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# Exploring communities' utilization of Jatropha based biofuels to transition towards cleaner energy sources

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PAPER

# Exploring communities' utilization of Jatropha based biofuels to transition towards cleaner energy sources

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## Abstract

Ethiopia is committed to using sustainable energy sources due to the limited availability of traditional fuel and their environmental damage. This study examines the viability of biofuels as an alternative fuel source in Ethiopia for community's sustainable transition to cleaner energy. The research reviews relevant publications, policies, initiatives, and programs, identifies barriers to implementation, and collects data through literature reviews, community discussions and observations of energy experts. Ethiopia has 8.6 million hectares available for energy crops and governmental policies are encouraging the use of clean fuels. The study suggests that biofuel can support rural development and environmental sustainability. However, challenges to the widespread adoption of alternative fuels by communities exist such as flawed policies, limited technical skills, insufficient maintenance experts, a scarcity of biofuel production companies, and inadequate markets for biofuel seeds. To achieve a sustainable future through the use of clean energy in the country, policy interventions and investment strategies are necessary. All stakeholders must adopt policies and develop capacity-building programs while providing incentives for developers and users.

## 1. Introduction

In rural areas of Ethiopia, traditional biomass like wood, animal dung, and agricultural residues are mainly used for energy. It is crucial for Ethiopia to adopt alternative energy sources in these areas, as they heavily rely on traditional biomass [1, 2]. Although Ethiopia has substantial potential for renewable energy, with 95% of its electricity coming from hydro-power, almost 49% of the population does not have access to electricity [3]. Additionally, more than 90% of households in Ethiopia still use traditional energy sources, such as agricultural and forest residues, for cooking [4]. In addition to the lack of clean and affordable energy access, there are possible geopolitical issues related to Ethiopia's reliance on transboundary river for its hydro based power generation [5, 6]. To meet the growing energy demands driven by urbanization and population growth in a sustainable manner [7], Ethiopia has implemented policies and several programs to shift from traditional fuels to cleaner options such as ethanol and biodiesel for transportation, cooking, and off-grid electricity generation by considering environmental factors in energy project developments [8–11].

The Ministry of Water, Irrigation and Electricity introduced a bio-fuel development strategy in 2007 that prioritizes environmental protection, economics, culture, food security and land rights [12]. Jatropha, sugarcane, castor, and palm trees are suitable energy crops for biofuel production. Molasses can be used to produce ethanol while oil palm, castor, and Jatropha can be used for biodiesel production. Ethiopia's Climate Resilient Green Economy Strategy aims to achieve middle-income status by 2025 through sustainable

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measures like improved agricultural methods, forest conservation, increased use of renewable energy, and energy-efficient technologies [13]. Ethiopia has non-food plants like Jatropha, cotton, and castor that can produce biofuel [14, 15]. Ethiopia's biofuels program involves both local and external producers. Groups like the Relief Society of Tigray and the Organization for Rehabilitation and Development in Amhara have implemented community-based biofuel projects in Tigray and Amhara regions, supporting the shift towards sustainable energy [16].

To support energy security and growth initiatives, Ethiopia's government biofuel strategy is designed to increase domestic biofuel production, replace imports with locally produced biofuels, and possibly export excess biofuels [17]. Additionally, the strategy also focuses on ensuring energy and food security, promoting farmer participation, and mitigating environmental impacts for sustainability [18].

To improve energy access and consumption, Ethiopia's energy transition plan includes decentralizing energy systems using local resources. This is crucial for providing power to rural areas that are not connected to the national grid [19]. The transition to clean energy is a major concern for Ethiopia's global trade and development efforts, as it affects climate funding, foreign investments, and technology transfers [20]. However, biofuel production and utilization are lagging in supporting the transition. Although biofuels have great potential to transform the community and the country's fuel utilization landscape, there is a lack of evidence for why their adoption is slow and the available sources are being wasted.

This research examines the feasibility of biofuel resources focusing on Jatropha plants in the country, reviews current production levels, evaluates policies and directives, and identifies the challenges for stakeholders transitioning to alternative fuels such as biofuels. It provides valuable information on the country's biofuel potential and challenges related to their adoption. Additionally, a biofuel based off-grid energy system is designed for a selected community based on their power demand and the availability of biofuel resources within their vicinity. The results can benefit researchers, policymakers, developers, and other stakeholders seeking to shift from conventional fuels to cleaner and more sustainable options.

The paper has six sections. Section 2 explains the study's methodology, while section 3 explores the potential of biofuels and its production in the Ethiopian context. Section 4 designs biofuel-based off-grid energy systems based on the power demand of a specific community. Section 5 discusses the way forward to develop biofuels-based community energy systems, and section 6 provides concluding remarks.

## 2. Research methodology

### 2.1. Description of the study area

The research was conducted in Ethiopia, an East African country. It consisted of a literature review on all regions of Ethiopia and a case study that focused on the Tigray regional state to explore the potential of Jatropha plantations. The case study was conducted on three major sub-districts of the Tigray region (see figure 1(B)) of Northern Ethiopia (see figure 1(A)) such as Raya Alamata (Alamata and Raya Azebo) as shown in figures 1(C) and (F), Kolla Temben in figure 1(D), and Tanqua Abergele in figure 1(E).

### 2.2. Research framework

The study aimed to assess the viability of Jatropha biofuels in Ethiopia for developing biofuel based off-grid energy system. A location was chosen to examine the communities' socio-economic challenges, energy patterns and to design biofuel-based off-grid energy systems for the community. The study followed the research framework in figure 2 to outline a clear procedure connecting the political economy of biofuels, socio-economic community challenges, and proposing pathways to overcome these challenges.

#### *2.2.1. Data collection of biofuel potentials*

This study gathered information from both primary and secondary sources. We obtained secondary data from regional energy office reports, national policies and publications and international reports. The purpose of collecting primary data from the case study was to obtain more information and confirm the existence of Jatropha plantations presented in the secondary data. We spoke with local communities and energy specialists through focus groups and key informant interviews to evaluate potential Jatropha plantations and the difficulties faced by Jatropha growers and the community. We also visited Jatropha development farms selected as a case study in the Tigray regional state to supplement our research. Three specific areas were chosen for the study following consultation with a representative from the Mining and Energy Agency of Tigray regional state (see figure 1).

#### *2.2.2. Site selection and data collection of the energy patterns of communities*

As part of our case study, we chose the Chamo sub-district (located 40 km from the national grid) to study its current energy sources and usage in order to design off-grid energy systems (see figure 3). Using Arc GIS, we

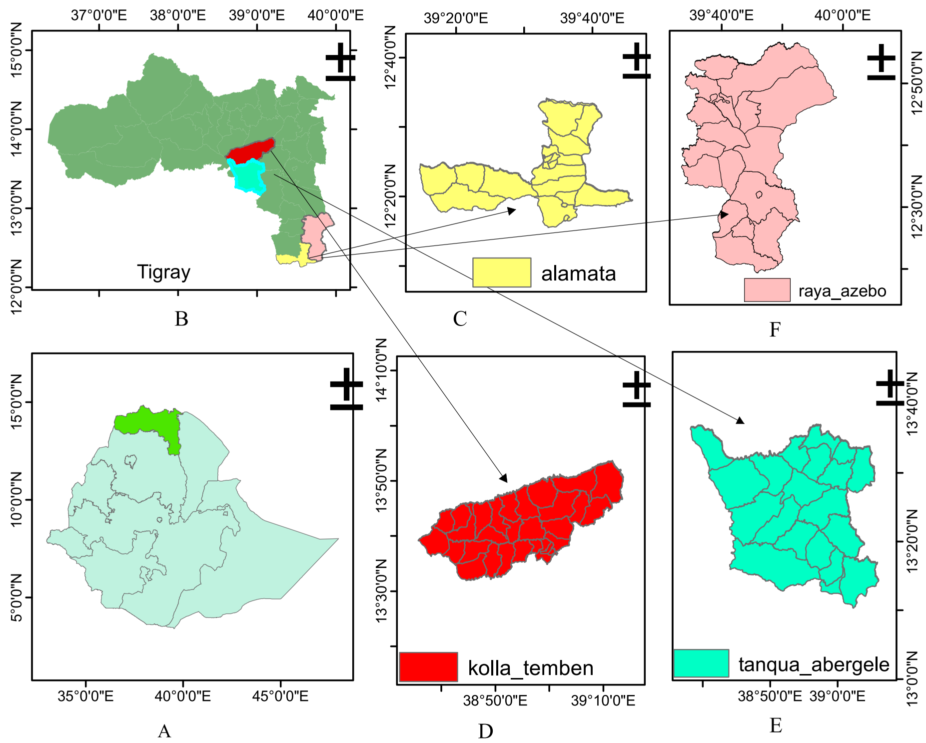


**Figure 1.** Potential areas of Jatropha plant in Tigray region.

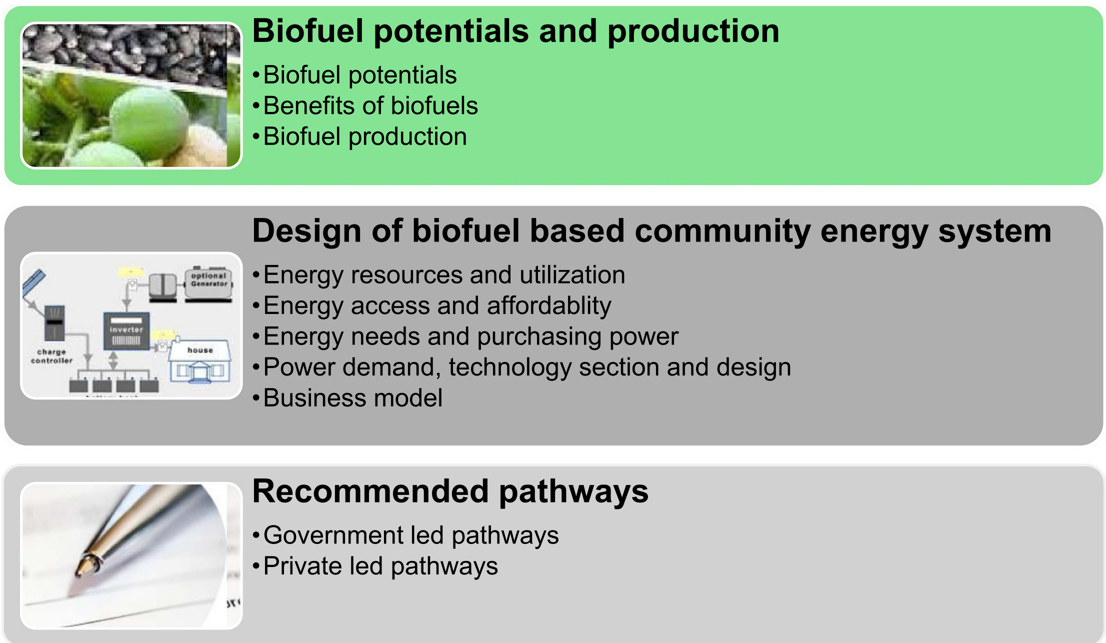


**Figure 2.** Research framework.

located a potential site for a biofuel generator based on factors such as population density, proximity to the national grid, resource availability, transportation accessibility, user proximity, environmental impact, and energy demand.

Figure 4 shows households are mostly located close to each other, but with some variation in dispersion. This has important implications for both the cable distribution network and electricity loss.

In the selected district, there are 200 households, one church, one health post, and one primary school. Primary data was collected through structured questionnaires (see appendix A) from all households due to the small population size. A local data collector who is fluent in local languages and English was hired to

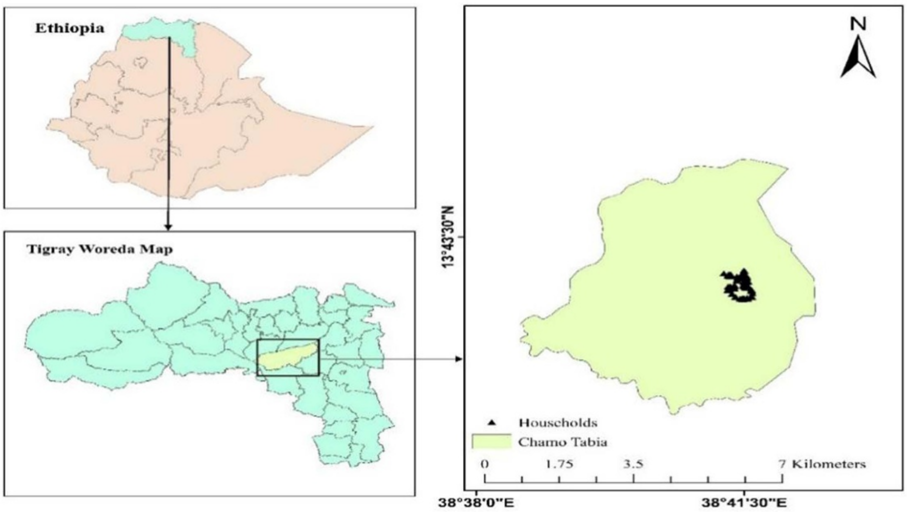


**Figure 3.** Specific site of the selected village.

**Figure 4.** Distribution of the households of the selected community.

conduct in-person interviews with households using the local language for filling out questionnaires. The data collector translated the English questionnaire into the local language during the interviews. The interviews allowed for interactive discussions with the communities to gather more information and complete the questionnaire. The individual interviews with each household ensured that a complete set of questionnaires was collected. The data collector translated the local language-based data into English for analysis. Secondary data included a systematic review of academic and policy publications, current legislation, and regulations from national and international sources.

*2.2.3. Design of biofuel based off-grid community energy system*

To use renewable energy resources effectively and affordably, an optimization method for sizing is required. The method ensures the technology is used efficiently and at full capacity, resulting in an optimal standalone system that works reliably and is affordable. To achieve the best outcome for cost and reliability, the system's long-term performance must be evaluated [21]. We used the Hybrid Optimization Model for Electric Renewables (HOMER), created by the US National Renewable Energy Laboratory, to design and model the most efficient biofuel generator-based systems for the chosen community [22]. HOMER utilizes energy balance calculations to simulate the system's operation for every hour of the year. It compares the system's ability to supply energy with the hourly electric demand and calculates the energy flows between components. The feasibility of the configuration is then determined and the project's lifetime cost of operation and installation is estimated [23].

HOMER requires input parameters such as fuel consumption, efficiency, load demand, and cost of biofuel resources for designing and modeling off-grid systems with biofuel generators. It is essential to consider site selection, system sizing, and optimization when using biofuel generators. Various factors, including resource availability, energy consumption patterns, and economic feasibility, were taken into account when designing the biofuel generator-based off-grid energy system to determine the optimal configuration.

## 3. Biofuel potential, benefits and production in Ethiopia

Ethiopia has a large amount of land, around 33 million hectares, available for non-food and non-environmental protection purposes, which includes approximately 8% suitable for growing energy crops as a potential source of biofuel [16]. Ethiopia is Africa's second-largest producer of biofuel, which can be made from oil-yielding plants like Jatropha, sugarcane, sorghum, cassava, cottonseed, and palm oil [11]. Ethiopia is promoting the production of biofuels as part of its strategy to increase renewable energy sources and mitigate environmental damage. According to Sapp's report [24], Ethiopia has 33 biofuel projects in preparation that plan to produce ethanol from sugar cane and biodiesel from Jatropha and castor beans. Most of these projects are linked to the country's sugar industry, such as the Fincha, Methara, and Wonji sugar plantations, as well as five other sugar estates. The goal is to increase ethanol production while also producing sugar. Additionally, about 25 major public investment projects have been approved for biodiesel production. The country has also given priority for mass plantation of Jatropha, a drought-resistant plant that produces oil-rich seeds for biodiesel. This initiative allows biofuel production without competing with food crops and conserving the environment. Jatropha is cultivated in areas that are not suitable for food crops, ensuring no interference with food security.

### 3.1. Jatropha plantation potentials

Ethiopia is promoting the production of biofuels as part of its strategy to increase renewable energy sources and mitigate environmental damage. The country has also given priority for mass plantation of Jatropha, a drought-resistant plant that produces oil-rich seeds for biodiesel. This initiative allows biofuel production without competing with food crops and conserving the environment. Jatropha is cultivated in areas that are not suitable for food crops, ensuring no interference with food security.

Jatropha availability in Tigray, Ethiopia has been confirmed through case studies in three districts. The potential for producing Jatropha biofuels in the selected areas of the Tigray region depends on topography, soil, climate, and availability of resources. Those parameters influence the amount and quality of Jatropha oil [25–27]. Jatropha is well-known for its capacity to grow and survive in extremely arid, poor soils that are deemed unsuitable for cultivation, which is a suitable plant for the Tigray's arid locations. Jatropha can even take root in cracks in rocks, however productivity may be restricted [28].

The researchers visited the districts to verify the presence of Jatropha plantations, which are mostly used as living fences due to limited demand and market for seeds and lack of animal feed applications. While Jatropha wood is not suitable for indoor firewood due to smoke pollution, it can be burned once dried and is effective in preventing soil erosion. The experts from the mining and energy agency of Tigray Region have been guiding the decision-making process, and in Kola Temben alone, there are approximately 11.8 hectares of Jatropha plantation as shown figure 5.

During the case study, the district of Tanqua Abergele in Tigray was examined. Farmers, pedestrians, and officers were consulted about the benefits of the Jatropha plantation in the district's survey. The survey revealed that the plantation currently covers 3.5 hectares of land and takes 2–3 years to yield seeds (see figure 6). The Jatropha plant can grow and produce twice a year, even in dry conditions. Initially, the community and government were interested in the potential of Jatropha as a source of biofuel for small and large-scale production. Farmers were drawn to it due to its ability to grow on unused land without affecting food security or rural livelihoods. However, farmers are now unhappy because the government did not establish a market supply chain for Jatropha seeds as promised, resulting in a limited supply in the current market.

Raya-Alamata (Alamata and Raya Azebo) is the third district investigated as part of the case study. There are communal Jatropha plantations in Raya-Alamata covering around 4.5 hectare, which is situated at an altitude of 1178–3148 m and has an average annual rainfall of 663 mm and an average annual temperature of 29 °C. Figure 7 indicates that the Jatropha plantation in this area is suitable and has considerable potential. Currently, the community uses the plant as a hedge and sometimes uses its seeds for fuel.

The visual examination shows that the real Jatropha-growing districts in the region align well with the high suitability zones on the Jatropha map [15].

### 3.2. Benefits of biofuels

The biofuel industry can benefit developing nations like Ethiopia by promoting clean energy, enhancing rural development in biofuel-producing areas, and improving local infrastructure. Introducing a biofuel

**Figure 5.** Jatropha plant in Kola Temben.

**Figure 6.** Jatropha plant in Tanqua Abergele.

**Figure 7.** Jatropha plantation in Raya-Alamata.

sector can bring numerous benefits to the country, particularly for rural areas through small farmer development. These benefits may include but are not limited to:

- Studies in the selected districts indicate that promoting Jatropha cultivation can bring environmental benefits like ecosystem restoration, improved soil quality, and decreased erosion [29, 30]
- Creating biofuel production sectors can lead to increased employment and economic growth [31], especially in rural areas. Additionally, it can encourage modernization in agriculture and offer farmers more funding and incentives. This means that establishing Jatropha plantation and biofuel production can provide significant job opportunities for local communities.

- Establishing biofuel farms and oil-producing facilities in rural areas can promote the use of biofuel for household energy, farming machinery, and transportation in accordance with the country's blending policy [32, 33]. This can also stimulate infrastructure growth by attracting investments to rural areas with biofuel potential and reduce deforestation by limiting the use of fuelwood for domestic energy use.
- Introducing biofuel programs in Ethiopia can reduce reliance on oil imports, diversify fuel options, and promote equal access to energy sources [34, 35]. This initiative can also create new job opportunities and attract more service providers, especially in rural areas, thereby expanding the range of available goods and services.

Developing effective biofuel production facilities could provide clean, decentralized energy sources and create jobs, while reducing reliance on imported kerosene fuel and fuelwood. This can enhance energy security for the communities that lack access to electricity.

### 3.3. Biofuel production from Jatropha

The Ministry of Petroleum & Natural Gas in Ethiopia has opened up opportunities for private companies to participate in the biofuel sector through public partnerships to reduce foreign currency expenditure through import substitution [36]. New regulations developed over two years with input from 22 organizations aim to promote collaboration and investment incentives for small and medium-sized businesses to rapidly grow within the industry [37]. Jatropha is a suitable feedstock for biofuel production and land regeneration. The seeds of this plant can be used to create high-quality oil, which can replace kerosene, diesel, and fuel wood. Numerous local and international developers are pursuing large-scale commercial development with six companies extracting bioethanol, four of which are government-owned sugar estates. Only one of these companies, Fincha, is currently producing ethanol, while the other three are still in the planning phase [14, 38].

Sun Biofuels, a UK biofuel developer and majority shareholder of National Biodiesel Corporation, attempted to create a Jatropha plantation on 60 hectares of land, but stopped operations due to unsuitability. The Ambasel Jatropha Project aimed to produce up to one million metric tons of oil annually for domestic and potential export markets, but production is not currently taking place [39]. Despite this, the Organization for Rehabilitation and Development in Amhara and the Ethiopian Environmental Protection Agency have invested in a biodiesel plant for processing Jatropha seeds [10].

API Renewable Energy is the top biofuel developer in East Africa and is focused on increasing sustainable energy production, economic growth, land restoration, job creation, and environmental improvement. By 2025, API plans to construct nine new biofuel plants in Ethiopia, which will produce an estimated 730 million litres of biofuel annually [13]. API chose to develop biofuels in Tigray due to the region's underutilized land, but it is not still martialized. Therefore, Jatropha growers in this region lack confidence due to low market demand, hindering the transition to cleaner energy sources. Creating more market opportunities is crucial for Tigray's farmers and the country's energy transition, empowering local communities to adopt eco-friendly alternatives.

More than 1000 small oil extraction machines from China and India are operating in Ethiopia with low hygiene standards, risking contamination. Only a few large refining companies meet European safety and hygiene standards [40].

The biofuel production sector is progressing slowly, but Jatropha cultivation is moving forward at a steady pace. The government has been promising market access for farmers and offering training and seedlings for Jatropha cultivation in areas unsuitable for food crops, for example in the case of the Tigray region. However, farmers are frustrated by the lack of market opportunities and are losing confidence in growing Jatropha. The lack of a developed market for Jatropha products has hindered various projects nationwide. Other challenges include the absence of proper feasibility studies on soil compatibility for large-scale Jatropha plantations, as well as conflicts arising from top–down decisions on land allocation for developers in opposition to community interests [10]. Therefore, it is essential to address market challenges and enhance policy support for biofuel production to fully utilize the benefits of Jatropha cultivation in these areas.

## 4. Design of biofuel-based community energy system

We selected the Chamo sub-district community in Kola Tembien, located 40 km from the national grid, to design a biofuel-based generator system. By analyzing their energy sources and needs, we designed off-grid energy solutions. This community was selected for its lack of electricity access and proximity to Jatropha plantations, which can provide biofuel for the generator.

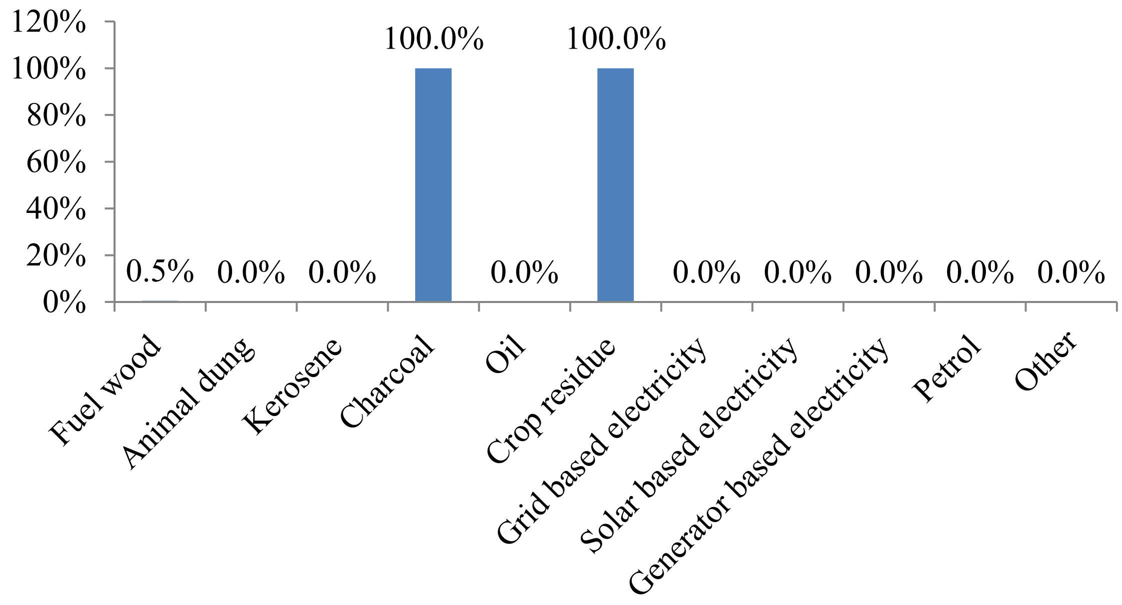


**Figure 8.** Energy sources used by the community for cooking.

### 4.1. Energy sources and utilization

The use of energy sources differs based on location, income, and infrastructure. A survey asked about daily cooking energy sources and found that 100% used charcoal and crop residue while only 0.5% used fuelwood. However, the dependence on biomass can lead to deforestation and indoor air pollution (see figure 8). The reduced use of fuelwood is due to the semi-urban living conditions of the communities.

In rural areas with limited electricity access, communities primarily rely on portable solar lanterns for lighting. About 95% of surveyed householders reported using these lanterns, which can be easily obtained at wholesale stores and use assembled solar panels to store energy during the day. It is important to note that these lanterns have limited capacity. Only 1% of households use crop residue for lighting, and 4% use alternative fuel sources as shown in figure 9.

### 4.2. Access to and affordability of energy sources

Similarly, the investigation found that the community lacks accessible and available energy sources. The main reasons given were the scarcity of nearby sources (99.5%), lack of land ownership (72%), expensive fuel (5.5%), and lack of suppliers (2%) (see figure 10).

According to community ratings, crop residue, fuel wood, and solar-based electricity are less affordable, with 91%, 83% and 67% of respondents respectively (see table 1). A small percentage, 12% and 3%, found fuel wood and solar-based electricity to be highly unaffordable. None of the respondents knew the prices of biofuel-generator based electricity, kerosene, oil, animal dung, and petrol as they are not using these sources. It is possible that the community is also not unaware of the price of animal dung due to it being locally produced and not sold in the market.

### 4.3. Fuel and technology supply chain

Based on community surveys, 92.5% reported that the government supplies solar electricity (Lanterns), and 96% reported that charcoal is provided by retailers. 100% of respondents said fuelwood is collected or provided by individuals, while 98.5% reported the same for crop residue. The community has no supplier for the remaining fuels (see table 2). Communities mostly use conventional energy sources that have negative effects on the environment and health.

Heavy dependence on traditional energy source harms forest ecosystems and increases greenhouse gas emissions. The communities indicate that girls are more affected by the time spent on collecting fuels, which hinders their ability to attend school and contributes to gender-based disparities among children. Table 3 reveals that women are primarily responsible for collecting fuel from distant areas.

Traditional energy sources can lead to drudgery and health problems (99%) as well as deforestation (98.5%) as indicated by the respondents (see in table 4).

Currently, the chosen community is employing two energy technologies. Household responses indicate that charcoal stoves and wood stoves are the most widely used technologies (see figure 11).

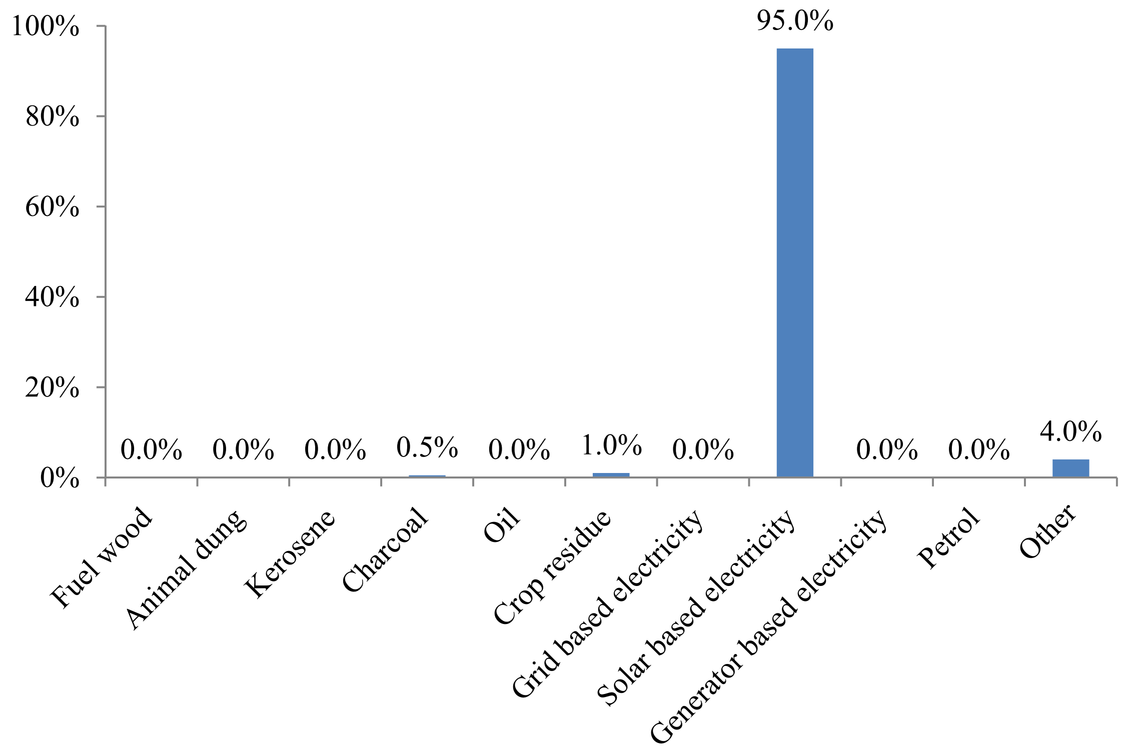


**Figure 9.** Energy sources used by the communities for lighting.

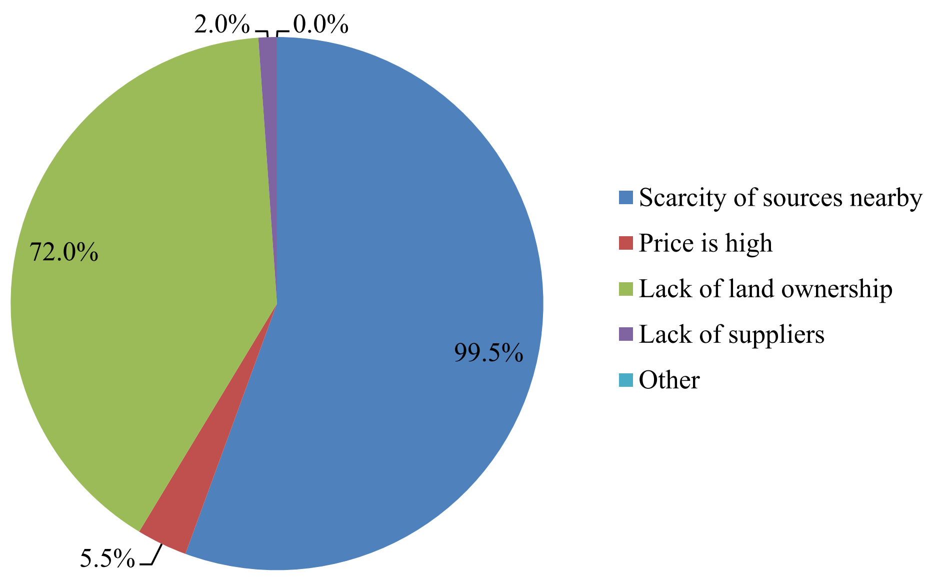


**Figure 10.** Reasons for energy access.

In figure 12, it is shown that individuals and retailers are the primary suppliers of energy technology in the community, accounting for 97.5%. The remaining 93.5% of respondents believe the government plays the biggest role in supplying energy technology, while only 1% feel that companies are the main players in this area.

### 4.4. Energy needs and purchasing power

The study examined community preferences for different energy sources, not based on cost. Results indicated that 69% were interested in biofuel technology for electricity, 30% preferred solar-based electricity, and the rest wanted grid-based electricity for lighting (see figure 13).

Communities believe electricity access is essential regardless of cost and are willing to pay supplier-determined tariffs.

Table 1. Affordability of energy sources for cooking (%).

| Type of energy | Highly affordable | Affordable | Neutral | Less affordable | Highly unaffordable | No answer |
|---|---|---|---|---|---|---|
| Fuel wood | 0 | 0.5 | 4.5 | 83 | 12 | 0 |
| Biofuel based electricity | 0 | 0 | 0 | 0 | 0 | 100 |
| Solar based electricity (lanterns) | 0 | 0 | 25.5 | 67 | 3 | 4.5 |
| Grid based electricity | 0 | 0 | 0 | 0 | 0 | 100 |
| Kerosene | 0 | 0 | 0 | 0 | 0 | 100 |
| Crop residue | 0 | 0.5 | 8 | 91 | 0.5 | 0 |
| Oil | 0 | 0 | 0 | 0 | 0 | 100 |
| Animal dung | 0 | 0 | 0 | 0 | 0 | 100 |
| Petrol | 0 | 0 | 0 | 0 | 0 | 100 |

Table 2. Energy source providers in the community (%).

| Fuel source | Individuals | Government | Retailers | Last-mile distributors | Donors | Cooperatives | No answer |
|---|---|---|---|---|---|---|---|
| Fuel wood | 100 | 0 | 0. | 0 | 0 | 0 | 0 |
| Charcoal | 3.0 | 0.5 | 96 | 0.5 | 0 | 0 | 0 |
| Solar based electricity | 0.5 | 92.5 | 0.5 | 1 | 0 | 0 | 5.5 |
| Grid based electricity | 0 | 1 | 0 | 0 | 0 | 0 | 99 |
| Kerosene | 0 | 0 | 0 | 0 | 0 | 0 | 100 |
| Crop residue | 98.5 | 0 | 0 | 0 | 0 | 0 | 1.5 |
| Oil | 0 | 0 | 0 | 0 | 0 | 0 | 100 |
| Animal dung | 0.5 | 0 | 0 | 0 | 0 | 0 | 99.5 |
| Petrol | 0 | 0 | 0 | 0 | 0 | 0 | 100 |
| Generator based electricity | 0 | 0 | 0 | 0 | 0 | 0 | 100 |

Table 3. Collection of fuel sources.

| Families | Count | Percentage (%) |
|---|---|---|
| Women | 179 | 89.5 |
| Men | 150 | 75.0 |
| Children | 63 | 31.5 |

Table 4. Possible consequences of collecting traditional fuels.

| Consequences | Count | Percentage (%) |
|---|---|---|
| Create conflicts between neighbors | 0 | 0 |
| Affects educational involvement | 61 | 30.5 |
| Sex and gender-based violence | 0 | 0 |
| Restricts involvement in other economic activities | 101 | 50.5 |
| Drudgery leading to health consequences | 198 | 99 |
| Deforestation | 197 | 98.5 |
| Other | 0 | 0 |

### 4.5. Power demand of the community

We determined the energy requirements of the selected community by visiting the location and gathering primary data through interviews and questionnaires from residents who expressed a desire for electricity. This allowed us to estimate the community's potential energy consumption.

To ensure the needs of rural communities are met, affordable and easy-to-use electric appliances were analyzed. Table 5 shows the number and power ratings of each appliance. The total power consumption is

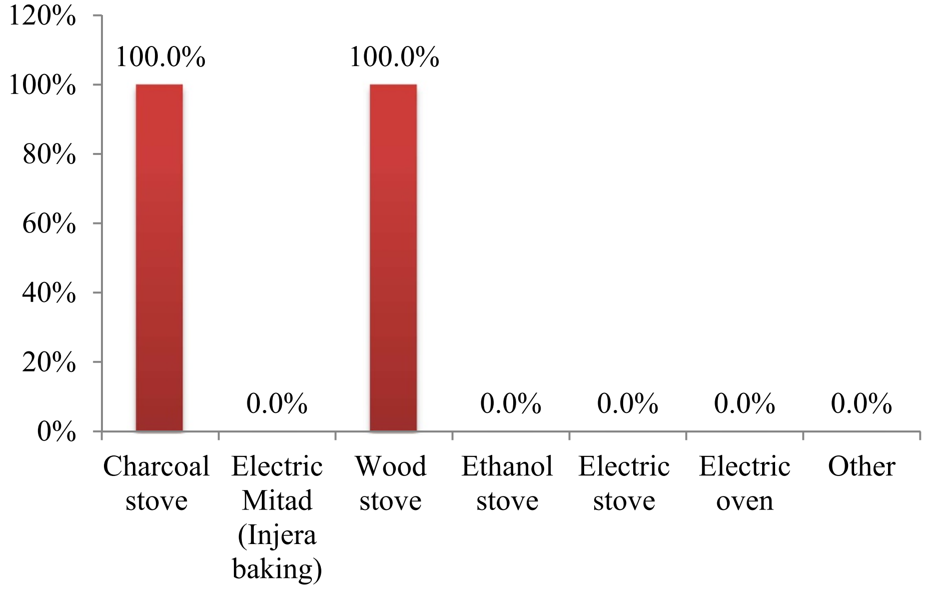


**Figure 11.** Type of stove being used for cooking by the communities.

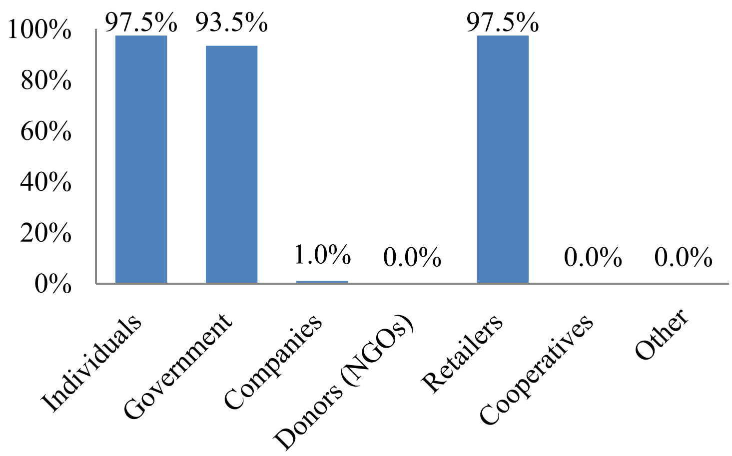


**Figure 12.** Key players in supplying energy technologies.

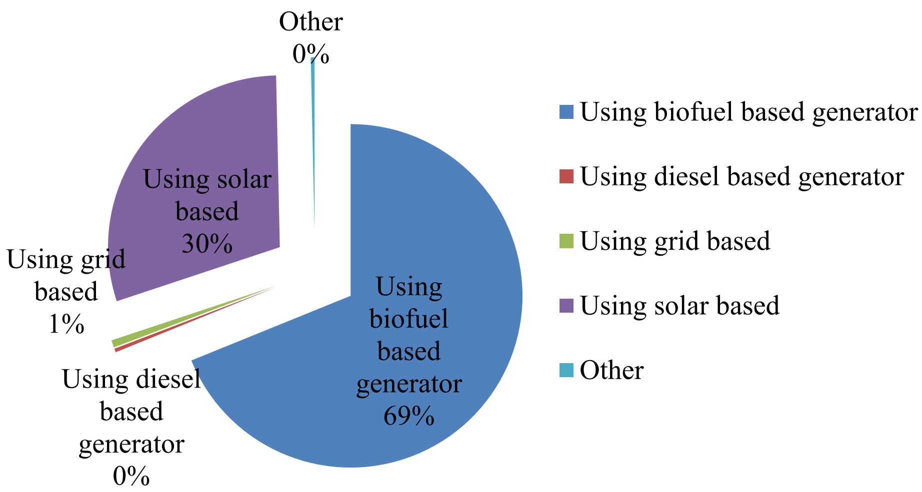


**Figure 13.** Perspectives on how to change the lighting system.

**Table 5.** Appliance power matrix.

| No. | Appliance | Wattage (watt) | Quantity | Total power consumption (watt) |
|---|---|---|---|---|
| 1 | Light bulb | 9 | 527 | 4743 |
| 2 | Television | 15 | 200 | 3000 |
| 3 | Refrigerator | 100 | 1 | 100 |
| 4 | Electric injera baking | 2000 | 200 | 400 000 |
| 5 | Radio | 12 | 100 | 1200 |
| 6 | Mobile charger | 4 | 202 | 808 |
| 7 | Cooking stove | 500 | 200 | 100 000 |
| 8 | Microphone | 15 | 1 | 15 |
| **Total (kW)** | | | | **509 866** |

calculated by multiplying the power rating by the number of appliances. Results indicate a high demand for energy, with a total power demand exceeding 509 kW for the selected community.

### 4.6. Design of the community energy system

The HOMER modeling tool was used to optimize an off-grid biofuel generator system by testing different input parameters, including fuel cost, minimum generator load ratio, and interest rate. The minimum load ratio represents the lowest percentage of a generator's capacity allowed to be used, preventing it from running at excessively low loads. In this study, it was assumed that the community requires more than 509 kW of electricity, and building a mini-grid system powered by biofuels would be expensive and require a lot of fuel. Therefore, it is crucial to plan and assume how the available power will be used efficiently. To reduce energy generation costs, the community needs to follow a strict energy utilization plan for the biofuel generator.

Off-grid systems using biofuel generators only operate for six hours each day, so appliance use must be scheduled accordingly. This study assumes all 200 households will use light power from 6–10 pm and watch TV from 6–9 pm simultaneously. If everyone uses an electric stove at once, the community's power consumption will be 245.2782 kWh $d^{-1}$. To reduce consumption, households should not use electric stoves simultaneously, which shall be introduced as a plan when and if the system is developed. To save costs, only half of the households will use the electric Injera stove at a time, with one group using it from 6–7 PM and the other from 7–8 PM. Also, 50 households, or 25% of households, will use the electric Injera baking at varying times each day. Out of 50 households, 17 will use electric injera baking in the morning (5:00–6:00), 17 in the early evening (18:00–19:00), and another 16 in the late evening (19:00–20:00). The electric injera cooking stove works on a shift basis.

Figure 14 shows the hourly demand load profile for a 24 h period. However, the genset output power must take into account efficiency loss and distribution/transmission losses, despite the community's total energy demand of 432.69 kWh $d^{-1}$. It is important to note that the electricity generated by power plants does not directly translate to the amount of power supplied to customers, as a certain percentage of units are lost within the distribution network. End users will not be responsible for paying for transmission and distribution losses.

Electricity delivery includes both transmission and distribution networks. Two types of losses occur during this process: non-technical and technical losses. Technical losses happen because of physical or technological deficiencies such as poor quality infrastructure and maintenance problems. Some electricity is lost in the delivery process, meaning not all generated electricity reaches the end user. Up to 10% of electricity consumption can be lost in the system, with the distribution network being responsible for most of that loss.

When generating electricity, it is recommended to have some extra power to handle unforeseen demand and added an estimated value of 5766 kWh annually (see table 6).

There is no clear data that shows the production of biodiesel from the selected districts. However, it is experimentally proved that the physicochemical properties of Jatropha oil were found to be suitable for biodiesel production in Ethiopia, despite variations across different growing areas [41]. For this main reason, we calculated the potential diesel production from the Jatropha plantations in the case study areas of Kolla Temben (11.8 hectares), Raya Alamata (4.5 hectares), and Tanqua Abergele (3.5 hectares) based on facts on biodiesel production from Jatropha per hectare annually [42]. The generator needs around 32 0 12 l/year (see table 6), and these nearest Jatropha plantation areas can produce a combined 34 6 50 l annually. This indicates there is enough existing biofuel potential to power the generator for the community but there is huge opportunity to encourage farmers to grow more Jatropha if they get market access to their products.

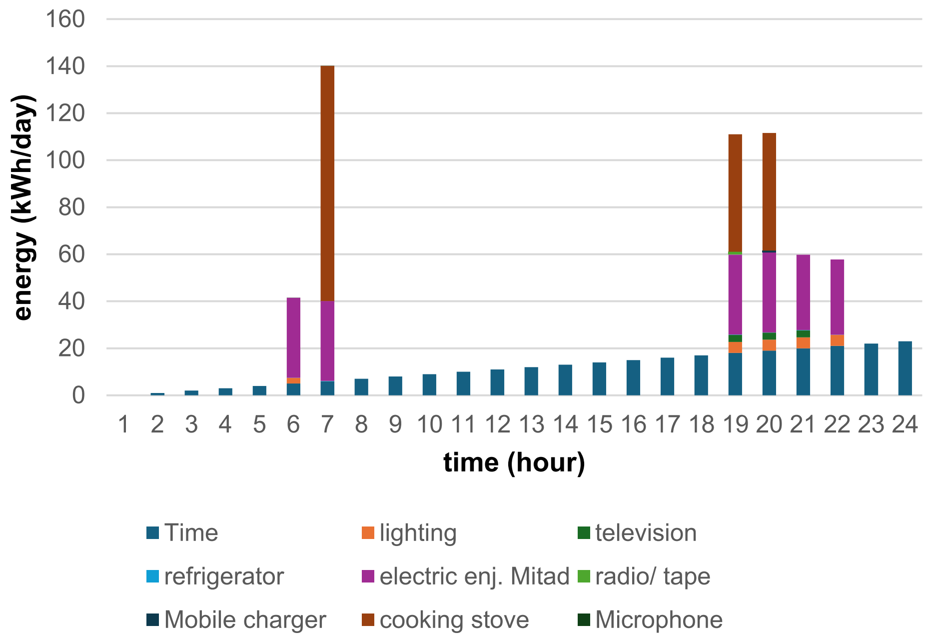


**Figure 14.** Schedule of demand matrix.

**Table 6.** Electrical output of the Genset.

| Quantity | Value | Units |
|---|---|---|
| Electrical production | 226 870 | kWh yr$^{-1}$ |
| Mean electrical output | 25.9 | kW |
| Min. electrical output | 15.0 | kW |
| Max. electrical output | 81.9 | kW |
| Fuel consumption | 32 012 | L Yr$^{-1}$ |
| Excess electricity | 5766 | kWh yr$^{-1}$ |

### 4.7. Selection of business model and financial feasibility

To create the optimal business plan for a project, one must consider the local climate, financial and legal factors, institutional structure, and available support. Additionally, the business model must be adjusted to fit the project's risk profile and local conditions [43]. The proposed business model's success and private sector involvement are dependent upon regulatory and administrative frameworks, financial, and economic conditions [44]. In Ethiopia, off-grid business models can be categorized as wholly subsidized, partially subsidized, or profit-oriented [45]. However, research on community energy systems utilizing solar, hydro, and hybrid solar-wind technology in Ethiopia found that stakeholders, including the community, lack understanding of business models. This lack of knowledge has significant implications for the sustainability of energy services provided to the community. The research also shows that many of these systems have failed due to inadequate financing for their operation [46]. Therefore, developing a suitable business model is crucial for the biofuel-based generation in order to ensure sustainability of the project.

The proposed project would benefit from a partially subsidized business model that considers the recipients' finances and the country's legal framework. The regional government can cover investment costs, while the local cooperative manages O&M expenses. NGOs can also provide investment funding. The study suggests using the current local cooperative for its financial and managerial expertise. However, because not all target households are members of the cooperative, a user cooperative model is also suitable.

Financial metrics such as payback period, net present value (NPV), benefit-cost ratio, and internal rate of return (IRR) help determine if a project is feasible. In this case, the project has a production price of 0.52 USD/kwh and a benefit-cost ratio of 1.33. It also has a four-year payback period, a NPV of 141 682.1 USD (at a 14% discount), and an IRR that is significantly higher than the discount rate of 15%. However, the project's tariff is high for the target group's economic capacity, so a partially subsidized business model is recommended. The subsidized version of the project removes investment and depreciation costs, lowers the tariff rate to 0.15 USD/kwh, and has a 45 952.04 USD operational NPV at a 14% discount rate. It also has an operational BCR of 1.39 when only operational costs and revenue are taken into account.

More than 90% of Ethiopia's electricity comes from hydropower, with the rest from wind, geothermal, solar, and biomass sources [47]. According to the Ethiopian Electric Utility the electricity tariff is 0.01 USD/kWh, which is considered as one of the lowest electricity Tariff in Africa. The government is revising the tariff to improve services as the current tariff is highly subsidized. However, biofuel-based electricity has higher tariff (a subsidized tariff of 0.15 USD $kWh^{-1}$) than grid-based electricity. Remote communities face challenges accessing the grid due to dispersed living arrangements, making grid expansion costly. For this reason, communities are willing to pay higher tariffs for electricity if access is provided though any forms such as the designed biofuel-based generator.

## 5. Discussions and recommended pathways to promote biofuel production and utilization

### 5.1. Discussions

Ethiopia has significant potential for Jatropha plantations and oil production due to its abundant marginal land amounting to nearly 16.61 million ha, which can help in the shift towards cleaner fuels [10, 34, 41]. For this reason, various investments were approved for different national and international companies, including Sun Biofuels Eth/NBC 80 000 ha, Amabasel Jatropha project 20 000 ha, Jatropha Biofuels Agro-Industry 100 000 ha, IDC Investment 15 000 ha in the Benshangul region; ORDA 884 ha, Jemal Ibrahim 7.8 ha in the Amhara region; Petro Palm Corporation Ethiopia 50 000 ha, Emami Biotech Limited 11 000 ha in the Oromia region; and Sun Biofuel Eth/NBC 5000 ha in the SNNPR [10, 34]. Our study also revealed that farmers in the Tigray region have been given a green light by the government to grow Jatropha plantation in marginal lands covering more than 19.8 ha.

Despite being lower than the anticipated investment levels based on Ethiopia's substantial Jatropha potential, successful implementation of these approved investments could lead to a significant biofuel production estimated at around 174 223 tons. Considering the design of a community energy system and the power demand for the 200 people in the chosen community in section 4, these investments could potentially power around 15 411 villages with an average population of 200. On a national scale, these approved investments of Jatropha-based biofuels could help over 3 million people gain access to electricity, boosting the rate of electricity access by over 2%.

However, many of these investments have not fulfilled their promises and some have already ceased operations for different reasons [48]. For instance, Emami Biotech Limited closed down its operations in 2011 due to poor agronomic performance and land disputes with communities. Likewise, Sun Biofuels ceased operations because of inadequate soil suitability studies and insufficient rainfall for growing Jatropha plants [34]. Further studies indicated that premature termination of the projects was primarily due to some key parameters such as moisture stress, low soil quality, and poor agronomic performance [49]. The farmers in the Tigray region are utilizing the Jatropha plantation for other purposes such as fences since there is a limited market for their seed yields. Therefore, the overall key challenges of the sector include but not limited to:

- Lack of strict follow up and implementation of the policies and strategies by all stakeholders
- Poor public private partnership leading to inadequate feasibility study to assess the key parameters that affect the whole Jatropha value chain
- Absence of community consultations and strong stakeholder engagement prior to Jatropha development
- Poorly established oilseed market
- Insufficient knowledge of effective business models affecting the motivation and entry of private sector to this business

Specific Jatropha potential areas have been identified in regions like Benshangul, Amhara, Oromia, SNNPR, and Tigray. However, these challenges impede the successful exploitation of these areas for Jatropha biofuel production. Given Jatropha's potential for supporting Ethiopia's shift towards greener fuels, it is essential for all stakeholders to collaborate in overcoming these key challenges by employing different practical mechanisms including the recommended pathways in this paper.

### 5.2. Recommended pathways

There are viable pathways that address the key challenges in the production and utilization of biofuels derived from Jatropha that could enhance both domestic energy security and rural development by creating jobs through adding value along the supply chain, from farming to distribution, and biofuel production and utilization. These pathways could be categorized as government and private led pathways.

#### 5.2.1. Government led pathways

**Developing conducive and practical policy support**: The government developed policies and strategies termed as 'Biofuel revolution' to promote biofuel production by encouraging the private sector and farmers to grow Jatropha and promising market access for their oilseeds [50]. However, poor implementation of the policies has resulted in farmers' oilseeds going to waste due to a lack of efficient supply chain connecting them to biofuel producing companies. This inefficiency has led to disinterest among growers. The government should take concrete actions, such as offering tax breaks and subsidies to biofuel companies to expand their operations at Jatropha potential sites, to create a strong market for Jatropha growers, thereby supporting the transition to cleaner fuels as envisioned in the policy.

**Infrastructure development:** Encouraging the development of infrastructure for biofuels projects, such as building roads connecting Jatropha growing areas with processing facilities, will attract farmers and biofuel companies to enter the industry. Developing a biofuel value and supply chain requires proper infrastructure for processing, storing, and transporting feedstock. This involves from cultivation to handling the logistics of obtaining, preparing, and delivering feedstock to energy system sites. Planning is important to avoid affecting the development and sustainability of biofuel-based generators.

**Public–private partnerships:** Strong collaboration and coordination among government agencies, private sector entities, NGOs, and international organizations are essential for advancing sustainable biofuel projects involving Jatropha. Our study highlights inadequate collaboration between the public and private sectors in the biofuel industry, particularly evident in the lack of trust between parties in establishing market access and lack of conducting prior appropriate feasibility studies for the Jatropha development [34, 49]. This issue needs urgent resolution by offering support through incentive policies to enhance collaboration among stakeholders to promote and strengthen the biofuel sector and utilize the vast potential for the development of the rural communities.

#### 5.2.2. Private sector led pathways

**Supply chain and market access**: The private sector that owns biofuel production facilities should buy crops from farmers at fair prices and efficiently transport raw materials to processing units. The waste of Jatropha seeds due to lack of market should be addressed by establishing a clear supply chain [9]. Biofuel companies should create market connections between farmers and production sites to ensure sustainable market access, promoting long-term industry growth.

**Business model**: the government and NGOs play a significant role in setting up community energy systems at the start, but later transfer ownership to the community. However, stakeholders lack clear business models to support the sustainable operation of these systems as proved in other renewable energy based community energy systems [51], leading to the failure of many in Ethiopia. To address this situation, the government and NGOs should prioritize integrating business models into project planning and implementation. Adequate training and setting suitable tariffs are key to generating income and ensuring long-term operation sustainability. Leveraging successful international business models can help tailor solutions to the local context.

**Investment and financing**: Private companies have invested in Jatropha cultivation projects to create plantations and processing facilities for biofuel production. They provide funding for land acquisition, infrastructure development, research, and operational costs. Individual farmers are also encouraged to grow Jatropha in their own yards. All stakeholders have not succeeded in building enough processing facilities, which has impacted marketing opportunities for Jatropha seeds. To improve this, the private sector should prioritize establishing biofuel production facilities near potential Jatropha plantations to support Jatropha seed producers.

## 6. Conclusion

Ethiopia is seeking alternative energy sources to overcome environmental degradation and a shortage of traditional fuel. This paper examines the potential of biofuels to aid the country's community energy transition. It reveals obstacles to the widespread adoption of alternative fuels and emphasizes how biofuels can support rural development, amid challenges. Assessment results show that Jatropha and cottonseed are the best crops for biofuel production in Ethiopia since other oil-producing crops are used for food. The country's climate is also suitable for Jatropha plantation in most regions, and cottonseed production areas have potential for biofuel feedstock. Case studies in Tigray suggest significant Jatropha plantations in certain districts, confirming Ethiopia's Jatropha potential.

Despite the existence of policies promoting the shift to cleaner alternative fuels, developers, and users still face significant challenges in fully transitioning away from traditional fuels. These challenges include ineffective policy implementation, shortage of biofuel processing facilities, and underdeveloped supply chains and lack of market access to Jatropha seed producers should focus on the translation of policies into practice through the development of incentives to encourage expansion of biofuel production, develop effective supply chain by development the necessary infrastructure and encourage strong public private partnership to cooperatively address the key challenges. Additionally, stakeholders should prioritize financing the development of biofuel producing facilities in order to provide market access to the existing Jatropha plantations. Communities need appropriate training on business models to help develop and sustain biofuel-based energy systems.

## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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For the purpose of open access, the author has applied for a Creative Commons Attribution (CC BY) license to any Author Accepted Manuscript version of this paper arising from this submission.

## Conflict of interest

The authors have no personal conflicts of interest. Likewise, they are responsible for the publication of this paper.

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