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Energy Generation Policy Strategies for Low CO_2 Emission in Rwanda Using LEAP Model-Based Analysis

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Abstract

This article used the Long-range Energy Alternative Planning and scenario-based analysis to investigate Rwanda's future energy supply, the energy consumption and emitted GHGs from 2023 to 2053. Impacts of various energy policies are analyzed considering different scenarios such as low CO_2 moderate, low CO_2 advance, reference and green optimistic. It was found that by 2053 the demand will be 3075 PJ under reference scenario with a GHG emission increase of 201.3 Mt Co2 due to the consideration of aggressive strategies and energy policies from low CO_2 moderate to low CO_2 advance, as well as aggressive alternatives in green optimistic scenario. More aggressive policy intervention by government, as in green optimistic scenario, would result in a reduction in GHGs (124.4 Mt Co2e) and energy demand (2249 PJ) in 2053. This work also conducted the energy system and cost–benefit analyses.

Keywords: energy policy; scenario analysis; low-CO_2; LEAP model and energy forecasting

1. Introduction

To boost the development of social life, economy and well-being, energy sector is an essential element [1]. Energy demand is expected to have more demand in the future due to the massive global population growth, life standards increase and the global industrialization. However, the World total energy supply is 609.8 Mtoe, which is dominated by Coal that occupies 24.5%, Oil with 46.2%, Natural gas with 16.0%, Nuclear with 0.9%, Hydro with 1.8%, Biofuels and waste occupy 10.5% and the remaining that have 0.1%; this is a global concern to achieve the sustainable development along with these energy consumptions [2]. The conditions to attain the energy development sustainability through carbon (CO_2) reduction will be a benefit for global human survival and socio-economic growth worldwide.

Fossil fuels combustion in different sector such as transportation sector, electricity production, and other economic activities generate greenhouse gases (GHGs) contributing to climate change. However, this needs energy generation standardization as a critical method to increase energy efficiency, minimizing the GHG concentration in the atmosphere and the costs of energy [3,4]. Using different methods, processes and activities promoting new energy resources such as PV systems, wind turbines and hydropower with a good exploitation method will lead to the lower energy costs, low CO_2 emissions, while guarantying more efficient energy consumption. Energy consumption is the most indicator

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of country development and quality of life and the need of satisfying a projected energy demand is the key rationale for energy planning which is part of economics useful to energy problems, considering the analysis of energy supply and demand to ensure coverage of energy needs [5].

Different studies used various models addressing policy concerns of energy, economy and environment such as in [6] where authors presented the analysis of CO_2 mitigation potential of renewable energy efficiency in residential sector using LEAP model to examine the future energy and CO_2 emissions in the period of 40 years from 2010 to 2050. In [7] possible sources of air pollution were identified in Delhi households using LEAP and analyzed energy consumption under different policy and technology options from 2001 to 2021 and estimated the CO_2, methane (CH_4), monoxide (CO) and other gas emissions.

Clean energy accessibility in Rwanda is unreliable and has high disruption costs, impacting production efficiency and competitiveness, despite having the widest possible variety of energy sources. Energy consumption in Africa is very low in general particularly, more than 25 countries worldwide with lowest rates of access to electricity are in Sub-Sahara with the rate of 39% which is the lowest in world [8]. Rwanda experienced a remarkable inconsistency of the plenty of energy possessions and widespread energy crisis with 40% of the population accessing to the electricity, while 93% use firewoods. By the end of 2023, the 63.7% of the electricity access was 47.6% of households connected to the national grid whereas 18.1% are connected to off-grid systems including solar systems and microgrid [9], while the target is to achieve 100% access by 2025 [10]. The research in [11] reviewed the energy sector analyzing the renewable energy access in Rwanda but the outcome still showed that biomass and fossil fuels still dominate Rwanda's energy sources with 89% which are major sources of GHG emissions [12].

The adverse impacts of climate change in Rwanda are obvious. Many examples include the flooding from different places around the country every year such as the flood of 2016 in the North-Western part of the country where 10 people' lives were lost, 354 houses were destroyed, and damaged 3000 ha of the farmland. In 2022, in North-Western part of the country got flooded where 30 deaths with 348 houses totally destroyed and 1000 ha of cultivated areas were inundated [13]. Different conferences on climate change were held such as in December 2015, the United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP-21) was held in Paris where Rwanda with other countries reached an agreement to reduce the global average temperature below 2 °C above the level during the pre-industrial era [14].

The Rwanda government developed different micro power plants to respond to the energy deficit such as solar PV systems and mini hydropower plants also continues to develop new electricity generation projects such peat power plants, gas methane while different studies are still in progress to expand the generation capacity and transmission grids and introduction of new sources of energy [15] to meet the increasing demand [9]. Different researchers from government institutions, universities and private sectors are focusing on the development of new energy sources considering the GDP growth rate parameter [10–16]. This study addresses the following aspects to steer forward energy policy reforms in 30 years from 2023 to 2053; (a) to meet the projected energy demand efficiently with free GHGs at the minimum cost and (b) to suggest the CO_2 emission free sustainable energy policy option.

2. Methods, Data and Scenario Development

2.1. The Model

LEAP model analyzes energy policy and assess the climate change mitigation [17]. It is a terminal energy consumption model for long-term prediction of the electricity demand,

consumption and impact on environment for a specific region or economy based on the range of parameters such as population and the GDP [18]. In this work, LEAP simulates, calculates, evaluates, and forecasts energy policy, demand, consumption, environment impact, and GHG emissions under various scenarios based on the activity level, energy intensity, pollutant emission factors and other data.

Studies [19] applied the LMDI technique-based LEAP model discovering the factors that affect energy consumption, while [20] evaluated energy consumption and emissions. Authors [21] identified the multiple linkages between off-grid solar energy market and the strategies development goals (SDGs) in Rwanda. In [22], Yvan Ayuketah et al. assessed the Cameroon's future energy demand and GHG emissions from 2016 to 2045. Authors [23] examined the minimization of CO_2 emissions in energy system. Moreover, Majid et al. [24] suggested applied six Machine Learning algorithms such as SARIMA, ARIMA, ANN, SARIMAX, AR, and LSTM forecasting the electricity demand in Iran. In [25], authors proposed a new approach to sustainable energy transition in urban environments, focusing on the prediction and management of renewable energy outputs for low CO_2 development in China.

The author in [26] selected Guangdong–Hong Kong–Macao, the Greater Bay Area (GBA), as their research area and employs the LEAP model to simulate its power sector's power generation and energy consumption structures, as well as to forecast corresponding CO_2 emissions. Other authors Jiayi Zhang et al. in [27] conducted an in depth study on the path of building a new energy system in China, considering a region in China as a case study. The LEAP was applied in [28,29], analyzing Niger's and Ghana's electricity Supply and demand scenarios by exploring various resource potentials and their environmental impact. Many authors focused on mitigation of GHG emission.

Authors in [30] performed the LEAP model to analyze the relationship of Energy use, CO_2 Emissions and Economic growth in Rwanda, but with the research limiting time horizon from 1990 to 2020, they did not consider the long-term Rwanda energy and CO_2 projections. Other generic works studied the Rwanda LEAP model but fail to project for long-term energy and emissions for the country. However, there is no study that comprehensively investigated impacts of energy and CO_2 emissions policies for long-term period in the future energy system for Rwanda. This research aims to project the future energy demand and supply reducing the GHGs by imposing policies for the Rwanda energy system using the LEAP model.

2.2. Research Gap

Different short reports and studies in Rwanda such as [31] used the LEAP model for energy-planning studies but focused mainly on sub urban areas on national-level energy demand and electricity generation projections. Existing Rwanda-focused LEAP modelling research commonly neglects rural–urban subnational disparities in energy consumption and electricity access. Many prior analyses fail to incorporate seasonal fluctuations and uncertainties of domestic renewable resources (hydro, geothermal, biomass, solar), which shape national power system performance, while others adopt fixed parameters and narrow timeframes without rigorous scenario evaluation of long-term energy transition risks.

This study constructs and applies a LEAP model for Rwanda spanning 2024–2053 to explore sustainable electricity generation and sectoral energy consumption trajectories over the subsequent three decades under plausible socio-economic, technological and policy conditions. It seeks to deliver evidence-based guidance for low CO_2 technology deployment and actionable national energy planning, alongside adaptive policy recommendations for future energy system design. The analysis covers energy demand and supply projections, GHG abatement potential, and scenario-level cost estimation. The underlying hypothesis is

that embedding spatially disaggregated demand profiles, renewable variability and policy implementation barriers within the LEAP framework yields more credible projections of Rwanda's power generation and energy use relative to conventional modelling using homogeneous static assumptions.

2.3. LEAP Model Algorithm

2.3.1. Energy Consumption

The total final energy consumption is

$$Ec_n = \sum_i \sum_j AL_{n,j,i} \times EI_{n,j,i} \quad (1)$$

where E_C: aggregate energy consumption, AL: activity level, EI: energy intensity, n: fuel type, i: sector, and j is the device. Equation (2) calculates the Transformation net energy consumption.

$$ET_s = \sum_m \sum_t ETP_{t,m} \times \left(\frac{1}{f_{t,m,s}} - 1 \right) \quad (2)$$

where ET: net energy consumed, ETP: energy transformation product, f: transformation efficiency (%), s: primary energy, m: equipment, and t: secondary energy. The transport stock turnover is obtained by Equation (3):

$$EV_n = \sum_c s \times \frac{m}{fe} \quad (3)$$

where EV: energy consumption, s: number of vehicles, m: vehicle distance, fe: fuel economy, n: fuel type, and c: the vehicle type.

2.3.2. Transformation

The calculations for the transmission and distribution modules take into account the domestic fuel requirements that each module faces and translate them directly into input fuels for the module. The total domestic requirements are decreased by outputs of module and increased by inputs. For each process p, input is obtained by Equation (4).

$$INPUT_{p=} \frac{OUTPUT_p}{EFFICIENCY_y} \quad (4)$$

2.3.3. Transmission and Distribution

The transmission and distribution efficiency is calculated in the Equation (5) below:

$$EFFICIENCYp = 1 - LOSSESp \quad (5)$$

where *INPUT* is the fuel, the *OUTPUT* is electricity and the *EFFICIENCY* (p) is the power plant efficiency.

2.3.4. CO_2 Emission

The CO_2 emission is calculated by Equation (6).

$$CEC = \sum_i \sum_j \sum_n AL_{n,j,i} \times EI_{n,j,i} \times EF_{n,j,i} \quad (6)$$

where *CEC*, *AL*, *EI* are CO_2 emission, activity level and energy intensity respectively, *EF*: emission factor from *n* fuel for equipment *j* from sector *i*. The CO_2 emission in energy transformation (CET) is obtained by Equation (7).

$$CET = \sum_{s}\sum_{m}\sum_{t} ETP_{t,m,s} \times \frac{1}{f_{t,m,s}} \times EF_{t,m,s} \quad (7)$$

where *ET*: energy transformation product, '*f*': energy transformation efficiency, and *EF*: emission factor from one unit of primary fuel's' producing secondary fuel *t* through equipment *m*.

2.3.5. Costs

The total cost of a sector is calculated using Equation (8) below:

$$C = \sum_{i}\sum_{j}\left\{\left[(e_{n,j,k}ep_n) + \sum_{k}(m_{k,j,i}mp_k) + fc_{j,i}\right]p_{ji}\right\} \quad (8)$$

where *C* is the total cost of sector, ep_n: price of fuel type *n*, $mk_{j,i}$: demand for raw material *k* per unit of production in equipment *j* within production process *i*, mp_k: unit price of raw material *k*, and $fc_{j,i}$ is the fixed cost per unit.

2.3.6. Cost–Benefit Analysis Definition

In the LEAP model, the cost–benefit analysis estimates the costs of each part of energy system, such as the capital, operating and maintenance costs. LEAP model executes cost–benefit estimations from a societal perspective by counting system costs and comparing the costs of two scenarios.

2.4. Scenario Development

The scenarios are based on the government's planned expansion of electricity, energy services, and suggested mitigation options for reference (REF) scenario. The formulation in REF is available in energy master plan. The REF scenario is used as a benchmark to develop three alternative scenarios including low CO_2 moderate (LCM), low CO_2 advance (LCA), and green optimistic (GO). The REF scenario represents the base case without any energy policy intervention. Table 1 shows the key assumption parameters and features for scenarios used.

Model inputs are grouped into two categories. Exogenous socio-economic assumptions—including GDP growth, population growth, urbanization rate, and industrial growth—establish the underlying development pathway and remain fixed across REF, LCM, LCA and GO scenarios. By contrast, policy levers correspond to energy mitigation measures that differ across these scenarios. This modelling framework guarantees that cross-scenario disparities in energy demand and emissions stem from policy interventions rather than differences in macroeconomic trajectories.

Table 1. Socio-economic parameters data assumptions for the Rwanda LEAP model.

Key Assumption	Ref		LCMS		LCAS		GOS	
	2024	2053	2024	2053	2024	2053	2024	2053
GDP (Billions USD)	13	55.5	13	77.5	13	95.2	13	107.2
GDP growth rate (%)	4.1	4.2	4.1	5.9	4.1	7.3	4.1	8.3
Income (thousands (USD)	996	3604	996	3750	996	5566.87	996	5994.76
Income growth rate (%)	4.8		4.8		4.8		4.8	

Table 1. *Cont.*

Key Assumption	Ref		LCMS		LCAS		GOS	
	2024	**2053**	**2024**	**2053**	**2024**	**2053**	**2024**	**2053**
Population(million)	13.5	16.4	13.5	17	13.5	18	13.5	19.5
Population growth rate (%)	2.5	3	2.5	3.20	2.5	2.40	2.5	3.70
Households(million)	3	6	3	6.4	3	7	3	7.9
Households size (people)	5		5		5		5	
Household growth rate (%)	3		3		3		3	
Urbanization rate (%)	17.89	35.7	17.5	39.5	17.5	40	17.5	35
Industrial growth rate (%)	6.1	6.5	6.1	7.2	6.1	7.3	6.1	7.7
Commercial/service growth rate (%)	12.0	12.5	12.0	13.2	12.0	13.6	12.0	13.9
Agriculture growth rate (%)	6.1	6.4	6.1	7.2	6.1	7.3	6.1	7.8

2.5. Data Collection Process

The LEAP model for Rwanda forecasts the energy demand, supply, and GHG emission for the future under all scenarios. Many sources including the institute of Statistics in Rwanda [32], Rwanda Energy group [33], the World Bank, International Energy Agency and different reports were used to collect data for the Rwanda LEAP model.The following Table 2 displays the cooking fuel switching scenario parameter assumptions with various scenarios.

Table 2. Cooking fuel switching scenario parameter assumptions under the various scenarios.

Cooking Fuel (%)		REF		Moderate		High		Advanced	
		2024	**2053**	**2024**	**2053**	**2024**	**2053**	**2024**	**2053**
LPG	Urban	50.1	65	50.1	70	50.1	80	50.1	95
	Rural	13.6	25	13.6	45	13.6	60	13.6	70
Firewood	Urban	36	14	36	5	36	3	36	1
	Rural	77.1	35	77.1	31	77.1	10	77.1	14
Charcoal	Urban	7.2	8	7.2	13	7.2	7	7.2	4
	Rural	5.3	8	5.3	15	5.3	15	5.3	12
Kerosene	Urban	7.4	2	7.4	2	7.4	0	7.4	0
	Rural	1.3	9	1.3	9	1.3	5	1.3	3

Figure 1 shows the Rwanda LEAP dataset with the main inputs including: (1) Socio-economic assumptions (the population, GDP, economic growth rate, industrial structure, value-added by sector, household size, income levels and urbanization rate). (2) Energy demand-side inputs in residential, commercial, industry, transport, agriculture. (3) Energy conversion and supply-side inputs (power plants, primary energy resource data: fossil reserves, renewable resource potential (solar/wind/hydro), fuel supply costs, fuel loss factors during processing and transmission, plant retirement schedules and new capacity investment plans). (4) Environmental and technical parameters—technology cost data (capital, O&M) for economic analysis, non-energy emission data (agriculture, industrial processes) and scenario assumptions where the demand subsectors include households, transport, industry, service and agriculture. Each sector is split into main branches sub-branches as the figure shows. The urban and rural are split into electrified and nonelectrified. The industry, energy use is divided into shares of energy use (i.e., biomass, electricity, gas and coal). The transformation branch includes transmission and distribution, energy generation, charcoal production, oil refinery and coal mining. The final resource branch is split into

primary and secondary energy resources. Figure 2 represents the energy demand shares at the base year of 2023.

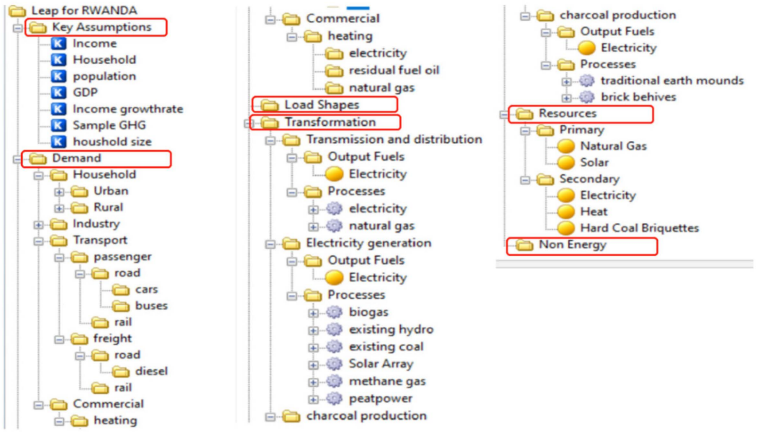


Figure 1. LEAP model dataset from 2023 to 2053 for Rwanda.

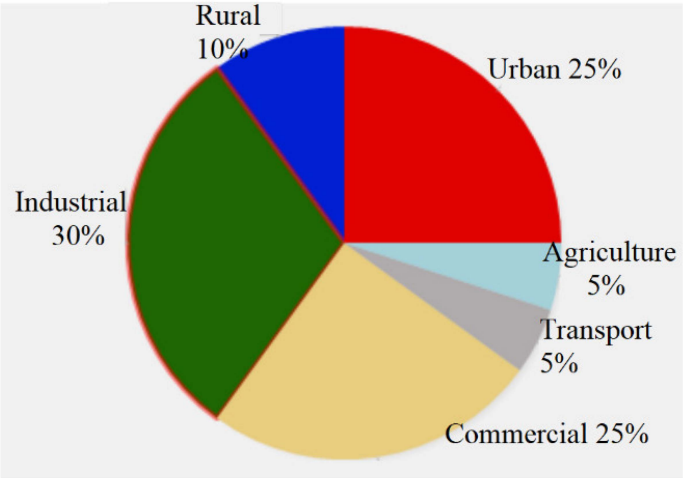


Figure 2. Total energy demand sharing at the base year 2023 in different sectors.

2.6. Model Calibration and Historical Validation

The validation results show all relative differences remain below 3%, indicating the LEAP model reproduces Rwanda's 2023 baseline energy system with good accuracy. This close match between simulated and historical observed data supports the reliability of the long-term scenario projections to 2053. The Relative difference = (simulated − observed)/observed × 100%. Table 3 below presents the comparison between the observed, LEAP simulated energy and GHG indicators in the base year.

Table 3. Comparison of observed and LEAP-simulated energy and GHG indicators in 2023.

Indicators	Observed Value (2023)	LEAP-Simulated Value (2023)	Relative Different (%)
Total final energy demand (PJ)	142.6	144.1	+1.05
Total electricity generation (GWh)	1782	1756	−1.46
Hydropower generation (GWh)	995	982	−1.31
Solar PV generation (GWh)	247	254	+2.83
Biomass consumption (PJ)	101.3	103.0	+1.68
Total GHG emissions (Mt CO2e)	16.71	16.91	+1.14

3. Results and Discussion

3.1. Results

3.1.1. Energy Demand

Using various parameters from Tables 1 and 2 and socio-economic development in Rwanda, the values of energy consumption, Rwandan LEAP system for REF, LCM, LCA, and GO scenarios are illustrated in Figure 3a from 2023 to 2053. Mostly, the consumed energy will increase gradually until 2053 under each scenario. In REF scenario energy consumption is projected to be 3075 Petajoules (PJ) by 2053, from 1039 PJ with a growth rate of 3.68%. The household accounts for 40% of total consumption in REF scenario in the base year, followed by the industrial (29%), and transportation (22%). However, there is a slight change in 2053, with a rise in residential and business sectors and a decline in the transportation and industry sectors. The overall amount of energy consumed in alternative scenarios will be less due to a number of technological advancements and increases in energy efficiency. In LCM, the consumed energy is decreased to 2941 PJ with 3.53% growth rate. Energy saving efforts, such as replacing 70% of incandescent light bulbs with CFL bulbs, were responsible for the slight improvement in the demand sector. The LCA scenario's more aggressive energy policy caused the consumption rising to 2488 PJ at 2.95% growth rate. Due to the LPG introduction in the transportation sector, the share of energy consumption in household decreased while the share in transport increased as shown in Figure 4. The GO scenario, with higher-level application of renewable energy including solar PV and the use of firewood efficiently for households, results in low consumption of 2249 PJ with a 2.61% growth rate. Compared to LCA scenario, households had a slight reduction in consumed energy, as shown in Figure 4, caused by the use efficient light bulbs and PV modules.

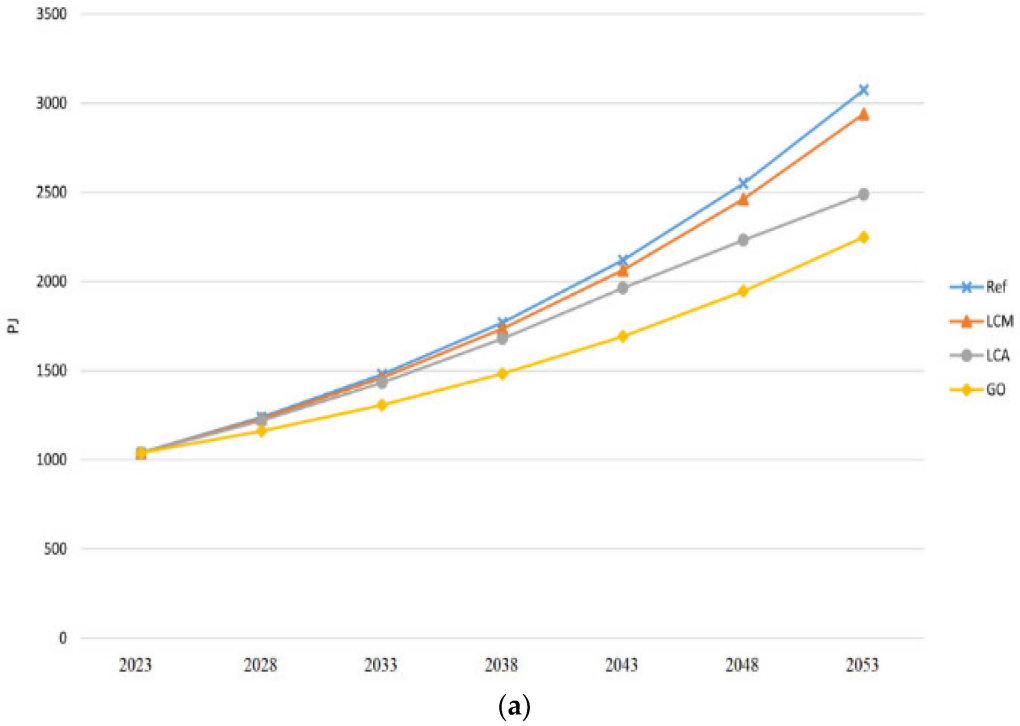
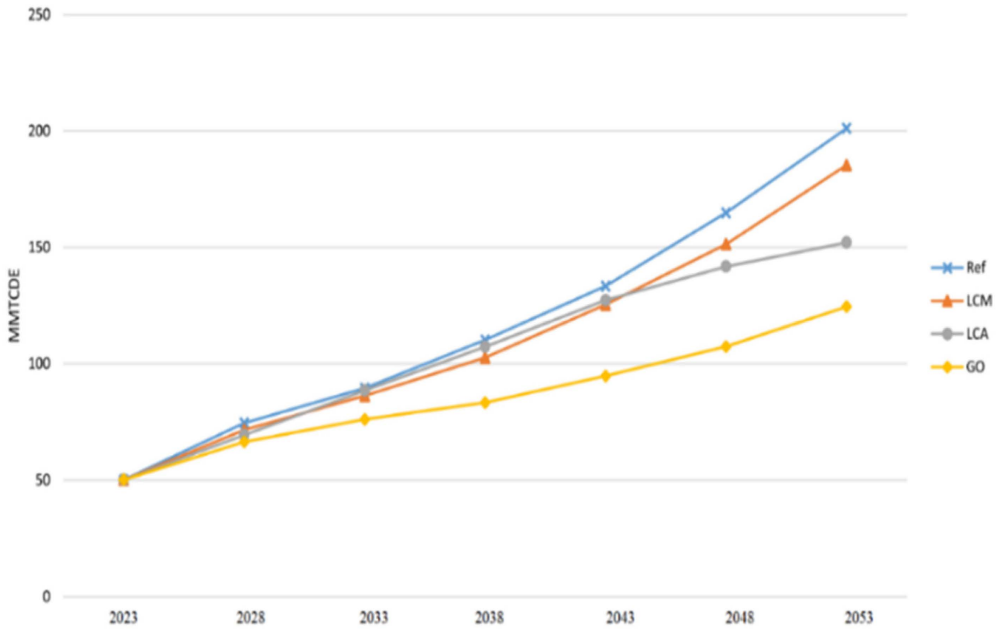


Figure 3. *Cont.*



(**b**)

Figure 3. Four scenarios from 2023 to 2053: (**a**) energy consumption and (**b**) GHG emissions.

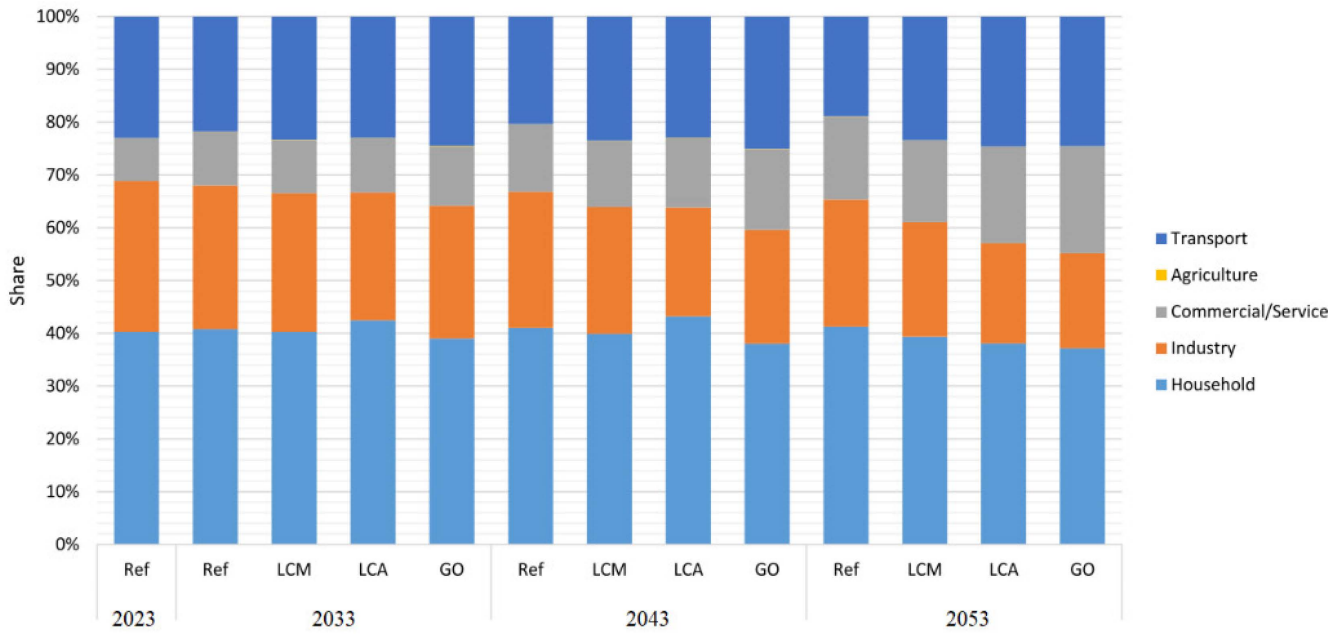


Figure 4. Proportion of energy use by sector.

3.1.2. Final Energy Use by Fuel

Figure 5 displays the structural changes in the ultimate energy consumption for each of the four policy scenarios in 2023, 2033, 2043, and 2053. The energy usage structure will mostly remain identical in REF scenario as was in 2023, with the exception of a minor rise in electricity consumption to 19%. According to the REF scenario by 2053; gasoline, kerosene, and biomass will continue to dominate Rwanda's energy consumption system. On the other hand, the alternative scenario predicts a decrease in the percentage of kerosene use to 23%, 21% and 20% in LCM, LCA, GO scenario respectively. The fuel use reduction observed as effects of energy efficiency improvements. Due to CNG (4%) and LPG (10%)

popularity increase as fuel source options for transportation industry, the share of gasoline used in the GO dropped from 11% to 10% in the alternative scenarios. Additionally, the proportion of clean energy consumption which includes natural gas, electricity, LPG, CNG, and propane, will increase quickly in all potential scenarios and surpass 50%.

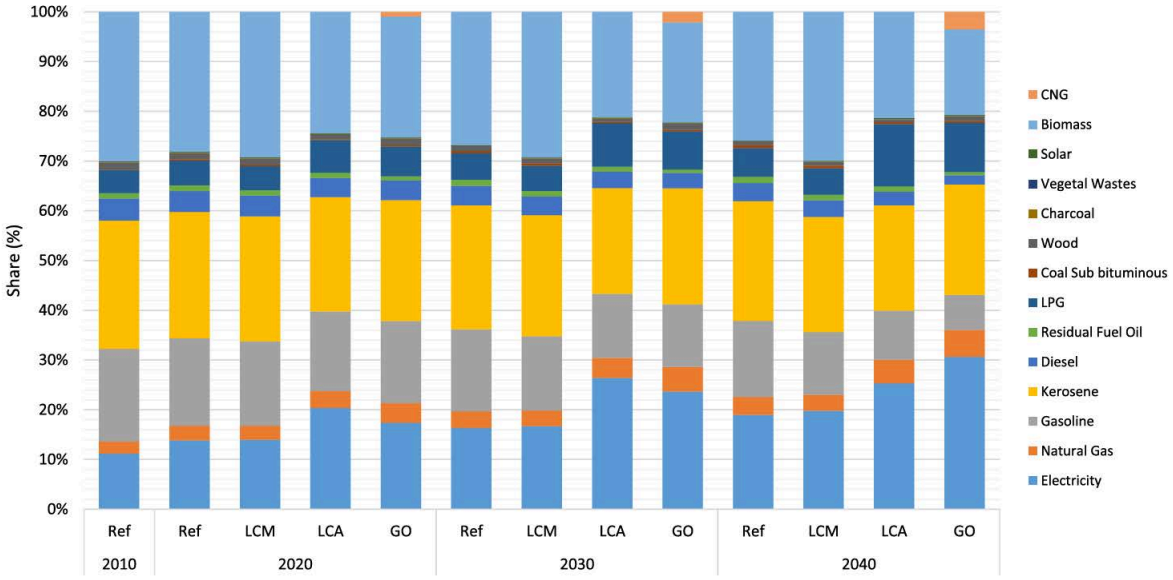


Figure 5. Proportion of final energy use.

3.1.3. Electricity Production

To meet the rising the energy demand, REF scenario assumes the extension of electricity production to produce 179,000 MWh in 2053, as Figure 6 illustrates. As Rwandan government's REF scenario, electricity mix by 2053 will consist of 36% single cycle gas turbine (SCGT), 18% combined cycle gas turbine (CCGT) on grid and 18% off-grid power generation.

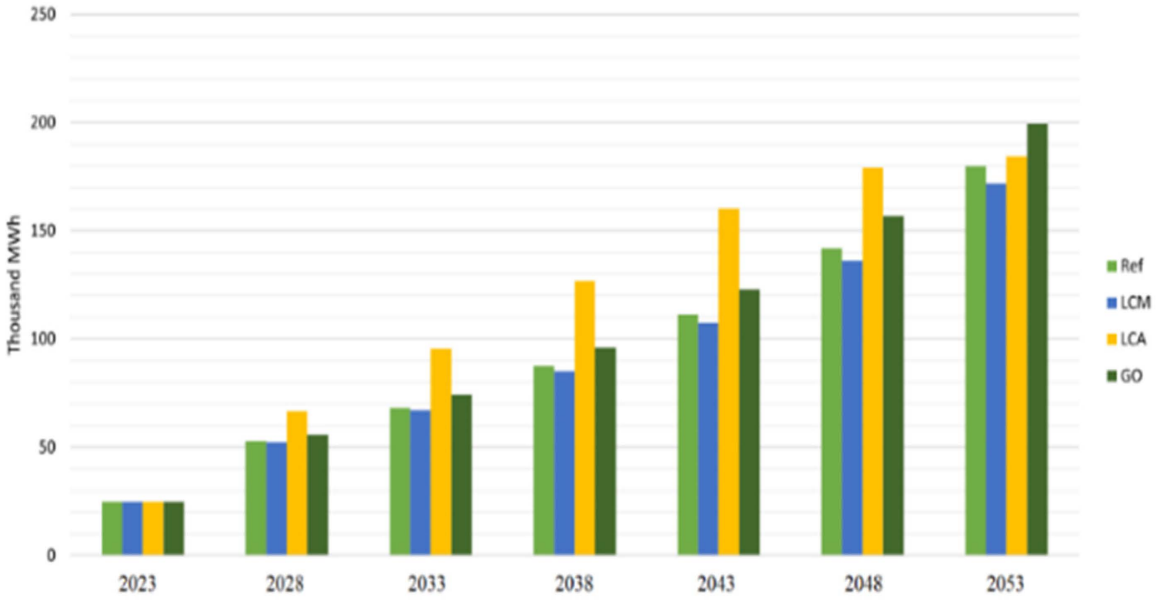


Figure 6. Predicted electricity supply by 2053.

The renewable energy systems contribution is small comparing with other scenarios. By 2053, combined power plants in the LCA scenario will provide 184,000 MWh of electric-

ity, with 60% coming from fossil fuels and 40% from renewable sources. Renewable energy systems will consist of large hydropower plant (9%), biomass power plant (5%), on-shore wind power plant (2%), solar PV at 2% as illustrated from Figure 7. In GO scenario, the mix is further enhanced by adding a higher amount of renewable electricity generation roughly 70%. The goal was to minimize GHGs by 2053 and enhance the production of power from sustainable and clean sources.

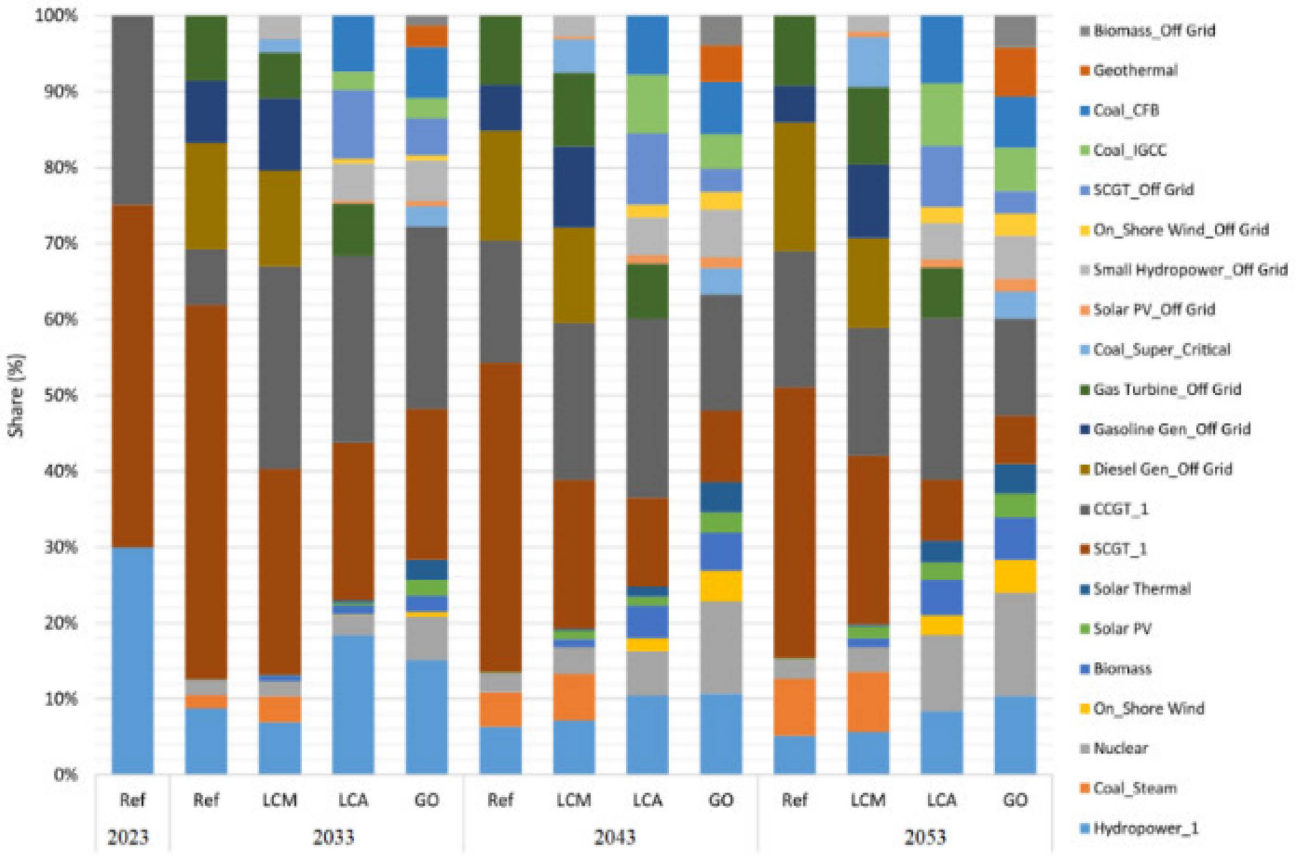


Figure 7. Electricity generation mix share under 4 scenarios.

3.1.4. GHG Emission

Figure 3b shows the GHG emissions from energy use for each scenario from 2023 to 2053. REF scenario predicts that GHG emissions will increase with 4.74%, annual growth rate from 50.2 million metric tons of CO_2 in 2023 to 201.3 Mt in 2053. The GHG emission rate can be correlated to the level of electricity consumption as shown from REF compared to Figure 3a, and LCM at 185.4 Mt of CO_2. According to the LCA scenario, emissions will rise at a rate of 3.87% to reach 152 Mt CO_2 in 2053. This is consistent with the trend in total energy consumption that LCA scenario forecasts in Figure 4.

However, in 2053, the emission will peak at 124.4 Mt under GO scenario. The LCA scenario's 2043 turning point in greenhouse gas emission pathways could result from the energy structure's optimization. In the GO scenario, technology will also be replaced in energy-intensive sectors like the steel and iron sectors, and all sectors would use more electricity in an effort to reduce fossil fuels use. From Figure 3b, the increase in renewable energy utilization in GO scenario contributed to the reduction in GHG emissions on the supply side. It illustrates how the increasing usage of renewable energy also helped to lower GHGs on the supply side of GO scenario. It is shown that achieving low CO_2 development in Rwanda; while introducing and implementing renewable energy technology the supply and demand should be taken into consideration.

3.1.5. Cost–Benefit Analysis

In this research the cost–benefit analysis was conducted in various scenarios. Table 4 presents the results and net NPV of various scenarios in relation to REF scenario. Table 4 illustrates that the cost of implementing the LCM scenario under the demand variable is 35.62 million $, compared to 30.32 and 30.51 million $ for LCA and GO scenarios. The costs of implementing the LCM scenario with the demand variable are displayed in Table 4 as well. The comparable costs for GO and LCA scenarios are 30.41 million $ and 31.12 million $, respectively. The government will save 2.23 million $ by putting the LCM scenario's policies into practice, compared to 37.93 million $ for the transportation and 41 million $ for the housing. The LCA proposes a higher expenditure of 570,000 $ on energy efficiency initiatives for households, compared to 36.11 million $ that will be for transportation sector.

Table 4. Cost–benefit result analysis.

Cumulative Costs& Benefits: 2023–2053. Relative to Scenario: REF			
Discounted at 5% in 2023. Unit: Million USD			
	Low CO_2 Moderate	**Low CO_2 Advance**	**Green Optimistic**
Demand	35.62	30.32	30.51
Households	0.41	0.57	0.56
Industry	—	−1.61	−2.35
Commercial service	−2.73	−5.74	−9.56
Transport	37.93	36.11	40.95
Transformation	14.65	35.12	81.62
Electricity generation	14.65	36.12	81.62
Resources	1640.19	23,790.23	41,269.17
Production	−209.43	44.14	−303.14
Imports	1849.62	23,746.09	41,572.32
Environmental externalities	−4.02	−24.05	−34.48
Net present value	1688.44	23,833.61	41,346.92
GHG savings (MMTCDE)	221.73	332.14	952.00
Cost of avoiding GHGs	7615.00	71,757.93	43,431.71

Energy efficiency, fuel switching, and introduction of renewable energies and growth of LPG vehicles will all be costly for the transportation industry. The LCM scenario was less expensive compared to LCA scenario (USD 36.12 M) in terms of strategy implementation expenses. Every alternative scenario benefited from environmental externalities, with the GO scenario yielding the highest gain (USD 34.48 M) and the LCA scenario yielding the second-largest profit (USD 24.05 M).

For LCM, LCA, and GO scenarios, the total net present value (NPV) is 1.6 billion $, 23.8 billion $, and 41.3 billion $, respectively. The total NPV is the difference in expenses between REF scenario and the alternative scenarios. Finally, compared to GO (43.4$/TCDE) scenario, the GHG emissions avoided cost was higher in the LCA (71.8$/TCDE) scenario.

3.1.6. Future Energy Structure

Particularly, it is anticipated that energy consumption in businesses, transportation, households and industrial sectors will increase significantly due to the rapid population growing, urbanization, and living standards improvement which will affect the total consumed energy from the base year, as illustrated in Figure 8 in comparison with four scenarios in Figure 9: (a) REF, (b) LCM, (c) LCA, and (d) GO.

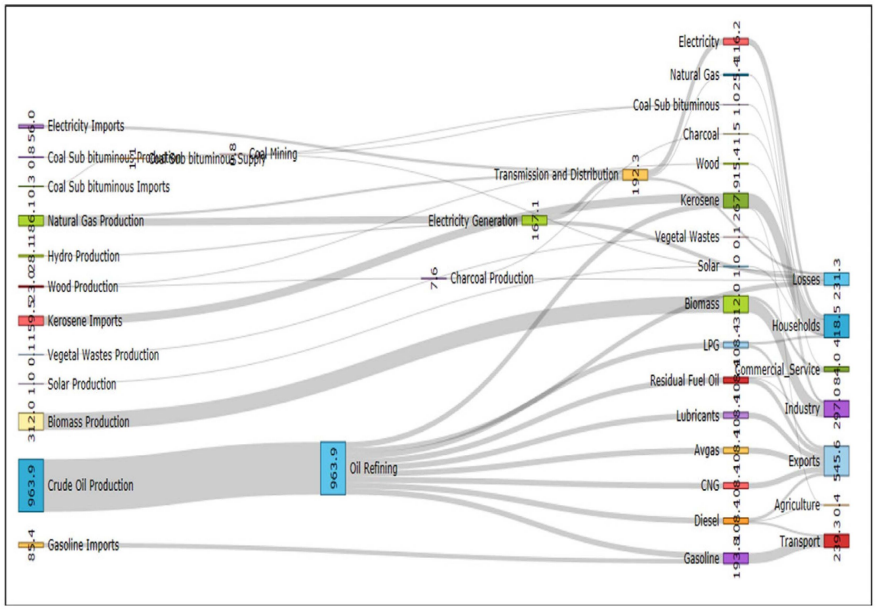
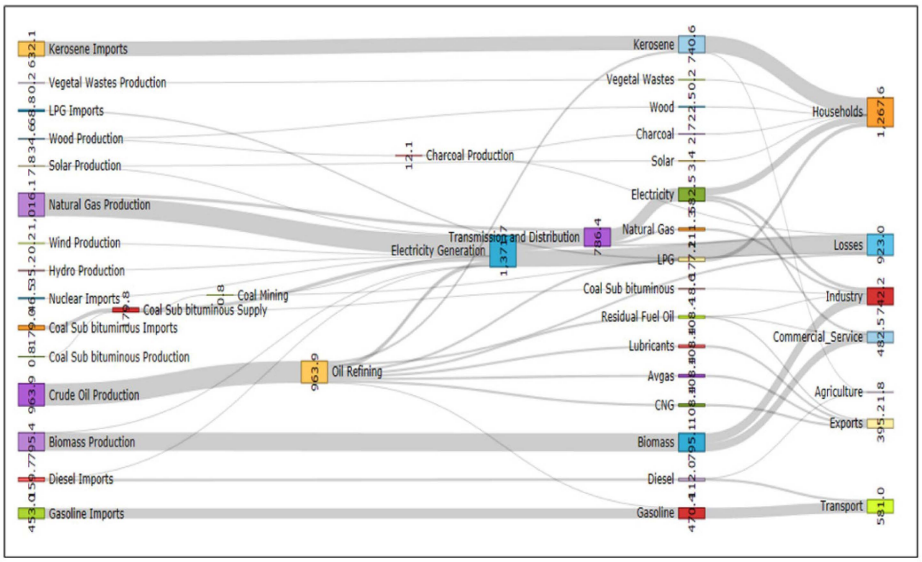


Figure 8. Rwanda energy system in 2023.

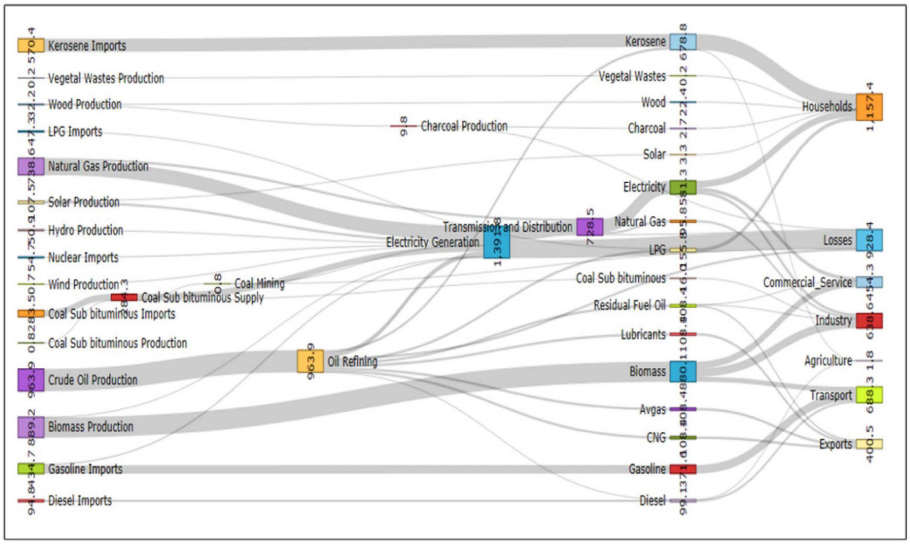
3.2. Discussion

Rwanda as a member, must abide by the United Nations Framework Convention on Climate Change (UNFCCC) to reduce GHG emissions in the interest of eliminating poverty and fostering economic growth to fulfil its international obligations to promote low CO_2 development. Alternative policy scenarios will reduce greenhouse gas emissions and enhance energy use. Among the four policy scenarios, the alternative scenarios will achieve some improvement in energy and GHG reduction. Under the LCA and GO scenarios, the emission will be 24.51% and 38.19% lower by 2053 than under the REF scenario, respectively. The GO scenario shows that increasing the number of policies and strategies implemented can result in reductions in CO_2 emissions. Energy technology efficiency (LPG and solar cookers) should be prioritized by including them to the mix of home energy sources. The adoption of new energy technologies is being hampered by a number of urgent policy challenges, modern issues include inadequate research and development.

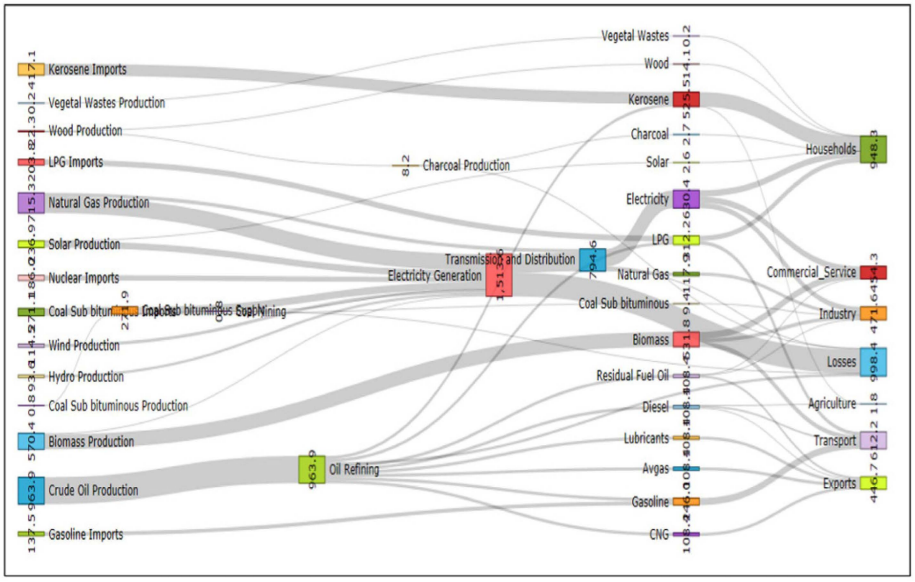


(**a**)

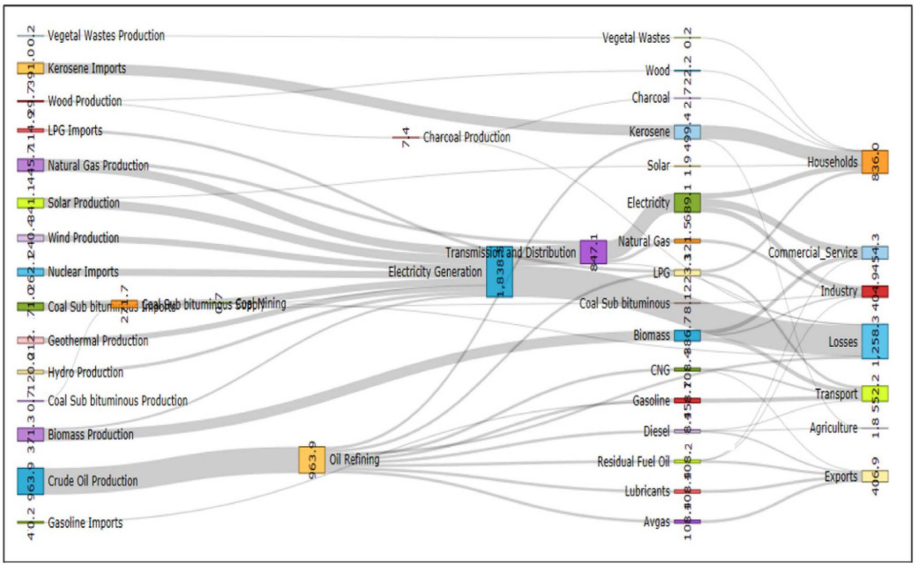
Figure 9. *Cont.*



(**b**)



(**c**)



(**d**)

Figure 9. Rwanda energy structure in 2053 under various scenarios: (**a**) REF, (**b**) LCM, (**c**) LCA and (**d**) GO.

However, if government targets to achieve energy demand decrease and GHG emissions, these obstacles need to be addressed. The implementation of energy standards for refrigeration, electric stoves and air conditioners should be the primary focus when it comes to increase the efficiency of domestic electrical appliances. The phase-out of inefficient electric appliance policies has been adopted in several in China, USA, and others. Thus, in addition to offering subsidies to consumers who use energy-efficient appliances, the government also encourages people to increase the efficiency in household by using renewable energy sources like solar thermal and photovoltaic systems and also engage in creating mini power plants such as hydropower and biogas. The establishment of suitable electricity generation and supply will ensure a proper transition towards utilization of electric power as final energy consumption, replacing the fossil fuels.

As this investigation newly applied to project the pathway for energy system in Rwanda, it should make great attention to understand the term low CO_2 development for a developing country as Rwanda, the path towards low CO_2 development should be based on the nation's circumstances and ability to go the extra mile in attaining a low CO_2 economy. This study examined effects of upcoming energy policies and tactics necessary to lower CO_2 transition, and it offers some likely developmental pathways through scenarios generated for the Rwandan energy system.

4. Conclusions

The possibility of low CO_2 development in Rwanda's energy scheme will depend on policies implementation in energy sector. In this work four scenarios were created; the reference scenario and three others (LCM, LCA, and GO) involved different levels of policies and strategies that affected the various low CO_2 development pathways from 2023 to 2053. The results revealed that energy consumption and greenhouse gas emissions will be significantly impacted by implemented strategies. From the REF, energy demand will be 3075 PJ where the growth rate will be 3.68% in 2053, with an increase in GHG emissions of 201.3 Mt CO_2e. The LCM, LCA, and GO policy scenarios proved the minor energy consumption with 3.43%, 2.85%, and 2.51%, respectively, with the GHG emission decrease.

The optimization of energy system concentrated on replacing fossil fuel by clean energy, as in LCA and GO scenarios, which will contribute a big role to reduce GHGs. The LCM, LCA and GO policies will cost 1.69 billion $, 23.8 billion $ and 41.1 billion $, respectively, according to the cost–benefit analysis results. Energy saving from the generation side, demand-side's energy reductions, and environmental externalities partially balance the high costs associated with energy efficiency and fuel substituting. In Rwanda, transport and household are core sectors for low CO_2 development, industries and commercial sectors show considerable promise to consume less energy and low GHG emissions in the next decades.

To achieve low CO_2 development, Rwanda must investigate a range of policy alternatives pertaining to the decrease in energy usage and GHG emissions using clean energy resources as solar PV, wind, hydro, biomass, and geothermal power sources. Nevertheless, it is not predictable to easily reach low CO_2 emission, due to some challenges that cannot be disregarded. For example, it is difficult to implement clean energy technologies due to the high cost such as cooking efficient stoves and other clean energy use technologies. Because renewable energy systems need a significant capital investment, they are still expensive and tend to favour fossil fuels. It can be solved by introducing financial incentives from the government including loans and subsidies to purchase renewable energy, importing clean energy technologies, and public education to increase the interest in advantages of clean energies.

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Data Availability Statement: The data used in this manuscript is presented in the Tables 1 and 2 across this manuscript and the reference [32] used was added.

Conflicts of Interest: The authors of this paper entitled (Energy generation policy strategies for low CO_2 emission in Rwanda using LEAP model-based analysis) have no conflict of interest to declare. All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report. We certify that the submission is an original work and is not under review at any publication.

Abbreviations

UNFCCC	United Nations Framework Convention on Climate Change
GHGs	greenhouse gases
LCA	Low-Carbon Advanced
GO	Green Optimization
REF	Reference
LPG	Liquefied Petroleum Gas
LCM	Low-Cost Mitigation
NPV	Net present value
SCGT	single cycle gas turbine
CCGT	Combined cycle gas turbine
REG	Rwanda energy group

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