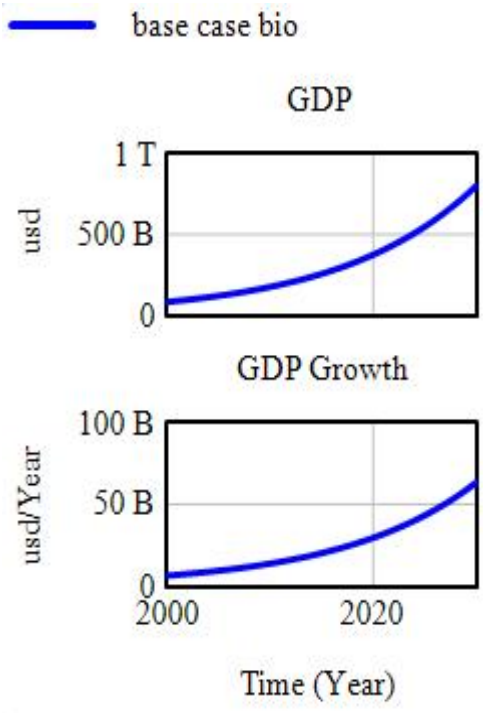
(73) TIME STEP = 1
Units: Year [0,?]
The time step for the simulation.

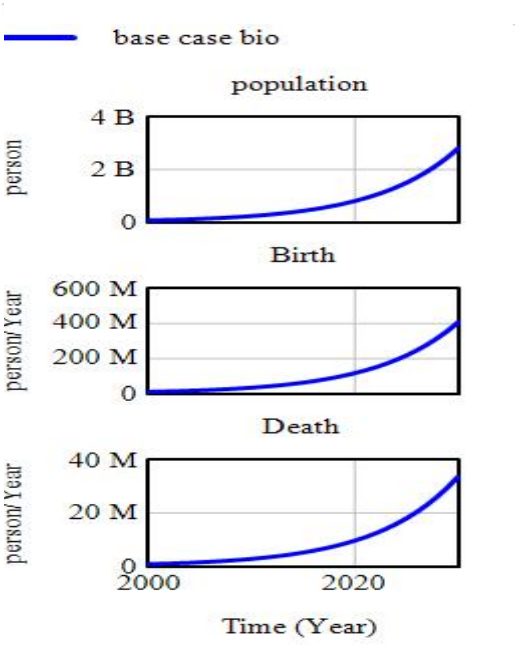
(74) Total Co2 emission= INTEG (
Incremental Co2 emission+Stock of Co2,
3.5e+07)
Units: tons

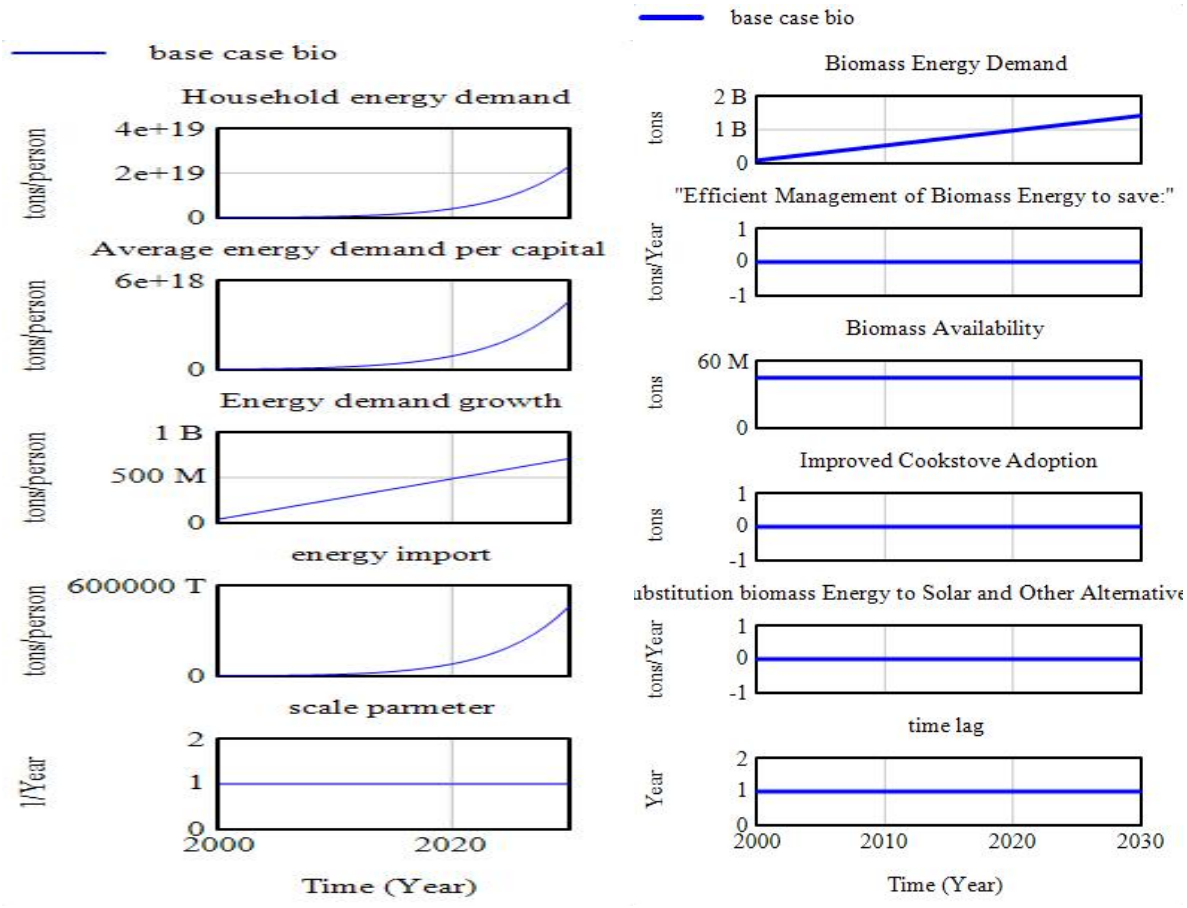
(75) waste biomass=
1
Units: 1/Year

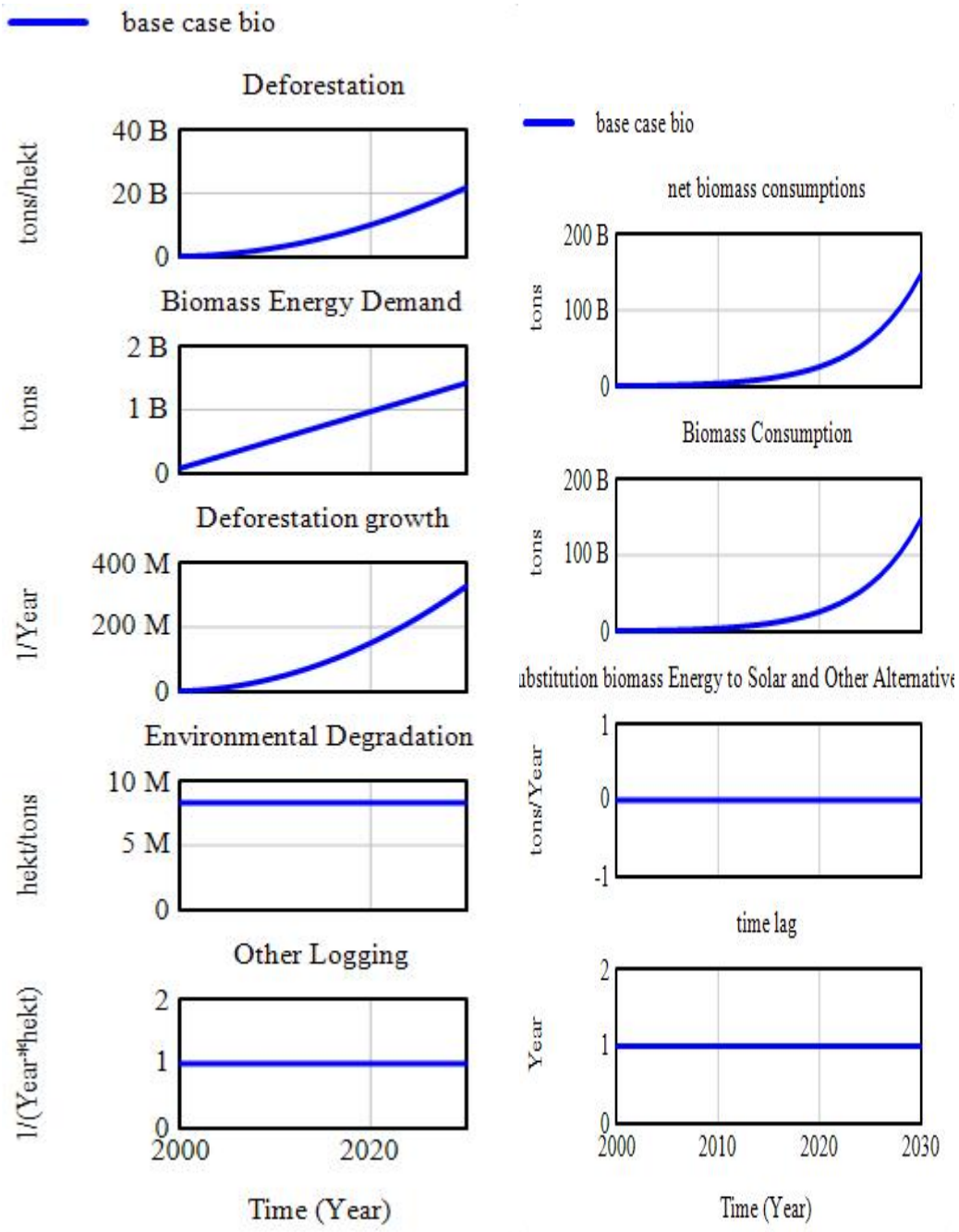
Appendix B)

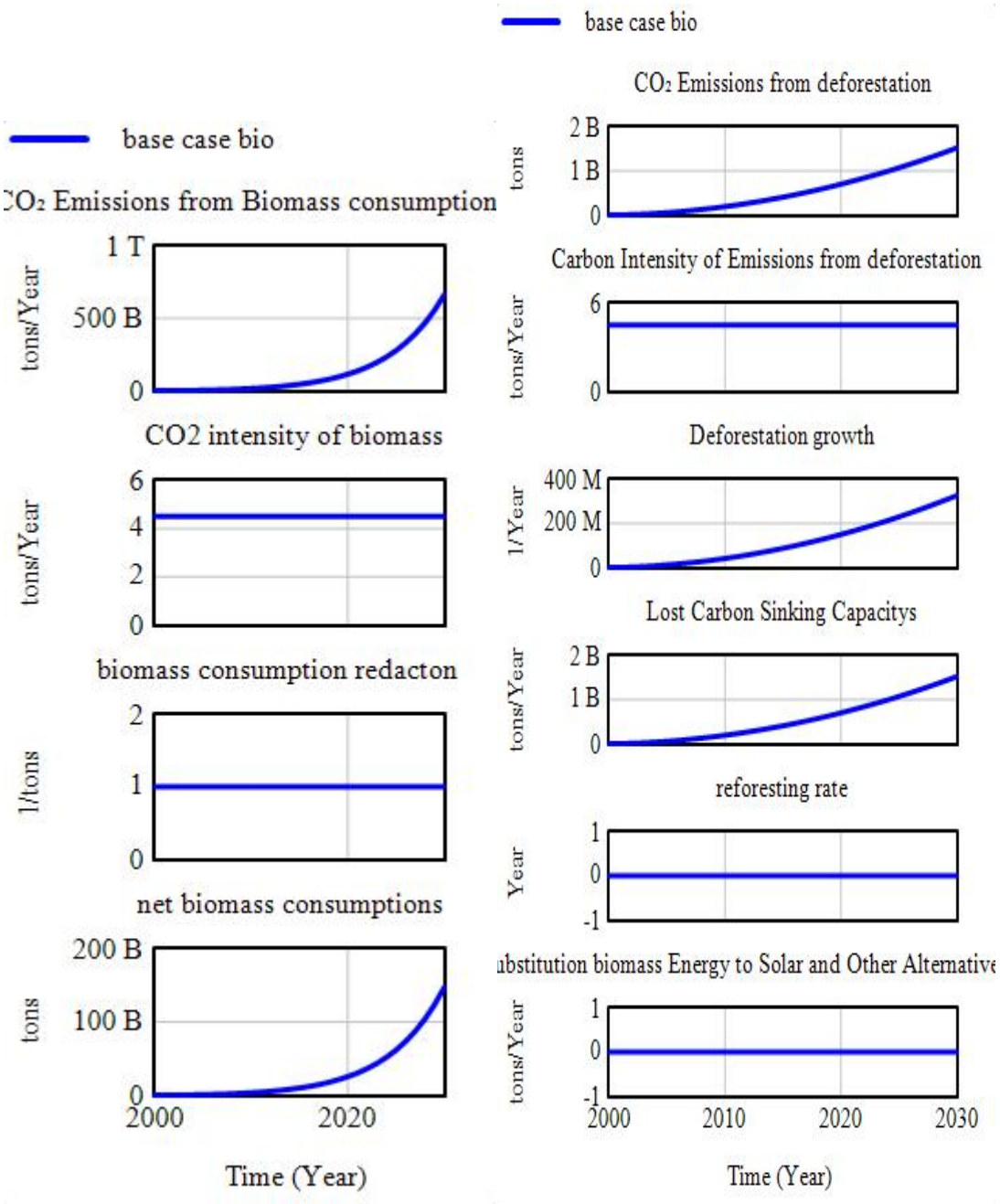
I) causes trip analysis

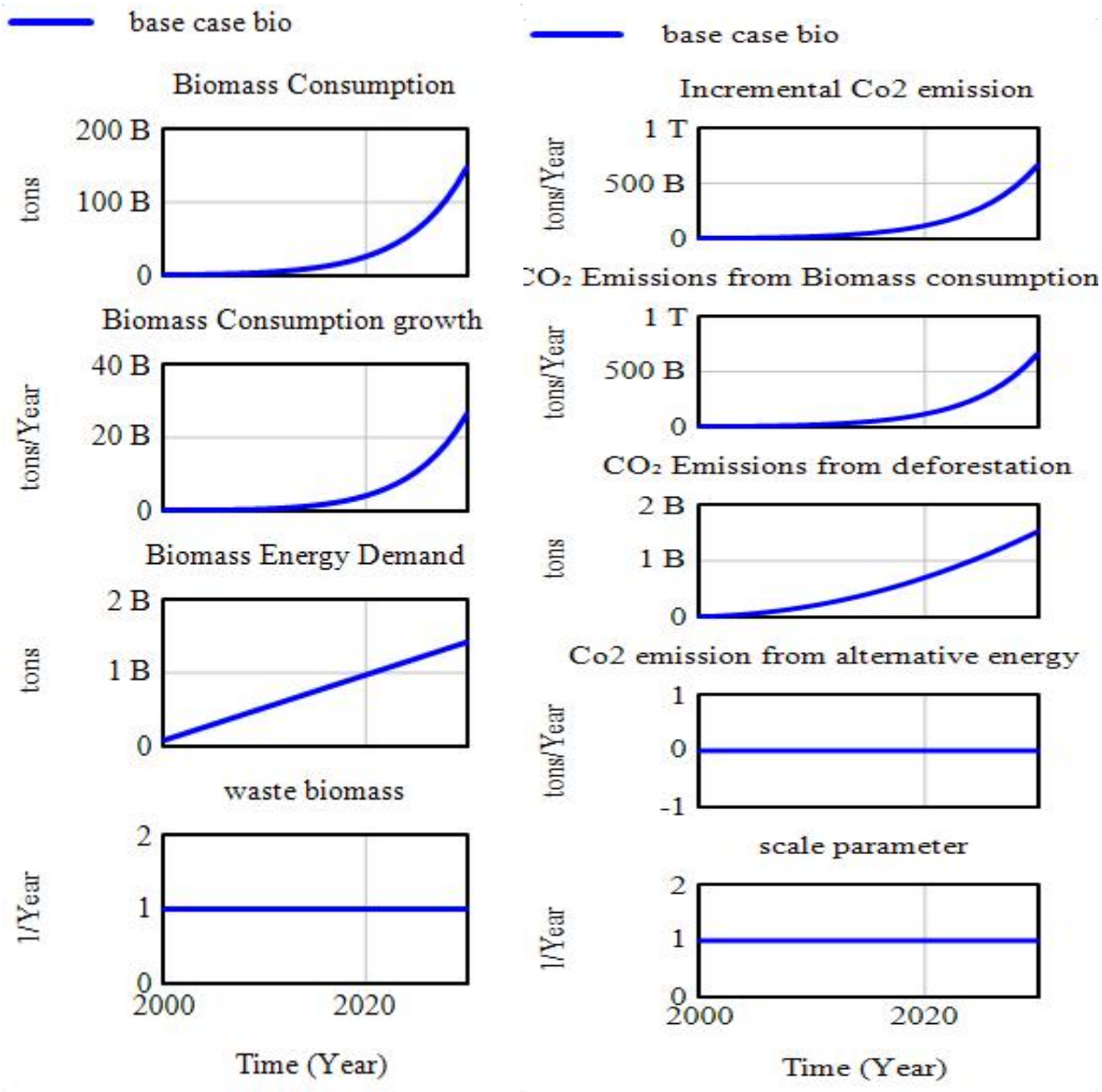

base case bio
GDP
1 T
500 B
0
usd
GDP Growth
100 B
50 B
0
usd/Year
2000
2020
Time (Year)


base case bio
population
4 B
2 B
0
person
Birth
600 M
400 M
200 M
0
person/Year
Death
40 M
20 M
0
person/Year
2000
2020
Time (Year)

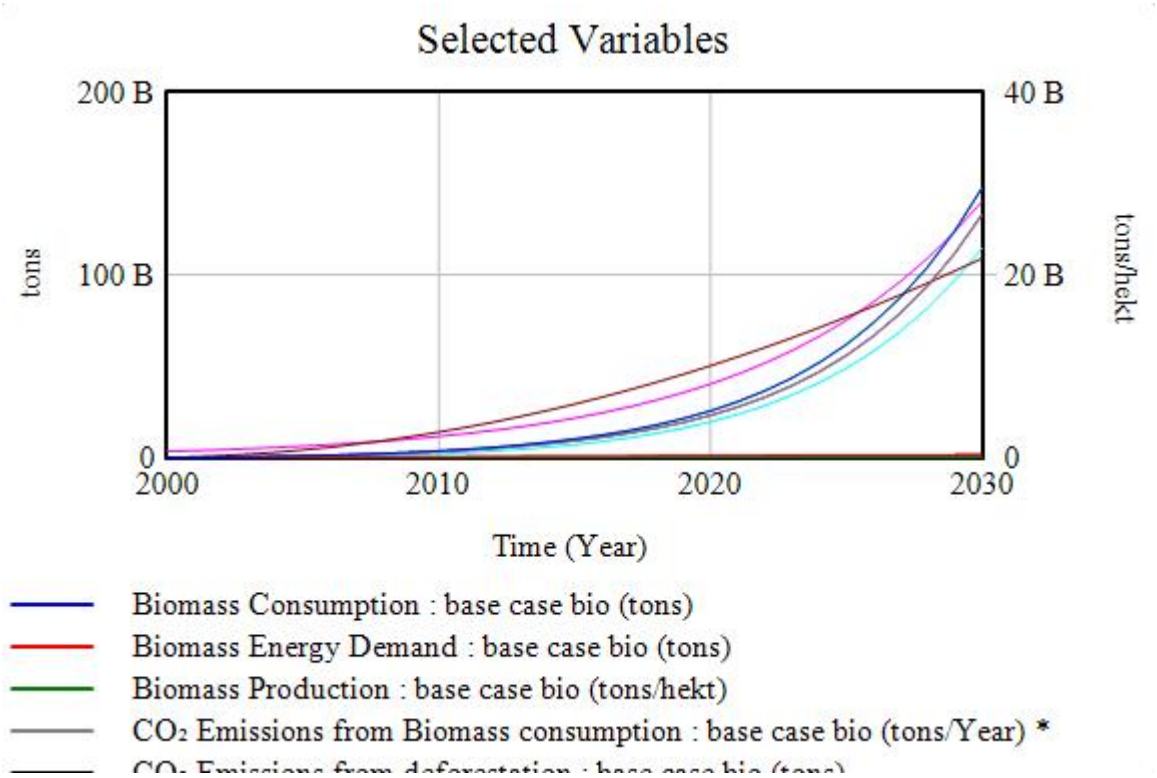

base case bio
Household energy demand
4e+19
2e+19
0
tons/person
Average energy demand per capital
6e+18
0
tons/person
Energy demand growth
1 B
500 M
0
tons/person
energy import
600000 T
0
tons/person
scale parmeter
2
1
0
1/Year
2000
2020
Time (Year)
base case bio
Biomass Energy Demand
2 B
1 B
0
tons
"Efficient Management of Biomass Energy to save:"
1
0
-1
tons/Year
Biomass Availability
60 M
0
tons
Improved Cookstove Adoption
1
0
-1
tons
ubstitution biomass Energy to Solar and Other Alternative
1
0
-1
tons/Year
time lag
2
1
0
Year
2000
2010
2020
2030
Time (Year)


base case bio
Deforestation
tons/hekt
40 B
20 B
0
Biomass Energy Demand
tons
2 B
1 B
0
Deforestation growth
1/Year
400 M
200 M
0
Environmental Degradation
hekt/tons
10 M
5 M
0
Other Logging
1/(Year*hekt)
2
1
0
2000
2020
Time (Year)
base case bio
net biomass consumptions
tons
200 B
100 B
0
Biomass Consumption
tons
200 B
100 B
0
ubstitution biomass Energy to Solar and Other Alternative
tons/Year
1
0
-1
time lag
Year
2
1
0
2000
2010
2020
2030
Time (Year)


base case bio
CO₂ Emissions from Biomass consumption
tons/Year
1 T
500 B
0
CO2 intensity of biomass
tons/Year
6
4
2
0
biomass consumption redacton
1/tons
2
1
0
net biomass consumptions
tons
200 B
100 B
0
2000
2020
Time (Year)
base case bio
CO₂ Emissions from deforestation
tons
2 B
1 B
0
Carbon Intensity of Emissions from deforestation
tons/Year
6
0
Deforestation growth
1/Year
400 M
200 M
0
Lost Carbon Sinking Capacitys
tons/Year
2 B
1 B
0
reforesting rate
Year
1
0
-1
ubstitution biomass Energy to Solar and Other Alternative
tons/Year
1
0
-1
2000
2010
2020
2030
Time (Year)


base case bio
Biomass Consumption
200 B
100 B
0
tons
Biomass Consumption growth
40 B
20 B
0
tons/Year
Biomass Energy Demand
2 B
1 B
0
tons
waste biomass
2
1
0
1/Year
2000
2020
Time (Year)
base case bio
Incremental Co2 emission
1 T
500 B
0
tons/Year
CO₂ Emissions from Biomass consumption
1 T
500 B
0
tons/Year
CO₂ Emissions from deforestation
2 B
1 B
0
tons
Co2 emission from alternative energy
1
0
-1
tons/Year
scale parameter
2
1
0
1/Year
2000
2020
Time (Year)

II) the patterns of the selected variables under base case



III) the graph of the incremental emissions and total co2 emission reductions under all scenarios

