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Evidence-Based Policymaking: Insights and Recommendations for the Implementation of Clean Energy Transition Pathways for Kenya's Power Sector

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Abstract: With ambitious targets to drastically increase economic activity over the next decade, Kenya's future is undoubtedly energy-intensive. Current power capacity expansion plans will see Kenya considerably ramp up fossil fuel generation, significantly increasing emissions. Therefore, Kenya is at a crucial stage of its national development, with critical decisions to make regarding its future power expansion and production. OSeMOSYS modelling software (clicSAND version v1.1) is employed to produce a series of possible clean energy transition pathways to increase renewable power production under rapidly intensifying demand. This study integrates existing national priorities and policies into six modelled scenarios to provide insights into their generation, total production, and costs, which can assist future policymaking and capacity-building efforts. The high-level insights gained in this research were employed to suggest key recommendations for Kenya's power sector. Most notably, policy alignment, increased wind power production, energy-efficiency penetration, finance and investment securement, the development of storage technologies, power transmission, and distribution improvements should be prioritised.

Keywords: Kenya; power sector pathways; clean energy transitions; OSeMOSYS; energy modelling; policymaking; renewable energy

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1. Introduction

Globally, over 80% [1] of the total energy supply is derived from fossil fuels (FFs), having a wide-reaching and damaging impact on the environment, ecosystems, and humans [2] through their production of greenhouse gases and other pollutants. The energy sector is responsible for around 35% of total greenhouse gas emissions, resulting in an important challenge for policymakers in their attempts to reduce and respond to climate change [3]. Kenya has undergone recent changes through its active experience of and recovery from COVID-19, revised energy policy (2018) [4], national climate action plan (2018) [5,6], and the continuous development of its Vision 2030 blueprint (2007) [7], and the country is consequently at an exciting and crucial stage of its national development in terms of forging its energy future. As a result, there is great scope to assess the future role of renewable energy in driving a Kenyan clean energy transition (CET). This study assesses possible future pathways for Kenya's power sector, a sub-sector of the whole energy system, as, despite ambitious targets for 100% renewable generation within the next decade [7], Kenya's 2021 power mix still relied on over 10% FFs (Figure 1). A quantitative analysis of scenarios modelled on existing policy priorities is employed, producing open-source accessible data and insights to be built upon with further research by key stakeholders and local actors.

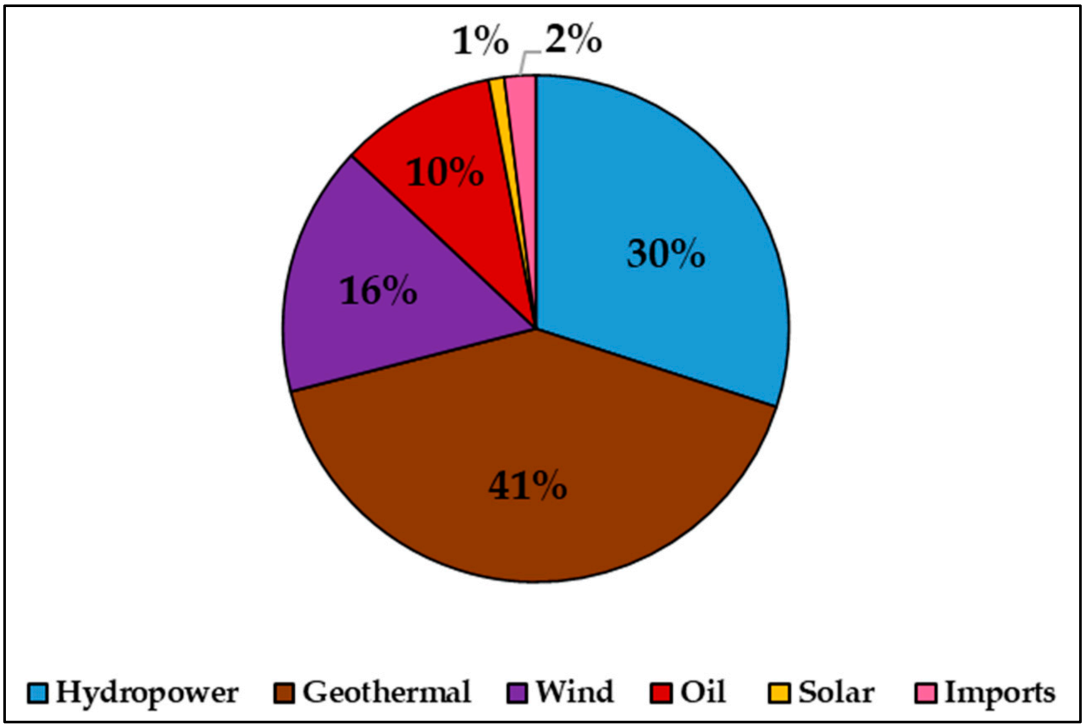

Figure 1. Total Energy Mix for Kenya's Power Sector in 2021.

1.1. Background

With a population of over 50 million, an annual gross domestic product (GDP) of USD 85 billion, and a yearly GDP growth rate of over 5.6% for the past decade, Kenya has become a regional economic leader [8]. Kenya's economic production is primarily driven by its agricultural, fishing and mining sectors [9,10], outpacing the average population growth of ~2.5%, allowing per-capita GDP to rise [11]. As Kenya's economy is currently the second largest in eastern Africa (after Ethiopia) and fifth in Sub-Saharan Africa (SSA), the country is seen as a regional economic giant with considerable influence. Kenya has made ambitious power statements through its Vision 2030 development plan, aiming to reach 100% renewable generation by the end of this decade [4]. Coinciding with its grid extension strategies and competitive affordability compared to fossil fuel sources, Kenya is in a prime position to implement a successful clean energy transition [12]. Therefore, Kenya has the potential to play an exciting role due to its capacity to produce climate-compatible economic growth and is widely considered to be a regional leader in the promotion and development of renewable and clean energies [13–15].

Kenya has several existing policies that relate to its CET and climate change commitments. These are:

1. African Union Agenda 2063: This states that the expansion of energy systems should be primarily provided by clean and renewable sources to promote security and contribute to decarbonisation measures [16–18]. Additionally, the blueprint states a target for all nations to achieve a GDP growth of at least 7% annually by 2063 [19].
2. Vision 2030: This aims to transform Kenya into an industrialised middle-income economy by 2030 through the core pillars of political, social, and economic advancement. The blueprint outlines the goal of achieving 100% renewable power generation by 2030 [4].
3. Least-Cost Power Development Plan (LCPDP): This identifies three main priorities: (a) increased diversification and supply of domestic energy; (b) increased connectivity and affordability of electricity; and (c) increased proportion of renewable energy resources and energy-efficiency (EE) measures [20]. The blueprint outlines a prediction of annual Kenyan GDP growth of 7% until 2020, with a progressive increase to 10%

from 2025 [4]. The updated LCPDP 2017–2037 models geothermal resources, through the expansion of existing binary-cycle geothermal powerplants, as the primary least-cost source of future power generation, accounting for 26% of all Kenyan production by 2036 [7].

1.2. Clean Energy Transitions (CETs)

CETs are widely deemed essential to ensure developing countries globally can meet national and international climate targets [21]. Rambo (2013) [2] discusses how sustainable economic development through a CET would be primarily achieved by replacing all fossil fuels with renewable and clean energy sources. Such a transition facilitates the promotion of a low-carbon economy, which would not only increase climate resilience but also enable a program of poverty alleviation [22]. Additionally, scholars have discussed a wealth of benefits from having an efficient energy (EE) system, including lowering consumer bills, keeping energy affordable, reducing reliance on fuel imports, softening demand growth, and reducing pressure on existing energy infrastructures [23]. A recent report by the IEA [24] found that increasing both energy and material efficiency could help reduce overall energy demand by up to 30%. Further, EE is seen as increasingly vital to curtail the increasing energy demand (up to 30%) expected across the African continent over the next decade [25]. The Kenyan National Adaption Plan 2015–2030 [20] therefore highlights the need for an energy transition within the region to increase both the efficiency and reliability of supply to develop the economy both successfully and sustainably.

1.3. Renewable Power Potential

As of 2021, Kenya had a 2865 MW total installed power capacity, resulting in a total generation of 58 PJ, and a power mix comprising 41% geothermal, 30% hydro, 16% wind, 10% thermal, and 1% solar, with 2% imported [26]. The country's geographical location means it has a wealth of attractive and affordable renewable energy options at its disposal [27,28]. Unique to the eastern African region is the substantial potential geothermal power capacity, at over 18 GW [29], of which Kenya could account for over 50%. This is primarily in the Kenyan Rift Valley and is estimated at around 10 GW [30]. Kenya's energy mix also contains a current installed hydropower capacity of over 800 MW, out of a potential estimated at between 3000 and 6000 MW [26]. Additionally, Northern Kenya is characterised by particularly strong winds, providing a wealth of wind power potential; this has begun with the development of the Lake Turkana wind farm, with an installed capacity of 25.5 MW out of the estimated 4600 MW potential [31,32]. Therefore, a significant percentage of renewable power sources within the nation remains unexploited.

1.4. Previous Modelling of Kenyan Energy Generation and Demand

Various previous studies have looked at the national-level modelling of Kenya's energy sector in some capacity. Irungu et al. (2013) [33] used a bottom-up approach with LEAP software (version 2012.0.0.49) to model various mid-term development pathways from 2013 to 2030 and subsequently connected greenhouse gas (GHG) emissions through business as usual (BAU), natural gas, and renewables scenarios. Similarly, Kehbila et al. (2021) [34] used the LEAP to model potential GHG mitigation scenarios in Kenya from 2010 to 2040, including the African Union Agenda 2063, the UN SDGs 2030, and the full exploitation of renewables. Carvallo et al. (2017) [14] utilised the bottom-up model SWITCH-Kenya to assess mid-term low-carbon pathways from 2020 to 2035, including varying geothermal capacity, coal power generation, and carbon emission tax scenarios. Lahmeyer International (2013) [35] employed LIPS-XP to evaluate the differing costs of universal electrification across Kenya under different mid-term economic growth scenarios from 2015 to 2035. Such Kenyan studies have focused on select mid-term scenarios that apply specific portfolios in isolation, such as electrification, hydropower, or increased demand. Consequently, there is scope for research to inform policy that brings together Kenya's various energy targets and takes into consideration both renewable-energy expansion and increased demand. This paper will utilise power systems modelling to produce key insights and policy recommendations for the implementation of a clean energy transition within Kenya.

2. Materials and Methods

2.1. Methodology

Power systems modelling was employed to produce insights gained from scenario resolutions [36]. Modelling software has developed rapidly over the past decade as a powerful approach to producing quantitative evidence and supporting energy planning, providing insights regarding energy production and sustainable development at local to global scales [37]. OSeMOSYS produces high-quality and accessible technical data based on established scenarios [38]. The software uses bottom-up, linear optimisation to generate the least-cost optimal solutions to meet pre-determined demand under defined constraints [39]. Within the model, technologies are defined by specified parameters such as cost (capital investments, fuel costs, and variable costs), the operational life of various types of generating plants, and current installed capability (residual capacity). OSeMOSYS is used due to its open-source free and accessible nature [40] and ability to facilitate capacity-building and enable future application by researchers and policymakers in resource-limited nations [41]. The research employs the CCG SAND interface (version v1.1), a spreadsheet-based software, to increase the accessibility of the OSeMOSYS system. Additionally, OSeMOSYS allows for the application of the Kenya low-cost energy 'starter data kit' produced by the Climate Compatible Growth (CCG) [42] as a base file for updated and nationally produced data to be added manually (Tables A1 and A2). Both current and potential power plants and commodities are included within the model, as shown in the reference power system (Figure A1). The power sector model produced within this study is consequently widely accessible and replicable for local stakeholders, experts, and policymakers to utilise and build upon in further studies.

2.2. Current Power System Data

Data for the total power generation mix from 2015 to 2021 were collected from the Kenyan Energy and Petroleum Regulatory Authority [43–45]. Additionally, the total installed capacity from 2015 to 2050 was added, utilising residual capacity parameters for current power plants, allowing for decommissioning based on power production start dates and estimates of plant operational life. All power plant types are modelled as a single technology, with existing power plants combined and represented as one resource type. The starter data kit capital costs for power generation technologies have been updated using current and national data sets [8,44]. This takes into consideration international predictions of a future reduction in renewable energy production prices [32,45]. Additionally, the total maximum energy potential per source within Kenya was added as a constraint, preventing the model from depleting more resources than exist within the region [45].

2.3. Main Modelling Assumptions

Assumptions are included within the model to account for the limited availability of national datasets. Certain technologies, such as fossil fuel plants, are defined by global and regional average costs as opposed to nationally specific values due to a lack of accessible data for Kenya. Additionally, annual demand growth rates are projected, taking into consideration previous trends and future plans. This model does not include energy technologies beyond the power sector, such as clean cooking, transport, and batteries, or the potential for integration of such sources in the future. Alongside this, as modelled technologies are simplified significantly to single categorisations, such as geothermal (PWRGEO), individual nuances and variations within resource types cannot be accounted for. The business as usual (BAU) power demand for Kenya to 2050 was taken from the results of early TEMBA projections [46]. TEMBA, a model of African electricity supply, looks to the potential for power trade within Africa to address electrification and increased demand. Finally, within this research, time scales are defined as short (up to 5 years), mid

(10–20 years) and long (20+ years) term. Despite these assumptions, the model is still able to provide critical high-level insights into Kenya's power system under varying scenarios to inform policy recommendations. Additionally, this research can serve as a building block to develop a more detailed and comprehensive model of Kenya's power sector in the future where such assumptions can be tested and varied.

2.4. Modelled Scenarios

Six scenarios were modelled for Kenya's power system to explore possible CET pathways, integrating existing policies through the assessment of increased renewable production, EE measures, and increased demand on the BAU baseline resolutions. Table A3 outlines the constraints applied in each of the produced scenarios.

1. Business as Usual: The BAU model is used as a baseline power system framework with Kenya for the different scenarios to be compared. Constraints were included to produce the power generation shares seen in Kenya from 2015 to 2021. No new investments into EE were considered and demand levels were kept as outlined in the TEMBA model. Policies such as the LCPDP and Vision 2030 are not achieved within this scenario. No new investments are included from 2015 to 2021.
2. Vision 2030: The Vision 2030 scenario follows a future where 100% renewable power production by 2030 is achieved. The model assumes no new investments in fossil fuels, nuclear power, or energy efficiency (EE). The share of total demand to be met by each source is constrained with upper limits to guarantee the system is realistic and operational under a high proportion of renewable sources.
3. Vision 2030 and EE: The Vision 2030 and EE scenario follows the 100% renewable power mix by 2030, as seen in the previous scenario. Additionally, the model sees a gradual increase in EE investments from 2022 to reach 25% of the total demand from 2030.
4. Increased Demand (LCPDP): This scenario involves a future where a revised 100% electrification target, as highlighted in the LCPDP targets, is achieved by 2025 (given the halt in progress following the COVID-19 pandemic). This is combined with a gradual increase in power demand from 2022 to align with a 10% annual GDP growth from 2030. The model assumes no investments in EE or nuclear energy after 2021, and no fossil fuel constraints are included to align with the existing LDPDP model. The share of total demand to be met by each source is constrained with upper limits to ensure viability and power diversity.
5. LCPDP and Vision 2030: This scenario involves a combination of the Vision 2030 and LCPDP scenarios, combining the targets set by both Vision 2030 and the LCPDP. Power demand is gradually increased to achieve 100% electrification by 2025 and 10% annual GDP growth by 2030. Upper constraints are applied to all fossil fuels to achieve 100% renewable generation by 2030. Additionally, the model assumes no new investments in fossil fuels, nuclear power, or EE.
6. Clean Energy Transitions (CETs): This scenario produces the prospect of achieving both Vision 2030 and LCPDP alongside increased EE measures. In addition to the constraints observed in the previous scenario, a minimum investment into EE technologies is gradually added annually from 2022 to meet 25% of Kenya's power demand from 2030.

3. Results

3.1. Main Observations

Scenario resolutions provide six key insights: (1) in the mid-term, geothermal and hydropower remain the most important technologies for a clean power system; (2) in the long-term, wind power will overtake hydropower in the power mix; (3) a 90–100% renewable power mix is produced under all scenarios by 2030; (4) a 100% renewable power sector without EE investments at current demand projections will be more expensive; (5) adoption of EE measures significantly reduces overall consumption rates; and (6) under all high renewable scenarios, flexible technologies and technologies with storage become increasingly important to counter the intermittency of renewable resources.

3.1.1. Power Generation

Figure 2 demonstrates the annual power generation for the six scenarios individually. Across all scenarios, 2030 power mixes show a least-cost future where Kenya's power sector is either 100%, 99%, or 94% fully renewable (Figure A2). Despite no fossil fuel constraints, from 2022, the LCPDP power mix consists almost entirely of renewable energy at 98.6%, until 2040 when combined cycle gas turbines (CCGT) are ramped up and 2050 when simple cycle combustion turbines (SCGT) are introduced. Across all but the LCPDP scenario, in 2030, geothermal energy comprises the largest source of power; hydropower energy is the second main source of power and wind energy is the third. Surprisingly, despite the BAU scenario containing no upper constraints on renewable production, the power mixes across all five other scenarios remain similar, relying on geothermal, hydro, wind, and solar power. Where the four renewable scenarios supplement the remaining generation through biofuels, the BAU scenario relies on small percentages of biofuels, oil-fired gas turbines, and CCGT. Interestingly, the LCPDP scenario produces a slightly different order in its 2030 generation mix compared to the other five, with hydropower producing the most energy, closely followed by geothermal and wind. Consequently, the scenarios demonstrate how the least-cost resolutions for 2030 under both current and a projected demand increase produce a 94–99% renewable mix, and under a similar power mix, a 100% clean power generation can be achieved.

When looking at longer-term projections, the mix of power produced by 2050 varies greatly depending on the scenario (Figure A3). The 2050 BAU power mix employs 18% fossil fuels, despite geothermal remaining the largest source of power. Similarly, the share of power generated by fossil fuels under the LCPDP scenario increases to 61%, with geothermal production reducing drastically. As a result, despite renewable capital costs decreasing annually, the model still finds fossil fuels to be the most cost-efficient solution in the long term. In the generation mixes under both the Vision 2030 and the Vision 2030 and EE scenarios, wind power overtakes geothermal power to become the primary source of power, with wind sitting at 39.5% and 40.3%, respectively, compared to 35.6% and 38.9% for geothermal power. In the LCPDP and Vision 2030 and CET scenarios, geothermal power remains the primary resource, with wind and solar energy overtaking hydropower in relation to percentage share.

3.1.2. Power Production

Figure 3 compares the total power production totals across all six scenarios in 2050. The rapid increase in power generation from the BAU, Vision 2030, and Vision 2030 and EE scenarios to the LCPDP, LCPDP and Vision 2030, and CET scenarios is due primarily to the rise in demand associated with both universal electrification and annual GDP growth. Alongside this, the rise could also be a result of the increased levels of wind and solar power production associated with the greater development of renewable power systems. The intermittent nature of such technologies means that a larger amount of power production, with appropriate storage facilities, is needed to account for the times when solar and wind power cannot be generated.

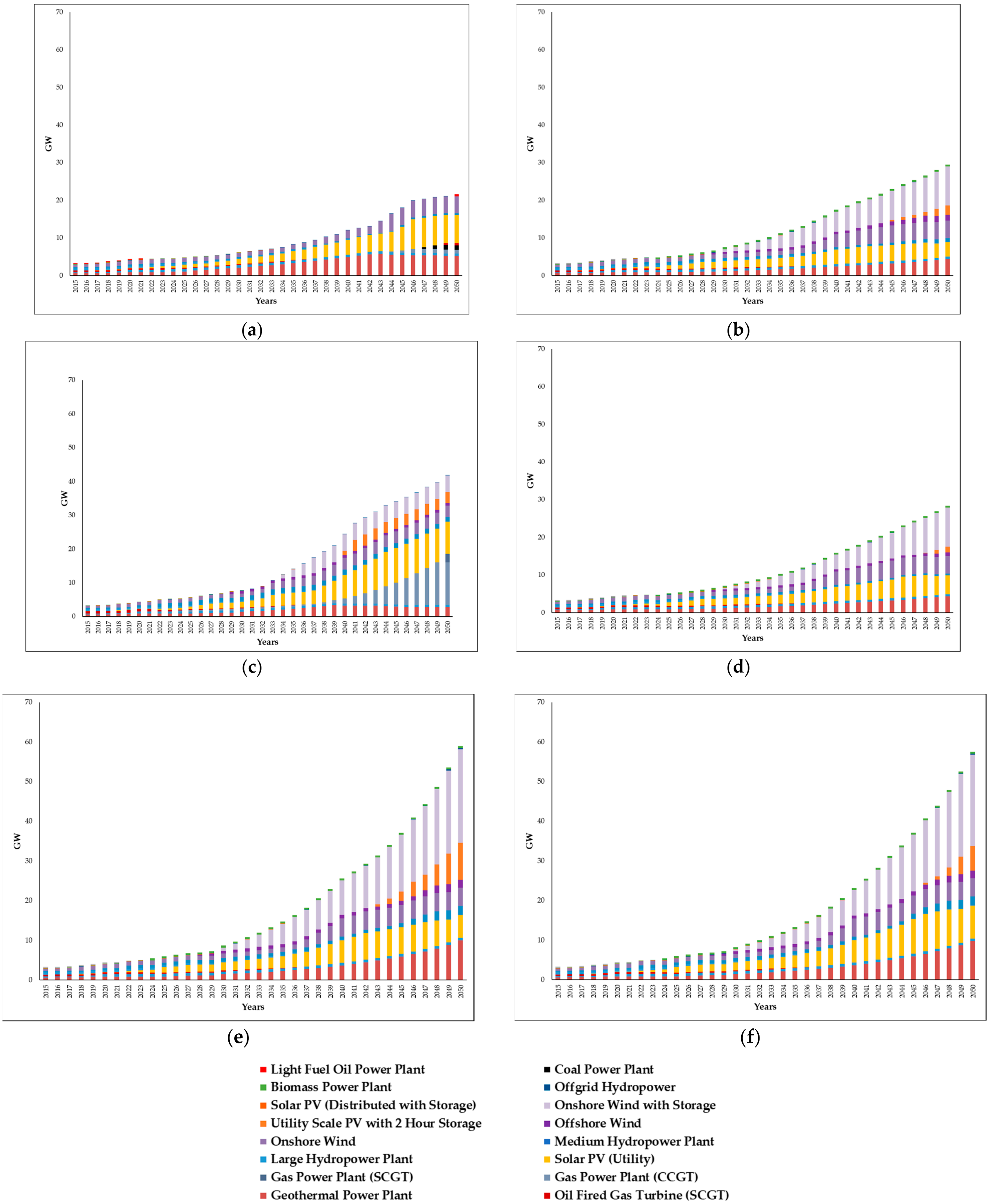

Figure 2. Annual Power Generation Production for Kenya for all six modelled scenarios by source from 2015 to 2050. (**a**) Business as usual (BAU); (**b**) Vision 2030; (**c**) Least-cost power development plan (LCPDP); (**d**) Vision 2030 and energy efficiency (EE); (**e**) Least-cost power development plan (LCPDP) and Vision 2030; (**f**) Clean energy transition (CET).

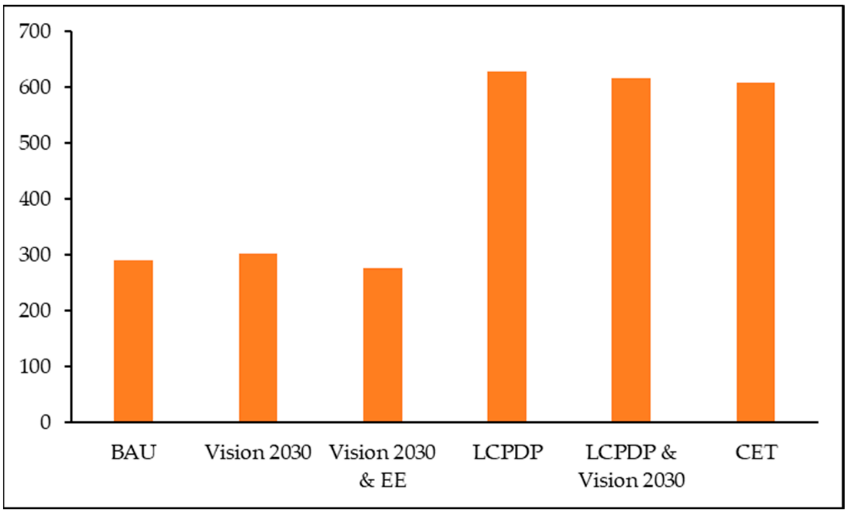

Figure 3. Total combined power production (PJ) comparison for Kenya in 2050 across all modelled scenarios.

Despite this, power production decreases by 8.2% in 2050 under the CET scenario compared to the LCPDP and Vision 2030 scenario with no EE investments. Similarly, power production decreases by 9.5% in 2050 from the Vision 2030 scenario compared to the Vision 2030 and EE scenario. EE measures can therefore be used to reduce consumption rates, providing a successful way to manage increasing power demand. Consequently, the CET and Vision 2030 and EE scenarios show how a fully renewable power system can be achieved through primarily geothermal, hydro, and wind power in 2030, altering to geothermal, wind, and solar by 2050. Such generation suggests that geothermal resources will provide a stable and reliable source of power, with the flexibility to meet demand in periods when these inherently intermittent resources are unreliable or unavailable [30]. However, system flexibility, optimal EE impact, and the associated costs of such variables should be examined further.

3.1.3. Total Costs and Capital Investment

Figure 4 shows the overall total system costs, and Figure 5 shows them compared to BAU, for all modelled scenarios. Overall, there is a USD 74.6 billion difference between the scenarios, and the LCPDP and Vision 2030 and CET scenarios result in the highest overall system costs (at USD 287.9 billion and 289.2 billion, respectively). Despite investments under the CET model into EE, the LCPDP and Vision 2030 scenario is the cheapest of the two. Regardless, both scenarios are significantly more expensive than the LCPDP scenario, with no fossil fuel constraints. At a total system cost of USD 276.3 billion, the LCPDP scenario is USD 11.6 and USD 12.9 billion cheaper than the LCPDP and Vision 2030 and CET scenarios, respectively. Consequently, the fully renewable, increased-demand scenarios will see a significant increase in costs. Additionally, the BAU scenario remains the cheapest scenario, reaching a total cost of USD 214.7 billion, with an additional increase of USD 9.5 billion to reach a fully renewable system through the Vision 2030 scenario. Despite the increased cost of the CET scenario relative to the LCPDP and Vision 2030 scenario, investment into efficiency in the Vision 2030 and EE scenario reduces overall system costs to USD 221.8 billion, a USD 2.4 billion saving compared to no EE investments.

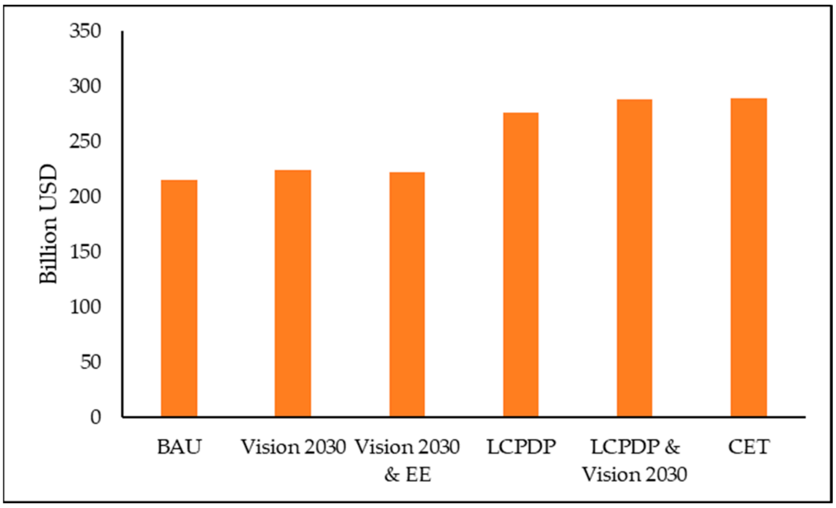

Figure 4. Overall cumulative total system costs for Kenya for all scenarios from 2015 to 2050.

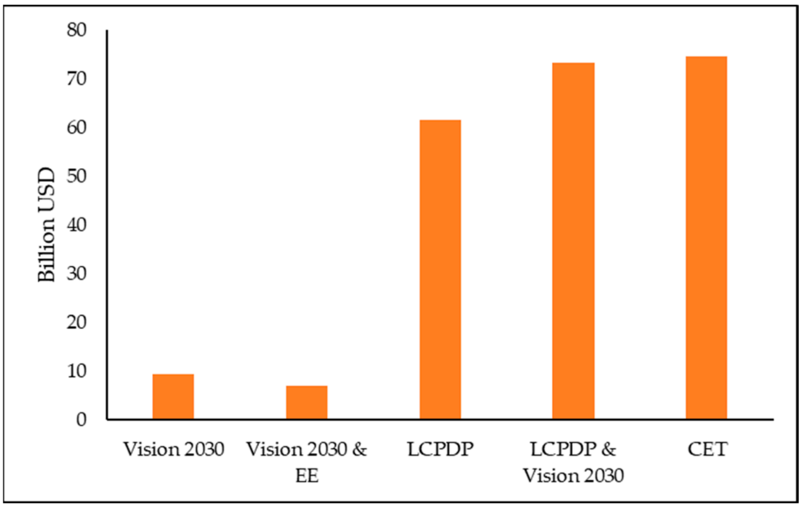

Figure 5. Overall cumulative total system costs for Kenya for all scenarios compared to BAU from 2015 to 2050.

4. Discussion

4.1. Comparison to Existing Policy

Both the existing LCPDP and the LCPDP modelled within this study identified geothermal power as the least-cost resource to meet Kenya's increased demand over the mid-term. The current LCPDP for 2037 predicts a power mix of 26.7% geothermal, 19.5% coal, 17.9% hydro, 8.6% solar, 8.5% wind, and 7.6% natural gas [7]. Results from the LCPDP model for 2037 in the current research varied greatly, consisting of 34% geothermal, 28% wind, 25.9% hydro, 9.5% solar, and 2% natural gas. Consequently, the overall fossil fuel generation mix in 2037 varies from 27.1% in the current plan to just 2% in this research. The LCPDP scenario only accounts for existing installed capacity and does not include any future project installations or expansions. This study does not assume the future installation of coal power projects, such as the Lamu power plant, which have not yet come to fruition due to political and economic barriers [47], despite being included within the existing LCPDP. Additionally, the existing LCPDP was published in 2018, and this study contains actual power demand levels, installed capacity, and power production from 2017 to 2021 and updated future renewable energy cost projections. Both factors could explain the significant disparities in coal production.

The current plan does, however, acknowledge the increasing role of wind and solar, also reflected in this research.

Additionally, the current LCPDP provides a mid-term projection (to 2037) of Kenya's power sector, identifying geothermal and hydropower as the two most significant and cost-optimal renewable resources to meet increased demand. However, through extending the modelling period, this study's LCPDP projected power mix changes significantly after 2037. From 2037, wind power, mainly through onshore wind technologies with storage, is the second most cost-efficient resource in all scenarios, which meets the 2030 100% renewable target. Despite hydropower producing a substantial proportion (25.9%) of the power generation mix in 2037, this falls significantly to just 7% by 2050. The increasing role of wind power, and reduction in the importance of hydropower, is seen in all modelled scenarios bar the BAU scenario. As a result, these modelled scenarios highlight the potential for changes in cost-optimal investment choices when looking at the long term, as opposed to short- and mid-term periods.

4.2. Model Insights

The clean energy transition (CET) is a long-term scenario that would allow Kenya to reach climate-compatible economic growth alongside SDG 7 and the Nationally Determined Contributions (NDCs), Vision 2030, and LCPDP goals. The implementation of a CET will be extremely beneficial by reducing environmental damage, boosting the economy through job creation, lowering power demand, and relieving pressure on power transmission and distribution [48,49].

Six main recommendations for the implementation of a CET within Kenya can be gained from the scenarios: (1) an updated LCPDP that integrates and aligns with all other climate and energy targets, including Vision 2030 goals; (2) the creation of a long-term power plan that outlines and implements a shift from significant hydropower generation to wind; (3) the penetration of high EE technologies and investments into the power sector; (4) secure long-term investments into infrastructure and power generation in order to ensure a shift in focus to renewable energy and EE; (5) ensuring a focus on the development and installation of geothermal and renewable energies (with storage) in order to account for power production intermittencies; and (6) improvements in the power transmission and distribution grids and networks.

4.2.1. Updated Least-Cost Power Development Plan (LCPDP) for Kenya

Future LCPDP revisions should prioritise the integration and harmonisation of all existing cross-sector policies and targets, including (but not limited to) the Vision 2030 plan, SDG 7, and Kenya's NDCs. The current LCPDP contains no fossil fuel constraints, resulting in a recommendation of increased non-renewable production, including the extraction and production of Kenyan coal for the first time in the eastern African region. This will see a significant increase in GHG emissions, contradicting the targets of Vision 2030, SDG 7, and Kenya's NDC. Kenya's unique position as a current regional, continental, and international leader in renewable power production will be lost, with the potential capacity to become a regional exporter of renewable electricity significantly reduced. Additionally, even in the event of political opposition or long-term barriers to the implementation of 100% renewable energy commitments, the least-cost solution should be updated to the 98% renewable generation mix by 2030, as suggested in this study. Consequently, this research recommends that the LCPDP should be reviewed.

4.2.2. Long-Term Power Plan for Kenya

Government-recommended long-term power policies would help promote private-sector investment in renewable technologies by increasing stakeholder confidence, increasing private-sector involvement, and reducing pressure on the Kenyan government to drive the renewable energy transition [50,51]. Currently, Kenya lacks a long-term nationally integrated renewable-energy expansion plan, which severely inhibits the country's ability to fully realise a CET within its power sectors. By extending the modelling and planning to a longer-term period of 2050, this study finds that the cost-optimal renewable power resource mix changes after 2037, highlighting the need to look to long-term priorities alongside short- and mid-term goals. Additionally, policy implementations should include compulsory social, economic, and environmental impact assessments, and capacity-building programmes should be prioritised to guarantee that rural communities benefit from associated job opportunities. Care and consideration should be prioritised when planning solar and wind expansion projects to avoid social harm or negatively impacting citizens residing within affected areas [10,52].

4.2.3. Energy-Efficiency (EE) Integration

The potential of, and need for, energy efficiency in Kenya's power sector to meet future demand levels is high. Without EE measures, the 7–10% increase in power demand from a rising GDP would be unrealistic, resulting in a minimum USD 61.6 billion increase in overall system costs, as seen in the LCPDP results. This highlights the critical need to make EE a national priority if Kenya is to reach climate-compatible economic development. Current policies such as Vision 2030 and LCPDP, which both outline EE as a key component of Kenya's future power sector, must be brought together to enforce clear and measurable short-, mid-, and long-term targets. Furthermore, additional regulation should be adopted that implements minimum energy performance standards for all appliances and technologies nationally, to curtail unnecessary losses [53]. Further studies should investigate increased EE investments to produce cost-optimal and realistic integration levels for Kenya's power sector. As a result, this study recommends further research into EE technologies within Kenya to elucidate the most realistic and economical level of investment needed to reduce total overall system costs.

4.2.4. Secure Long-Term Investments

This research shows how a highly renewable power system in 2030 is the least-cost projection and could propel the nation forward as a regional leader in renewable production. However, both the BAU and LCPDP scenarios indicate that from 2030 onwards, the least-cost resolution begins to rely significantly on fossil fuel technologies, reaching 18 and 61% of the total generation. This has significant implications for future power sector priorities and could lead to a challenging decision between increasing FF production to meet drastically rising demand levels (with emission level implications) and pursuing renewable expansions with higher financial pressure. If Kenyan Vision 2030 goals are to be realised and continued post-2030, significant capital funds and financing remain key barriers. Increased private financing can be encouraged within Kenya through the adoption of renewable energy auctions, feed-in tariffs, renewable energy portfolio standards, and tax exemptions [54,55]. The renewable power market within Kenya should also be opened to encourage international investment and development in both renewable technologies and EE [52]. Additionally, public–private partnerships will become key to overcoming economic and social barriers to renewable power expansion across the region [56]. If adequate financing is not secured, high-RE pathways post-2030 may not be realistic or achievable in the long term, and Kenya should prepare for increased FF reliance and the subsequent emissions associated with such generation.

4.2.5. Overcoming Intermittent Technologies: Geothermal Power

To ensure a stable and secure supply of power, Kenya should prioritise the overcoming of barriers associated with intermittent renewable production by developing geothermal power. This is a controllable technology with the capability to run constantly and ramp up production at any given point, to make up for variability in other renewable energy resources [47]. A move to renewable technologies with storage in the long term, such as onshore wind and solar PV, should also be prioritised to overcome issues associated with meeting demand when supply is intermittent and unreliable [57]. Installation costs for such technologies have already fallen rapidly over the last few decades and are expected to fall further in the coming years [58]. As a result, long-term capacity expansion planning in Kenya should project a shift in the coming decades to a significant increase in technologies with additional storage capabilities.

4.2.6. Power Expansion

To meet increased demand, renewable expansion, and energy-efficient installation optimally, Kenya should explore improvements to existing ageing transmission lines and sequence their grid extension and off-grid integration efforts. Further investment into enhancing transmission and distribution is needed to improve, or replace, the current inefficient infrastructure, drastically reducing electricity losses during transmission [59]. Additionally, mini-grid and stand-alone system incorporation should be prioritised to solidify last-mile electrification projects and identify areas where grid expansion is not technically feasible or cost-optimal [60]. Therefore, an optimal ratio for the grid to off-grid expansion will need to be explored, considering technical, economic, social, and political priorities and barriers. This is vital for a future power system that is predicted to increase in demand between 5 and 10% annually by 2030 [11]. Further, with the potential to transform into a regional exporter of clean power, a strong grid network with the capacity to interconnect with neighbouring power markets is critical [61]. Additionally, storage is poised to play an integral role in Kenya's future power sector, and such technologies will require developments and improvements to the grid, and off-grid, storage capacity [62]. Thus, significant national energy budget spending should be allocated to facilitate future grid, off-grid, and storage development.

4.3. Limitations

4.3.1. Methodological Limitations

Whilst long-term energy modelling as a method for quantitative analysis can reinforce the science–policy interface, allowing for the mitigation of unavailable data and future uncertainties, there are several methodological limitations.

Efficacy questions can be raised over the power sources being categorized as a single technology within this model, particularly relating to CCGT power plants. The model considers all CCGT power plants to have non-renewable primary energy sources and does not allow for primary source variation within power plant type, despite there being potential variation in technology input sources. The simplified model cannot therefore account for technological variations, which could affect the overall proportion of renewables in power mixes and impact the subsequent associated emissions. However, perhaps more significantly, through isolating the power sector and not taking a holistic approach, the methodology employed within this study does not account for the social, economic, and political scope in which policy decisions are being made. Some relevant barriers will be discussed below.

4.3.2. Economic Barriers

Despite capital costs decreasing rapidly, renewable energy systems remain cost-intensive procedures, and financing constraints could limit the development of such technologies within Kenya [52]. The overall power system costs produced within this study ranged from USD 214.7 billion to USD 289.3 billion—a significant and challenging sum of capital to be raised. Funding options will need to be explored in detail to assess how realistic and feasible it is for Kenya to source and cost such a system. Kenya will undoubtedly have to secure significant financial aid and support from international banks alongside climate finance, foreign direct investments, domestic capital, and commercial private investments [63] to consider the CET pathways. However, the high initial investment costs needed to pursue large-scale renewable projects, due to the lack of readily available RE equipment and the absence of long-term loans, may discourage prospective investors in Kenya [64,65]. Additionally, even in cases with agreed finance, unclear administrative procedures within Kenya may stall progress and increase investment risks, as with the Lake Turkana wind project, which took significantly longer than expected to reach financial closure [66]. Therefore, it may be that small-scale, off-grid and mini-grid community projects at a local scale are instead prioritised as alternative and more-accessible power sources for future development within Kenya.

4.3.3. Political Barriers

Policy success and implementation rely heavily on political will. Changes in electoral cycles and public opinion can alter attitudes to power developments, preventing the success of long-term expansion projects that span electoral cycles [12]. Political barriers within Kenya are experienced through public mistrust of technologies and infrastructure, and the government's prerogative to uphold the legitimacy of informal settlements [66]. Community concern over landscape changes associated with power development and the potential impact on the ways of life for local communities living and working close to development sites remains a significant barrier. Particularly, there are concerns regarding competing land uses with the agricultural sector, on which Kenya's economy heavily relies, and land-intensive renewable sources such as wind and solar power [10]. The potential for a long-term policy shift towards increased FF production, as identified within this study, could result in extensive divisive preferences, volatile political procedures, and unstable economic support. Such political barriers can be mitigated through mid- and long-term objectives to provide direction, broader political participation, and engagement in decision-making, yet they remain important factors to assess further when considering power development options.

5. Conclusions and Research Recommendations

5.1. Future Research Recommendations

As the scope of this study was confined purely to Kenya's power sector, there is scope to assess the wider energy sector through, for example, examining clean cooking [67] and EV penetration in the transport sector [68]. Qualitative studies should be undertaken 'on the ground' with the involvement of relevant stakeholders, academics, policymakers, and local communities to assess the feasibility of the insights identified within this study. Capacity-building efforts and skills development within Kenya should be promoted and prioritised to empower key actors and increase power-system development capacity. Flexibility is key to the integration of more renewable resources into generation mixes, given the variability and intermittency of renewable sources [20,24]. Further studies should assess the flexibility within Kenya's power sector, using software such as FlexTool (version 1.3) to evaluate how realistic the least-cost generation mixes are [69]. Additionally, the distribution of renewable resources across SSA determines how favourable conditions are for the success of regional power pools in providing an integrated electricity market and will play a key role in accelerating CETs regionally [70]. Finally, agriculture remains Kenya's biggest economic driver, taking up half of all land allocation and contributing up to 35% of Kenya's GDP [11]. The interaction of increased land-intensive renewable technologies such as onshore wind and solar PV farms, compared to alternative renewable resources, could be assessed through the exploration of CLEWs modelling [71]. Optimal EE penetration levels to reduce overall system costs could be found through additional research beyond this paper.

5.2. Conclusions

Due to Kenya's fast-growing population (~2% per year) and rapid economic expansion, power consumption levels are increasing rapidly and are predicted to rise further in the coming decades. Kenya's mission to become a middle-income country and regional economic leader by the end of this decade means it is set to become one of the most energy-intensive countries in Sub-Saharan Africa. Therefore, Kenya must be prepared to satisfy an ever-increasing power demand in the long term. The projections of rapidly growing power demand could be met by ramping up fossil fuel production, including tapping into national coal reserves for the first time in the region's history. However, a Kenyan power sector reliant on fossil fuel production will: (1) reduce national energy security; (2) regress Kenya's position as a regional and international renewable energy producer; (3) halt Kenya's progress towards climate and renewable energy targets; and (4) increase emissions of carbon and other pollutants contributing to global warming and decreasing local and regional air quality, causing negative impacts on the health and well-being of its own citizens and others. An alternative scenario to increasing fossil fuel production would be the implementation of a clean energy transition (CET), a solution where the power sector is formed of ~100% renewable energy generation and energy-efficiency (EE) technologies are effectively employed to reduce energy production levels needed to meet increased demand, lowering overall system costs by 2030. This provides Kenya with an opportunity to transform its power sector, fulfilling the Vision 2030 goal of reaching middle-income economic status, and become a regional and international leader in renewable energy production. The introduction of a CET would allow Kenya to harness its wealth of renewable resource potential and solidify its position in the Sub-Saharan region by spearheading a wave of energy transitions. However, significant concerns emerge relating to the financing and wider political will to implement such a renewable expansion agenda in the long term. This article serves to provide a quantitative analysis of and insights into possible future pathways for the implementation of a clean energy transition, in line with existing policies, for Kenya's power system. An additional qualitative evaluation of the social, economic, political and technical parameters of the power system insights identified within this study is needed.

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Data Availability Statement: The data presented in this study are openly available in Zenodo repository at https://doi.org/10.21203/rs.3.rs-2449948/v3. This work follows the U4RIA guidelines which provide a set of high-level goals relating to conducting energy system analyses in countries. This paper was carried out involving stakeholders in the development of models, assumptions, scenarios and results (Ubuntu/Community). The authors ensure that all data, source code and results can be easily found, accessed, downloaded and viewed (retrievability), licensed for reuse (reusability), and that the modelling process can be repeated in an automatic way (repeatability). The authors provide complete metadata for reconstructing the modelling process (reconstructability), ensuring the transfer of data, assumptions and results to other projects, analyses and models (interoperability), and facilitating peer-review through transparency (auditability).

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Appendix A

Table A1. Installed Power Plant Capacity in Kenya from 2015 to 2021 [43–45]. Adapted from Allington et al. (2022) [42].

Power Generation Technology	Estimated Installed Capacity (MW)						
	2015	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Biomass Power Plant	88.0	88.0	87.0	87.0	87.0	87.0	87.0
Geothermal Power Plant	627.0	652.0	652.0	663.0	828.0	863.1	863.1
Light Fuel Oil Power Plant	287.5	287.5	287.5	287.5	287.5	287.5	287.5
Oil-Fired Gas Turbine (SCGT)	447.0	447.0	447.0	447.0	447.0	447.0	447.0
Solar PV (Utility)	30.0	31.0	38.0	105.0	106.0	106.0	147.0
Large Hydropower Plant (Dam) (>100 MW)	593.45	593.45	593.45	593.45	593.45	593.45	573.0
Medium Hydropower Plant (10–100 MW)	320.8	320.8	320.8	248.8	248.8	248.8	248.8
Off-Grid Hydropower	5.78	9.27	15.38	15.38	15.38	15.38	15.38
Onshore Wind	261.0	261.0	261.0	336.1	336.0	335.5	437.0
Off-Grid Solar PV	29.67	30.83	37.97	49.39	49.93	49.47	49.47

Table A2. Estimated renewable energy cost projections for selected years from 2015 to 2050 [24,26]. Adapted from Allington et al. (2022) [42].

Power Generation Technology	Capital Cost (USD/KW)					
	2015	**2020**	**2025**	**2030**	**2040**	**2050**
Biomass Power Plant	2500.0	2500.0	2353.0	2353.0	2353.0	2353.0
Solar PV (Utility)	2165.0	1378.0	984.0	886.0	723.0	723.0
CSP Without Storage	6051.0	4058.0	3269.0	2634.0	2562.0	2562.0
CSP with Storage	8645.0	5797.0	4670.0	3763.0	3660.0	3660.0
Large Hydropower Plant (Dam) (>100 MW)	3000.0	3000.0	3000.0	3000.0	3000.0	3000.0
Medium Hydropower Plant (10–100 MW)	2500.0	2500.0	2500.0	2500.0	2500.0	2500.0
Small Hydropower Plant (<10 MW)	3000.0	3000.0	3000.0	3000.0	3000.0	3000.0
Onshore Wind	1985.0	1489.0	1191.0	1087.0	933.0	993.0
Offshore Wind	5000.0	3972.4	2858.0	2450.0	2275.0	2100.0
Solar PV (Distributed with Storage)	6840.0	4320.0	3415.0	2700.0	2091.0	2091.0
Geothermal Power Plant	4000	4000	3991	3991	3991	3991
Onshore Wind with Storage	2319.89	1735.26	1350.35	1202.89	1026.61	1004.32
Utility-Scale PV with 2 h Storage	3128.0	2087.0	1443.0	1220.0	992.0	927.0

Table A3. Maximum generation share constraints added to the total technology annual activity upper limit for each technology to produce a realistic and diverse energy mix.

Technologies	Percentage Share (%)
Biomass Power Plant	30
Geothermal Power Plant	40
Solar PV (Utility)	15
Onshore Wind	15
Offshore Wind	10
Utility Scale PV with 2 h Storage	15
Onshore Wind Power Plant with Storage	25

Appendix B

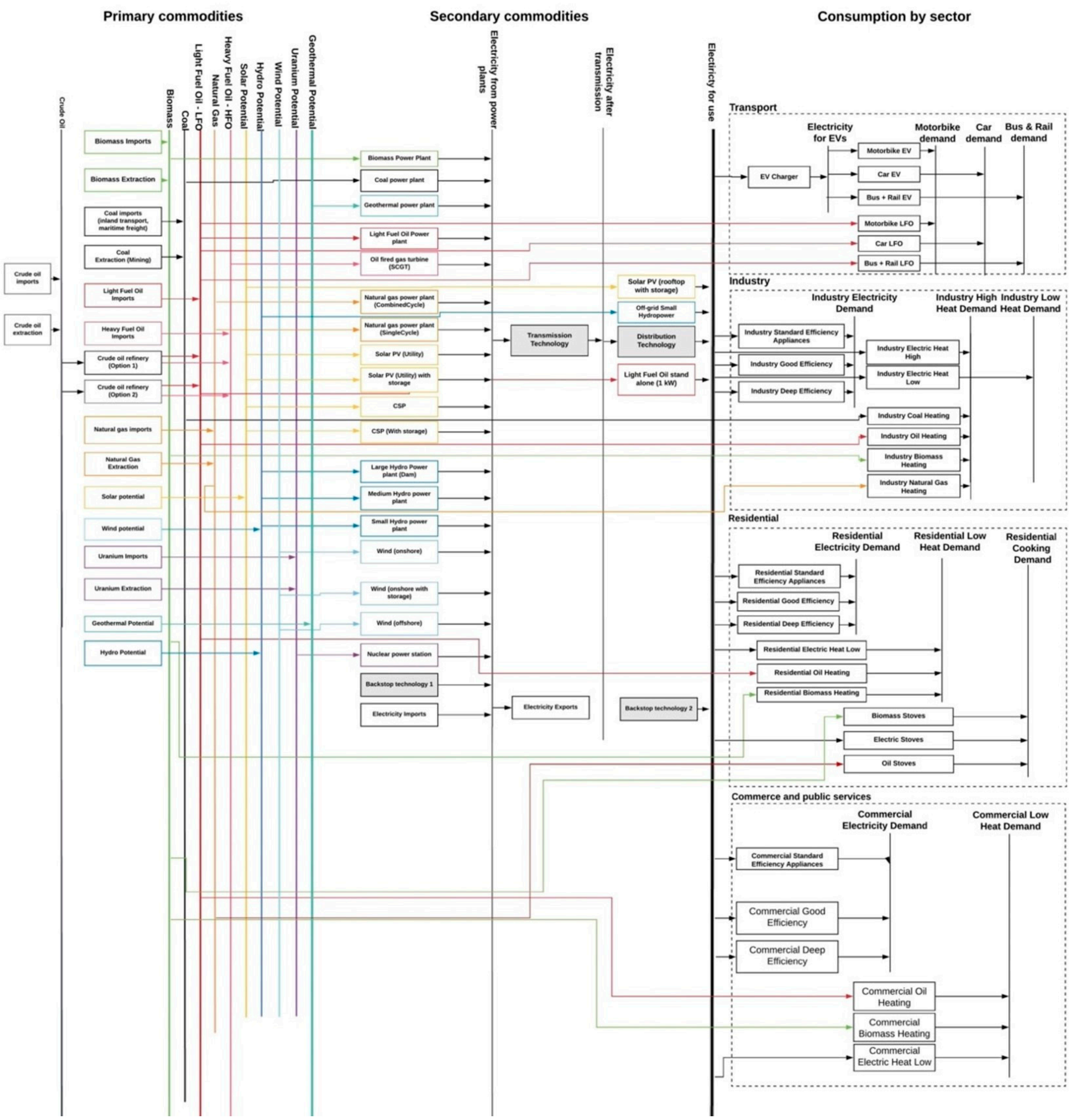

Figure A1. Reference Power System for Kenya [42].

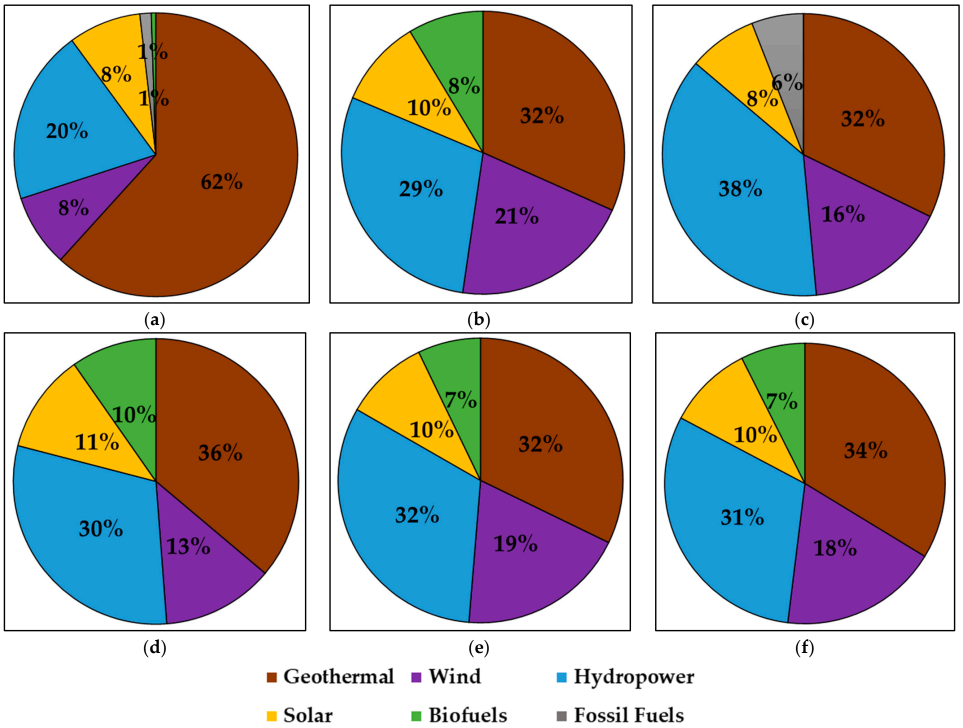

Figure A2. Power generation mixes for Kenya in 2030 by source across all modelled scenarios. (**a**) Business as usual (BAU); (**b**) Vision 2030; (**c**) Least-cost power development plan (LCPDP); (**d**) Vision 2030 and energy efficiency (EE); (**e**) Least-cost power development plan (LCPDP) and Vision 2030; (**f**) Clean energy transition (CET).

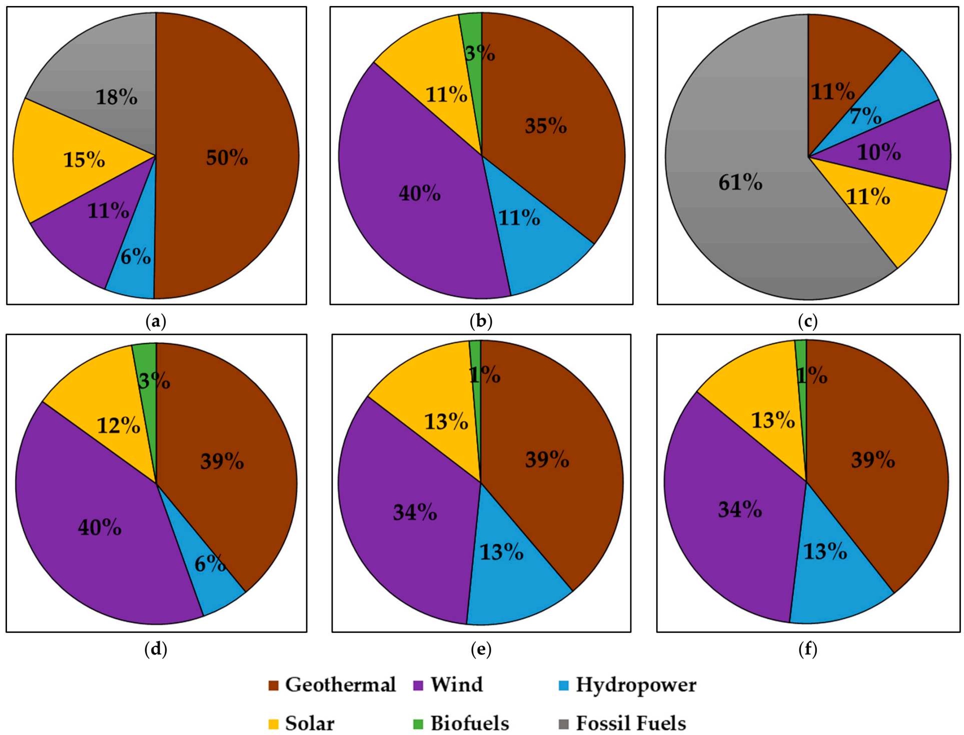

Figure A3. Power generation mixes for Kenya in 2050 by source across all modelled scenarios. (**a**) Business as usual (BAU); (**b**) Vision 2030; (**c**) Least-cost power development plan (LCPDP); (**d**) Vision 2030 and energy efficiency (EE); (**e**) Least-cost power development plan (LCPDP) and Vision 2030; (**f**) Clean energy transition (CET).

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