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Long-Term Energy System Modelling for a Clean Energy Transition and Improved Energy Security in Botswana's Energy Sector Using the Open-Source Energy Modelling System

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Abstract: This research examines Botswana's significant reliance on coal and imported fossil fuels for electricity generation, contributing to high carbon emissions and energy insecurity influenced by volatile fuel prices and supply challenges. The study utilizes the Open-Source Energy Modelling System (OSeMOSYS) to explore cost-effective renewable energy strategies to meet Botswana's Nationally Determined Contributions (NDCs) and enhance energy security by 2050, analysing six scenarios: Least Cost (LC), Business-As-Usual (BAU), Net Zero by 2050 (NZ), Coal Phase Out by 2045 (CPO), Fossil Fuel Phase Out by 2045 (FFPO), and Import Phase Out by 2045 (IMPPO). Our key findings highlight the critical role of solar technologies—photovoltaic (PV), storage, and concentrated solar power (CSP)—in transitioning to a sustainable energy future, especially under the Net Zero and Import Phase Out scenarios. This research demonstrates the economic and environmental benefits of transitioning away from fossil fuels, with the Fossil Fuel Phase Out scenario yielding a USD 31 million saving over the Business-As-Usual approach and reducing investment costs by USD 2 billion, albeit with a slight increase in light fuel oil imports. The study underscores the need for substantial capital investments, particularly in the Net Zero and Import Phase Out scenarios, necessitating private sector financing. Policy recommendations include adopting detailed strategies for solar PV and storage expansion, updating renewable energy targets, phasing out coal and natural gas, and bolstering the regulatory framework. These strategies are crucial for Botswana to achieve decarbonization and energy independence, aligning with global climate goals and national energy security objectives.

Keywords: Botswana; decarbonisation; solar; OSeMOSYS; energy policy

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1. Introduction

Historically, Botswana imported almost 80% of its electricity from neighbouring countries, predominantly from South Africa [1]. This reliance prompted the construction of the Morupule B coal-fired power plant in 2013, but its frequent defects led to low availability, around 52%, exacerbating the need for imports [2]. This plant's unreliability has meant that Botswana's sole power utility, the Botswana Power Corporation (BPC), has had to rely on electricity imports from South Africa's Eskom, which is itself experiencing a significant shortage of power supply, owing in part to problematic new coal facilities [3]. During Q3 2021, Botswana imported 42.3% of its electricity, with Eskom accounting for 53.7% of these imports. In addition, diesel-fired power has been required to meet domestic demand. Imports and diesel-fired generation are both costly, raising the total costs of power. The lack of functioning independent power producers (IPPs) and constrained private investments in power generation infrastructure also impact the reliability of electricity supply [4].

In addition to heavy reliance on imports, Botswana's energy system is highly carbon-intensive. CO_2 emissions in the country are expected to rise by 86% by 2030, relative to 2012 levels [5]. The energy sector stands as the primary contributor to these emissions, accounting for 87% of the total in 2015, excluding the land-use, land-use change, and forestry sectors [6].

To address this issue, Botswana has formulated its first National Determined Contribution (NDC) under the Paris Agreement, aiming to achieve a 15% reduction in overall emissions between 2010 and 2030 [7]. In alignment with these goals, the country has launched a National Energy Policy and is in the process of developing draft policies on climate change, waste management, and integrated transport [1]. These policies outline measures to combat climate change and fulfil the commitments outlined in the NDC document [7].

To address the challenges of energy security and climate change, Botswana considers renewable energy (RE) as a key solution. The country aims to source 15% of its energy from renewables by 2030, 36% by 2036, and 50% by 2040. In 2016, the government developed a Renewable Energy Strategy to drive the growth of the RE sector. Amendments were made to the Electricity Supply Act to allow for IPPs, and the Botswana Energy Regulatory Authority (BERA) was established. Additionally, in 2020, the government introduced a 20-year Integrated Resource Plan (IRP) for electricity generation which included various RE technologies such as solar photovoltaic (PV), wind, concentrated solar power (CSP), and energy storage through batteries. This RE development, albeit small, will enable Botswana to meet its goal of self-sufficiency and becoming a net exporter of power [4]. However, with the recent development of RE, Botswana faces the challenge of sourcing a workforce with the technical expertise needed to manage these RE projects successfully.

This study aims to identify the cheapest pathway to 2050 for Botswana's energy system that allows the country to improve its energy security whilst meeting its NDCs. The cost-optimisation modelling tool Open-Source Energy Modelling System (OSeMOSYS) is used to accomplish this aim via the creation of least-cost pathways and the input of constraints on emissions, fuels, capacity expansion, and power production. The study's scope focuses on Botswana's energy system from 2015 to 2050, including the cooking and high-heat sectors, as well as transportation.

The findings underscore the pivotal role of solar technologies (PV, storage, and CSP) in Botswana's future RE mix, particularly evident in the Net Zero and Import Phase Out scenarios. Notably, transitioning away from fossil fuels by 2045 is not only environmentally sound but also economically advantageous. The Fossil Fuel Phase Out scenario proves to be USD 31 million cheaper than the Business-As-Usual pathway, with USD 2 billion less in investment costs. This highlights the cost-effectiveness of committing to Fossil Fuel Phase Out and emphasises the potential savings when considering the costs of inaction. Furthermore, this research emphasises the necessity of reducing import reliance for enhanced energy security. Significant solar technology expansion is the key to achieving this. The Net Zero and Import Phase Out pathways are favoured for achieving decarbonisation and reduced import dependence. However, these pathways demand substantial capital investments (USD 43.23 billion and USD 40.77 billion, respectively), necessitating private sector financing to support a decarbonisation strategy independent of imports.

The study also identifies and addresses critical barriers to Botswana's energy transition. These barriers encompass policy and legal framework gaps, governance shortcomings, limited technical expertise, and insufficient private sector incentives. To overcome these challenges, the study proposes a set of policy recommendations, including the development of a clear long-term RE strategy, updates to RE targets, coal and natural gas phase-out strategies, empowerment of the regulatory authority (BERA), the adaptation of tariff-setting mechanisms, grid expansion, and the establishment of a favourable code for RE integration. Although the aim and objectives of this study were met, further research could explore the role of energy efficiency technologies in mitigating CO_2 emissions, as well as the impact of electrification rates on future energy demand in Botswana.

1.1. Botswana's Energy System

Botswana's energy market combines public and private entities engaged in energy generation, distribution, and supply, with the government playing a prominent role in shaping policy and regulations [1]. In terms of ownership, BPC serves as the pivotal state-owned utility responsible for a range of functions, encompassing electricity generation, transmission, and distribution. Facilitating oversight and coordination, BERA was established to regulate and monitor the energy sector's operations [8]. This includes the regulation of electricity tariffs, fuel pricing, licensing procedures, and adherence to technical standards. Recent times have witnessed a growing emphasis on involving private entities in the energy sector, particularly in electricity generation. Independent power producers (IPPs) are actively encouraged to invest in RE projects, such as solar and wind installations [1]. This strategic move not only diversifies the energy mix but also works towards reducing the nation's reliance on imported electricity [9].

RE has gained prominence on Botswana's agenda, prompting the involvement of private domestic and foreign enterprises which often take shape through public–private partnerships (PPPs), highlighting the possibility of a collaborative approach towards fostering RE development. In contrast, Botswana's oil and gas reserves are limited, necessitating the importation of petroleum products. This sector, managed by private companies, encompasses the distribution of fuels across the nation [1].

Botswana has significantly improved its electrification rate over the past decade, with approximately 73.7% of its population of 2.6 million connected to electricity, up from 16.1% in 1995 [10]. This rapid growth in Botswana's electrification rate since 1995 has also contributed to an increasing energy demand. Botswana's final energy consumption in 2020 (the latest year for which detailed data are available) was approximately 70 Petajoules (PJ) [11]. Figure 1 shows the breakdown of sectors using the final energy. Electricity provides approximately 12 PJ of energy for industrial, residential, and commercial use. Electricity generation sources consisted of 97% coal, 2.5% oil, and 0.5% solar [12].

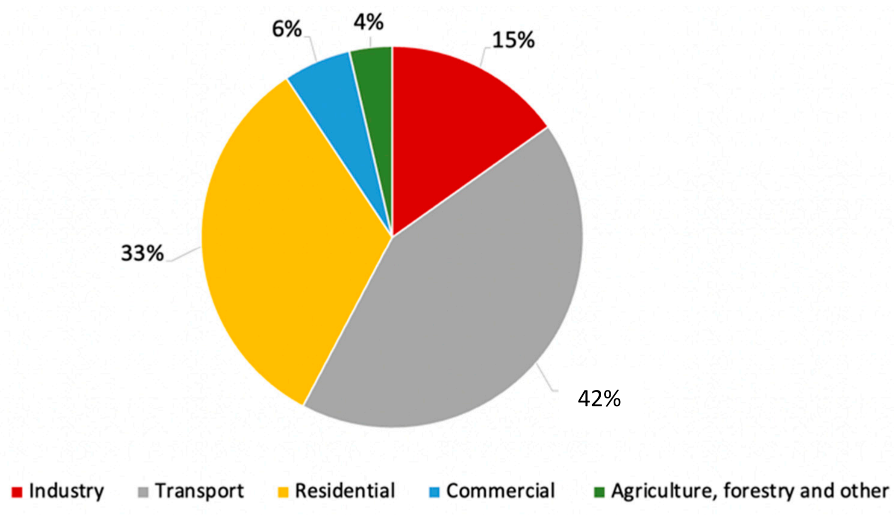


Figure 1. Final energy consumption by sector in Botswana in 2020, out of a 70 PJ total.

1.2. Botswana's Energy Policies

In 2021, Botswana unveiled its National Energy Policy, which holds the dual objectives of ensuring energy security and promoting environmentally sustainable economic growth [1]. A key ambition is to elevate the country to a high-income status by 2036. Part of this strategy involves a substantial increase in installed generation capacity, targeting an increase from 732 MW to 1450 MW by 2024. The policy places a strong emphasis on ramping up the integration of RE, with a specific focus on wind and solar power. Success in achieving these goals relies on attracting private-sector investments, which have historically been limited.

Another guiding document in Botswana's energy planning process is the 2020-published Integrated Resource Plan for Electricity. The plan outlines five objectives, including diversifying electricity sources, fostering competitiveness, ensuring security, achieving self-sufficiency, and addressing environmental impact. Aligned with the National Energy Policy, it emphasises expanding RE and "clean" coal technologies, attracting private investments, and securing 745 MW of new capacity with solar, wind, and coal allocations. However, the plan's on-grid focus raises concerns about rural electrification. The International Renewable Energy Agency recommends updating the plan to include strategies for off-grid technologies, like microgrids and rooftop solar PV systems, to ensure electricity access in remote areas [13].

Botswana outlines its RE targets surrounding its future energy mix, with a focus on ramping up solar PV and CSP capacity [4]. The total RE targets are outlined in Table 1.

Table 1. Botswana's RE capacity targets, in percentage of total capacity. Adapted from the Integrated Resource Plan [4].

RE Technology	2030 Target	2040 Target
Solar	14%	30%
CSP	14%	10%
Onshore wind	4%	2%
Total RE target	32%	42%

As part of their first NDC, Botswana has committed to reducing its overall emissions by 15% by 2030. A linear reduction trajectory is illustrated in Figure 2. This scenario is adapted from the GoB [7] and is used as a reference for the creation of the NDC emissions reduction target. Assuming a linear reduction for carbon emissions in modelling offers simplicity, baseline estimation, policy evaluation, long-term planning, and easy comparison [14]. However, a limitation of this approach is that it does not realistically capture non-linear factors influencing emissions reduction, and is therefore highly unlikely to occur in reality.

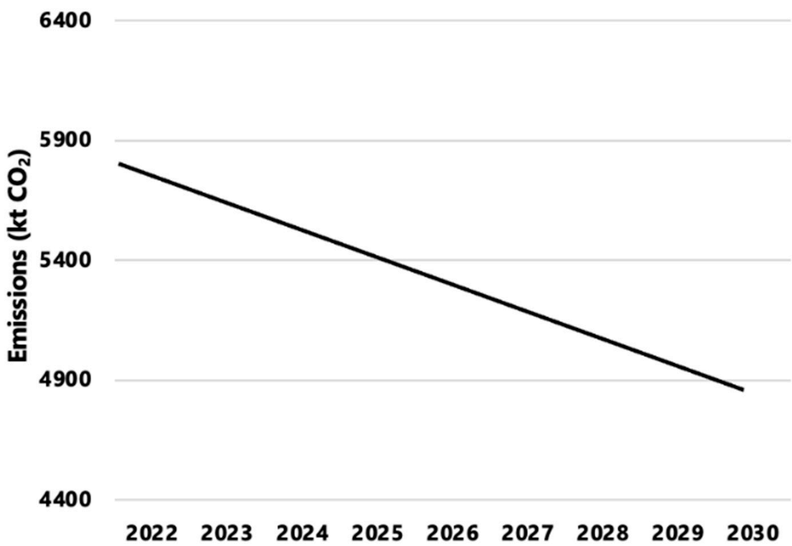


Figure 2. The projected NDC scenario of CO_2-equivalent emissions for Botswana extrapolated from 2022.

1.3. Literature Review

OSeMOSYS has been employed in a range of studies conducted at various levels. Examples include examining the ability of grid extension and off-grid supply to improve electricity access in Ethiopia [15]. On a larger scale, the Electricity Model Base for Africa (TEMBA) initiative investigated the electricity supply systems of 47 countries. This project constructed a scenario for 2040 that highlighted the potential of an enhanced grid network in reshaping Africa's generation mix and reducing electricity generation costs [16]. OSeMOSYS analysis has also extended to a global scope through a study utilising the GENeSYS-MOD Global Energy System Model. This assessment scrutinised the feasibility of worldwide decarbonisation pathways and concluded that the transformation of the energy system would be driven by the declining costs of RE sources, ultimately leading to the phasing out of fossil fuels [17].

Modelling work related to energy security and decarbonisation in Botswana is limited. Previous work has explored the issue of energy security in isolation from decarbonisation objectives. However, there has been some modelling work related to low carbon policies for the power sector in Botswana, with a focus on solar potential.

Essah et al. explore the energy supply, consumption, and access dynamics in Botswana, and find that the proposed aggregate capacity in their resource plan would fall short of satisfying the nation's energy requirements [18]. This deficiency in supply is anticipated to result in substantial growth in imports and/or the implementation of load-shedding measures to cater to the demand. Baek et al. explore the potential for Botswana to engage in a low-carbon transition [19]. They utilise a linear cost optimisation model to explore various scenarios with varying investment costs of RE technologies. The model outcomes indicate that coal will remain the most economical electricity generation resource in Botswana until 2030. However, the growing cost competitiveness of solar PV relative to coal is expected to increase substantially. Therefore, adapting the current national plan to incorporate a larger portion of solar PV instead of coal in the future energy mix proves advantageous both from an economic and social standpoint. This paper will examine how Botswana can achieve a low carbon transition whilst reducing reliance on imports to improve energy security.

2. Methodology

2.1. OSeMOSYS

In this study, the scenarios were modelled using the OSeMOSYS tool, with enhanced accessibility facilitated through the Simple And Nearly Done (clicSAND) interface [20,21]. OSeMOSYS serves as a bottom-up, cost-optimisation model designed for the projection of forthcoming energy supply systems. It ensures the fulfilment of all energy requirements and limitations in its solution for given scenarios [20]. The core equation of OSeMOSYS can be expressed as follows:

$$Minimise \sum_{y,t,r} TotalDiscountedCost_{y,t,r}$$

$$where\ y = year\ modelled,\ t = technology\ (power\ plant),\ and\ r = region$$
$$and\ where$$

$$\forall_{y,t,r}\ TotalDiscountedCost_{y,t,r} = DiscountedOperatedCosts_{y,t,r} + DiscountedCapitalInvestment_{y,t,r} + DiscountedTechnologyEmissionsPenalty_{y,t,r} - DiscountedSalvageValue_{y,t,r}$$

In OSeMOSYS, the progression of energy supply takes on a linear trajectory: initial energy sources (such as imported natural gas) undergo conversion into intermediary fuels (for instance, natural gas), which are subsequently transformed through various technologies (like solar power plant) to fulfil specific energy requirements (for example, residential electricity). An optimal scenario that minimises costs is valuable for analysing operational expenses, encompassing both variable and fixed costs, along with immediate upfront capital expenditures and long-term investment strategies [22].

OSeMOSYS is employed due to its unique advantages over other methodologies. While other modelling tools such as MARKAL/TIMES and LEAP offer valuable capabilities, OSeMOSYS stands out for its open-source nature, providing transparency, flexibility, and customisation capabilities that are often lacking in proprietary models. This also ensures the necessary input data are accessible to the public without cost. However, it is important to acknowledge some of the limitations of OSeMOSYS, such as its relatively simple representation of energy systems compared to more complex models like MARKAL/TIMES. Additionally, OSeMOSYS may require significant data input and technical expertise for effective utilisation, particularly in cases where detailed sectoral analysis or optimisation is required. Despite these challenges, OSeMOSYS offers a user-friendly interface that facilitates rapid model deployment and scenario analysis, making it accessible to a wide range of stakeholders. This modelling process is in alignment with the principles of Ubuntu: retrievability, repeatability, reconstructability, interoperability, and auditability (U4RIA) [23]. This effectively addresses a substantial hurdle in modelling energy systems for economies in development, as obtaining data has historically caused delays in decision-making processes [21]. Furthermore, OSeMOSYS supports thorough scenario-based analysis, allowing for the investigation of various energy policy and investment scenarios and the evaluation of their effects on energy supply, demand, and environmental consequences. The use of OSeMOSYS enables the representation of specific energy system characteristics, policy objectives, and planning constraints, making it applicable to diverse geographic contexts.

2.2. Modelling Inputs

The scenarios presented in this investigation were developed using the Botswana Starter Data Kit [24]. The foundational framework for all these scenarios was the Botswana Base model [25]. To optimise runtime with minimal loss of precision, the time intervals within the model were reduced from 96 to 8 slices for this study. These slices encompass winter daytime and night-time (December to February), spring daytime and night-time (March to May), summer daytime and night-time (June to August), and autumn daytime and night-time (September to November). The daytime slices encompass 06:00 to 18:00, while the night-time slices span from 18:00 to 06:00.

The energy demand from the Starter Data Kit was replaced by demand statistics detailed in the IRP, in particular the BAU demand scenario, in which a projected annual growth rate of energy demand is 3.3%, in line with the growth of Botswana's gross domestic product (GDP) [4]. The updated demands are shown in Figure 3.

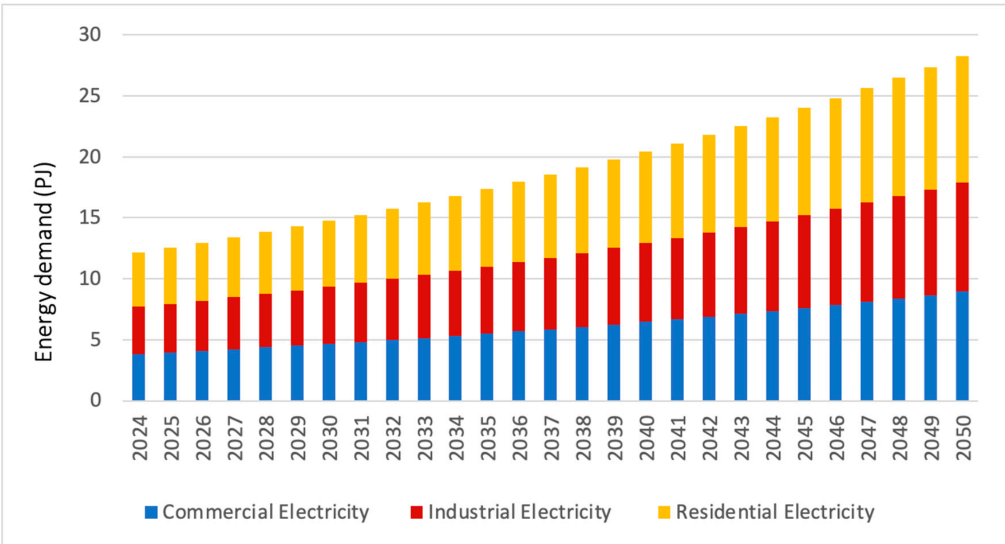


Figure 3. Projected energy demand in Botswana in PJ, from 2024 to 2050. Adapted from the Integrated Resource Plan [4].

The data related to technology and fuel parameters were obtained following the methodology detailed by Cannone et al. [24]. The technologies and fuels, and the corresponding codes utilised in this study, can be found in Appendix A.1. Each technology is characterised by factors such as capital, fixed, and variable costs, efficiency, capacity factors, operational lifetimes, maximum capacity potential, and emissions intensity [26]. The capacity factor for coal was updated from the Starter Data Kit to 53%, as reported in BPC's latest annual report [26]. Table 2 outlines the maximum RE potentials reported in the Botswana Renewable Readiness Assessment report and Estimating the Renewable Energy Potential in Africa paper [13,27]. Fuel price projections to 2050 and fuel-specific CO_2 emission factors are outlined on Zenodo [28].

Table 2. Maximum theoretical capacity potential for RE technologies.

	Unit	Estimated Renewable Energy Potential
Solar PV	TWh/yr	13,764
CSP	TWh/yr	13,070
Wind	GW	1.5
Biomass	PJ/yr	32
Hydropower	MW	0
Small Hydropower (<10 MW)	MW	1
Geothermal	MW	0

The interconnections and progression among the technologies and fuels are methodically depicted through a Reference Energy System (RES). This RES provides a visual delineation of the energy sector's layout, consisting of four tiers from left to right: the primary fuel supply, power-generation technologies, transmission and distribution infrastructures, and the ultimate demand sectors. A streamlined rendition of Botswana's introductory data kit RES is presented in Figure 4.

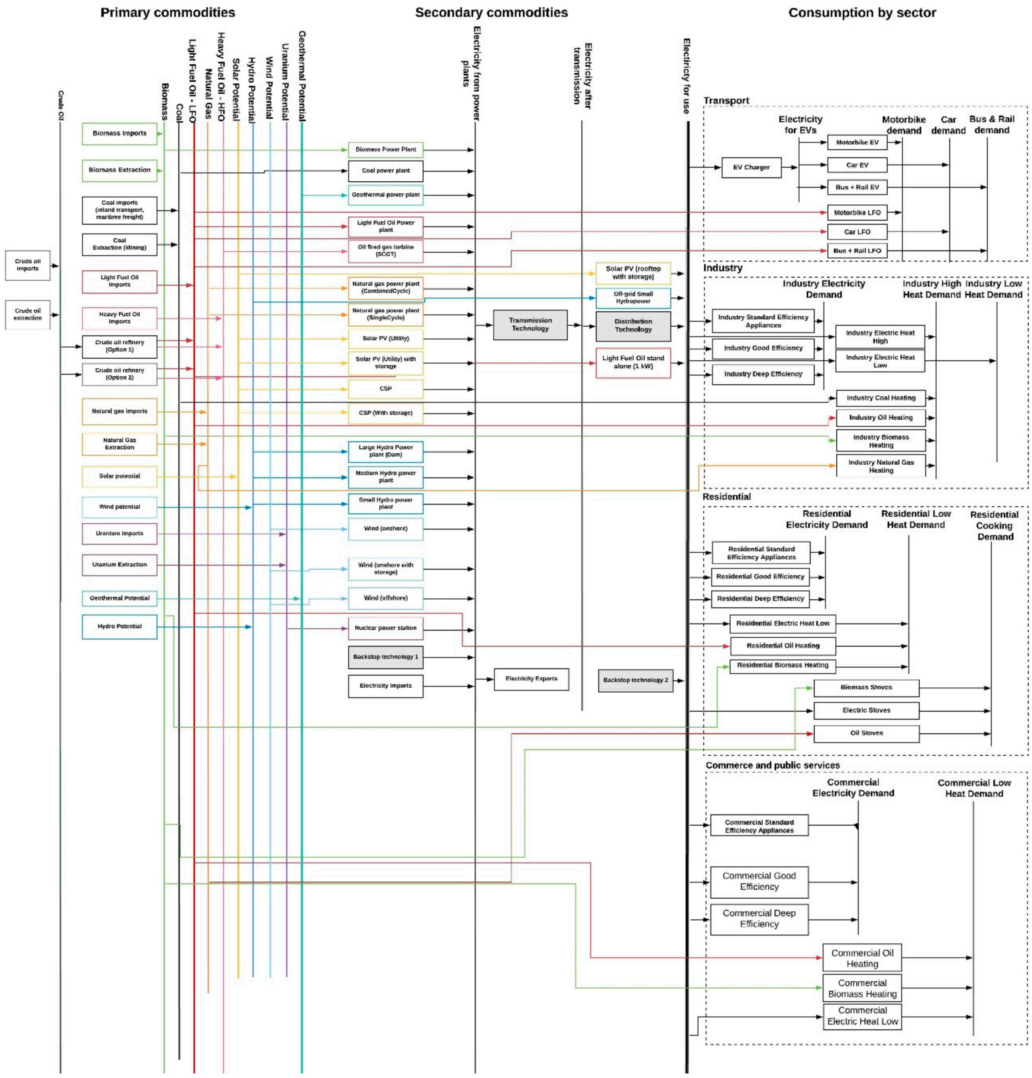


Figure 4. Botswana's Reference Energy System. Based on the Starter Data Kit RES [24].

2.3. Scenarios

To investigate the impact of reducing emissions and achieving greater energy security, six scenarios were modelled for Botswana's energy sector. An overview of the constraints applied is shown in Table 3.

Table 3. Names and descriptions of the six modelled scenarios.

Scenario Name	Description/Purpose	Constraint Overview
Least Cost (LC)	Represents the least-cost future of Botswana's energy system with no policy interventions.	Nuclear, hydropower, and geothermal investments constrained to zero. Renewable technologies constrained by a defined percentage of annual demand.
Business-As-Usual (BAU)	Models the current trajectory for the country based on the targets they have committed to, including the NDC.	Minimum capacity constraints are defined, biomass is constrained to 5% of annual demand in 2050.
Net Zero by 2050 (NZ)	Identifies the range of technologies needed to decrease CO_2 emissions to net zero by 2050.	Annual CO_2 emission limits decreased to 0 by 2050. Constraints on renewable technologies and transport investment are relaxed.
Coal Phase Out by 2045 (CPO)	Identifies the range of technologies needed to phase out coal by 2045 whilst meeting the NDC.	Annual coal-generation limits decreased to 0 by 2045.
Fossil Fuel Phase Out by 2045 (FFPO)	Identifies the range of technologies needed to phase out fossil fuels by 2045 whilst meeting the NDC.	Annual coal, natural gas, and oil-generation limits decreased to 0 by 2045.
Import Phase Out by 2045 (IMPPO)	Identifies the range of technologies needed to phase out all imports and fossil fuels by 2050 whilst meeting the NDC.	Annual coal, natural gas, oil, and import limits decreased to 0 by 2045.

2.3.1. Least Cost

There are constraints on the extent to which renewables can meet total demand: utility-scale PV, onshore wind, and utility-scale PV with storage are allowed to meet 15% of demand each, while onshore wind with storage is permitted to cover up to 25% of demand. This is to ensure the system is operational in the presence of higher RE integration. Capacity investments in hydropower and geothermal power plants are set to zero as the country does not have the potential for this [16].

2.3.2. Business-As-Usual

The BAU scenario models the current trajectory for the country based on the targets they have committed to. The BAU scenario is built upon the LC scenario and adds minimum capacity investment constraints for coal, natural gas, solar, wind, and CSP. These constraints reflect the country's investment projects outlined in Botswana's IRP. In addition, an annual emissions limit on CO_2 is set from 2023 onwards and follows a linear reduction to achieve Botswana's NDC [4]. Constraints on CSP maximum capacity and investment were set to reflect the amount of CSP capacity Botswana is economically and realistically capable of. Maximum capacity constraints were set to 1 GW for the period 2023–2045 and 2 GW for the period 2045–2050. A maximum capacity investment constraint was set to 0.5 GW across the whole modelling horizon.

2.3.3. Net Zero Emissions by 2050

The NZ by 2050 scenario is built upon the BAU scenario, with more stringent annual emissions limits imposed to achieve zero emissions by 2050. Reductions in CO_2 emissions also follow a linear reduction trajectory. Constraints on maximum capacity investment for electric vehicles (DEMTRACARELC, DEMTRABUSELC, DEMTRAMCYELC) were relaxed between 2048 and 2050 to allow the model to execute the investment needed to achieve NZ emissions by 2050. In addition, maximum activity limits on solar and wind power plants (PWRSOL, PWRWND) were relaxed to enable the model to invest in the RE technologies required to achieve NZ emissions by 2050.

2.3.4. Coal Phase Out by 2045

The CPO by 2045 scenario was built upon the BAU scenario. The coal power plant (PWRCOA001) was constrained by imposing a maximum activity limit. The activity limit begins from 2026, which is when Botswana plans to install 300 MW of new capacity, and linearly reduces to zero in 2045. Climate analytics suggest Botswana should decarbonise by 2040 at the latest; however, given the country's plans to build a new coal mine in 2026, the year 2045 was chosen as a more realistic target [4].

2.3.5. Fossil Fuel Phase Out by 2045

The FFPO by 2045 scenario was built upon the CPO scenario. Additional constraints were added on the maximum activities of natural gas and oil power plants (PWRNGS, PWROHC). These are linearly reduced from 2024 down to zero in 2045.

2.3.6. Import Phase Out by 2045

The IMPPO by 2045 scenario was built upon the FFPO scenario. The additional constraints applied include limits on oil, gas, light fuel oil, and biomass imports (IMPOIL, IMPNGS, IMPBIO, IMPLFO). These parameters' maximum activities are linearly reduced from 2024 down to zero in 2045. Constraints on electricity imports (PWRTRNIMP) from 2043 onwards were slightly reduced to enable electricity to be transmitted to power electric vehicles.

3. Results

3.1. Electricity Production and Installed Capacity

Figures 5 and 6 provide an overview of the annual electricity production and installed capacity, respectively, for the six modelled scenarios. In the Least Cost (LC) scenario, annual electricity production in Botswana is dominated by coal initially, averaging 75%, but decreases to 43% by 2040, replaced by solar and natural gas. Natural gas eventually dominates at 38% by 2050. Installed capacity is initially coal-dominated at 55%, decreasing to 16% by 2050. The Business-As-Usual (BAU) scenario sees a higher electricity production of approximately 120 PJ, with natural gas and solar PV dominating. Installed capacity nearly doubles that of LC, reaching 15.8 GW, mainly due to off-grid solar. The Net Zero by 2050 (NZ) scenario triples production to 342 PJ by 2050, primarily from solar, phasing out coal and natural gas by 2038 and 2050, respectively. Installed capacity is significantly higher at around 68 GW, with solar PV dominating. Coal Phase Out (CPO) mirrors BAU but phases out coal by 2045. Fossil Fuel Phase Out (FFPO) sees the lowest production of 62 PJ by 2050, dominated by solar. The installed capacity in the CPO scenario is slightly higher than that of the BAU scenario, reaching just over 16 GW in 2050. The installed capacity in the FFPO by 2045 scenario is slightly lower than that of the BAU and CPO scenarios, and substantially lower than the NZ by 2050 scenario. Import Phase Out (IMPPO) has higher production than BAU, phasing out fossil fuels by 2045, with solar PV dominating, reaching 94% of total installed capacity by 2050.

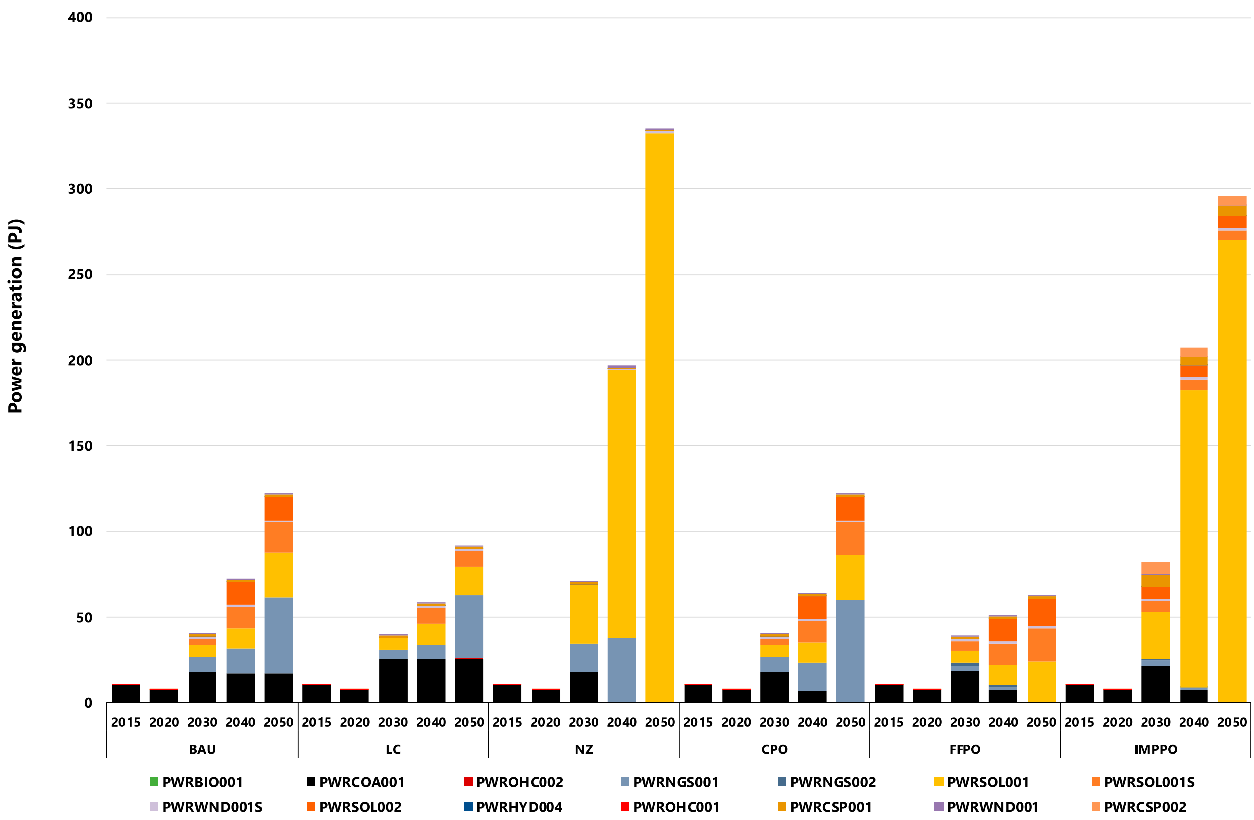


Figure 5. Annual electricity production for the six modelled scenarios in PJ.

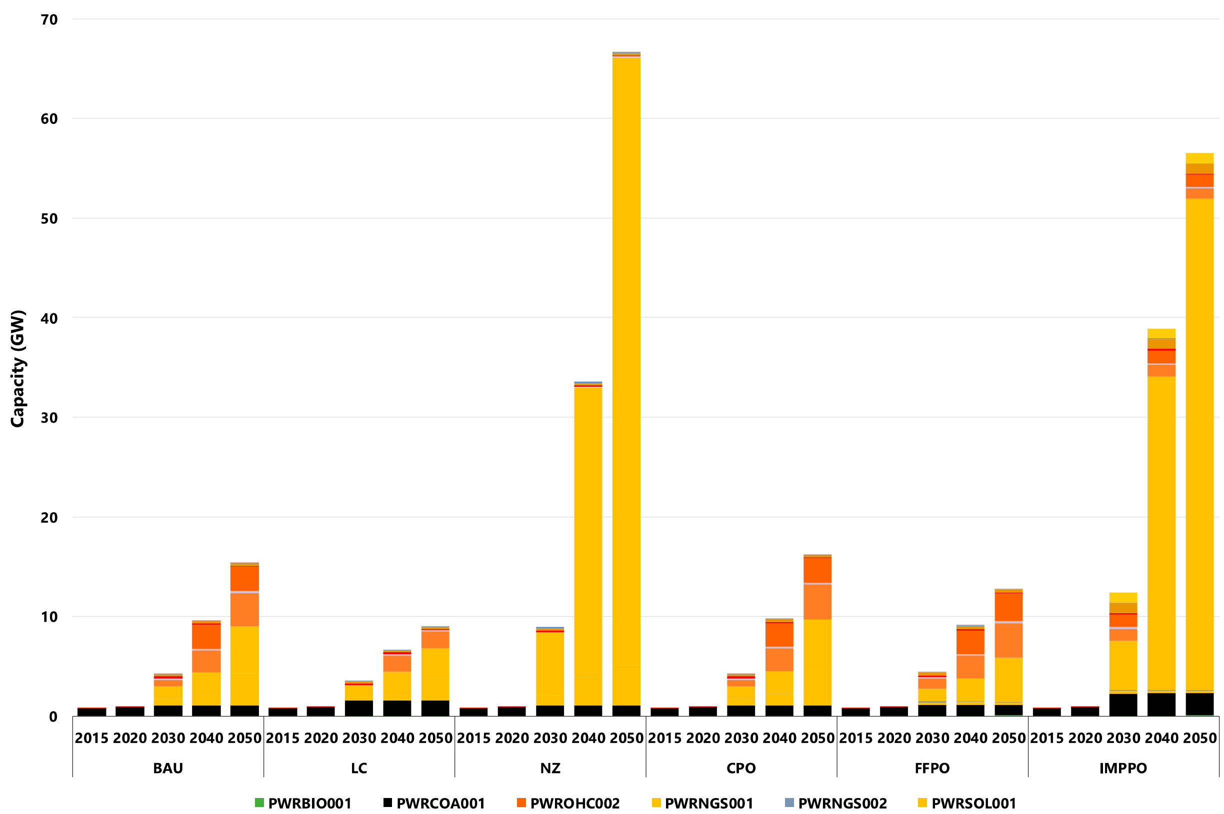


Figure 6. Annual installed capacity for the six modelled scenarios in GW.

3.2. Imported Primary Fuel Demands

In Figure 7, annual primary fuel demands for various scenarios in Botswana are depicted. The Least Cost (LC) scenario shows the highest imported fuel demand, reaching 775 PJ in 2050, with biomass dominating over light fuel oil (LFO) due to lower projected costs. Coal, being domestically produced, is not imported in any scenario. The Business-As-Usual (BAU) and Coal Phase Out (CPO) scenarios have similar demands until 2040, starting at 538 PJ in 2024. The rise in CPO imports toward the scenario's end reflects the need to replace phased-out coal-generated electricity, relying heavily on natural gas. The Fossil Fuel Phase Out (FFPO) scenario tops LFO imports at 367 PJ in 2042, compensating for fossil fuel constraints. The Net Zero by 2050 (NZ) and Import Phase Out by 2045 (IMPPO) scenarios start similarly but diverge. IMPPO will phase out imports by 2045, relying on biomass and LFO, while NZ gradually shifts to natural gas, eliminating imports by 2050.

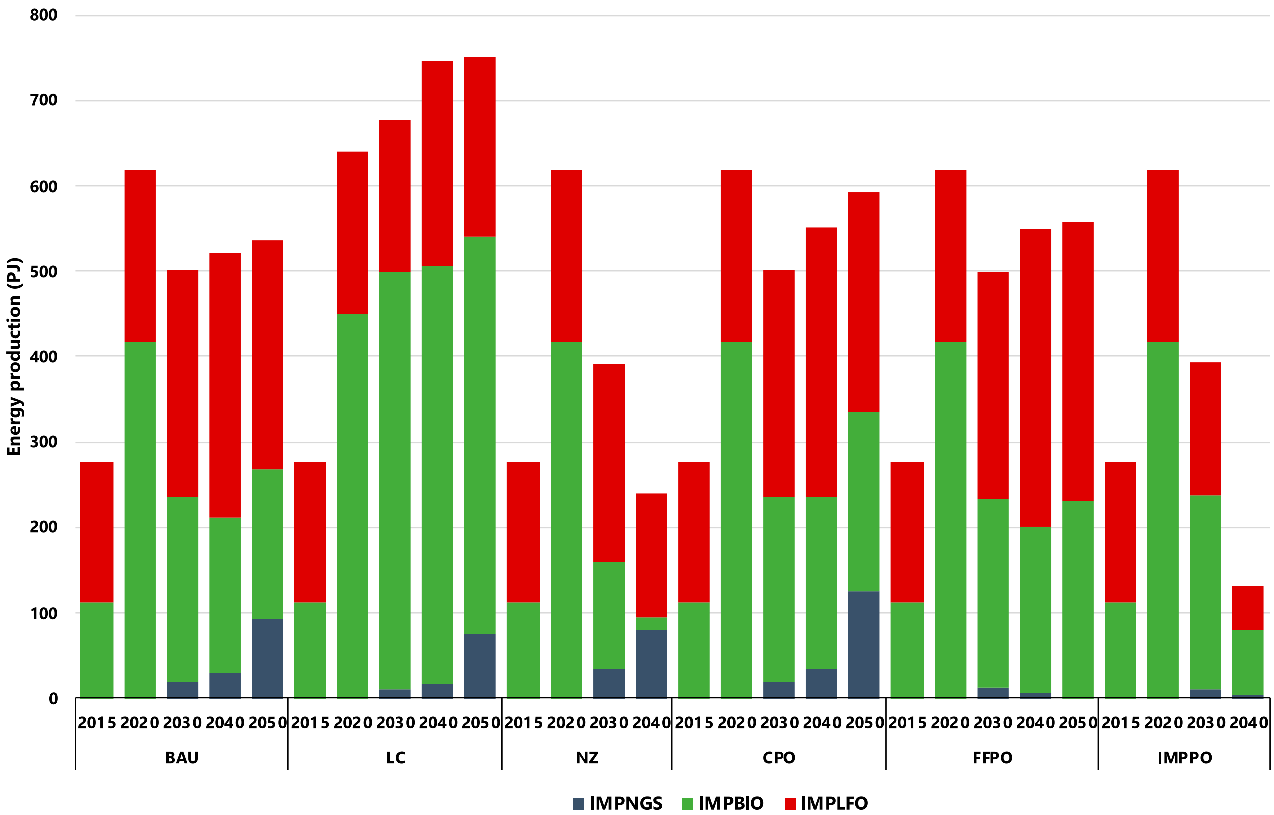


Figure 7. Annual imported primary fuel demands of modelled scenarios in PJ.

3.3. CO_2 Emissions

In Figure 8, CO_2 emissions from various scenarios in Botswana are compared up to 2050. The BAU, CPO, and FFPO scenarios have very similar emissions trajectories, and thus all four scenarios are combined into one line. The Least Cost (LC) scenario exhibits the highest emissions, stabilising at around 7658 kt from 2040, attributed to fossil fuel technologies and imports. Other scenarios, constrained by annual emission limits, show trajectories below LC. Business-As-Usual (BAU), Coal Phase Out (CPO), and Fossil Fuel Phase Out (FFPO) exhibit similar emissions, decreasing to 4899 kt after 2030 due to NDC constraints, reducing emissions by 61,916 kt compared to LC. Net Zero by 2050 (NZ) achieves zero emissions by 2050, reducing emissions by 42,469 kt, while Import Phase Out by 2045 (IMPPO) stabilises around 320 kt CO_2, reducing emissions by 38,527 kt compared to BAU, emphasising the importance of import reduction for emissions reduction.

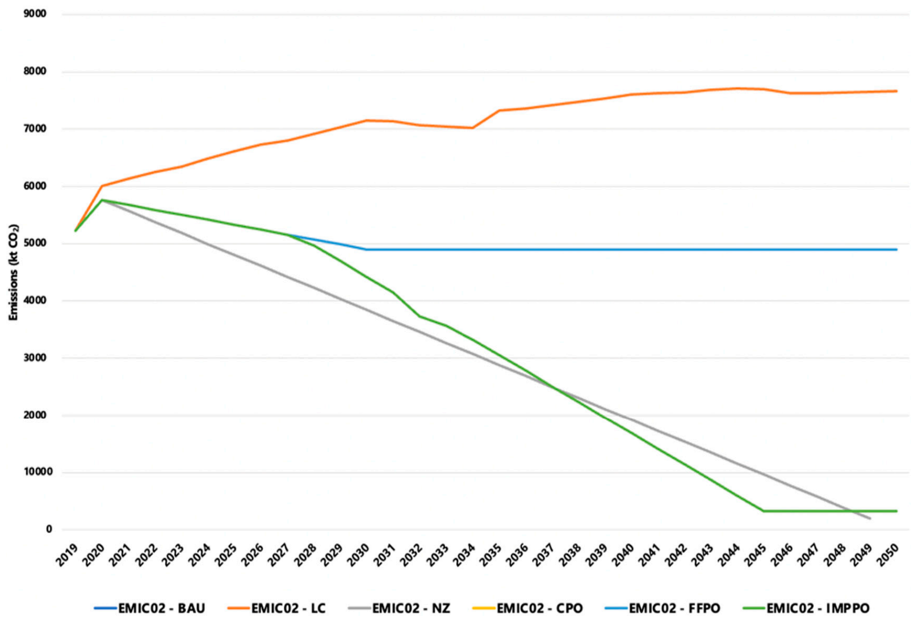


Figure 8. Annual CO_2 emissions for the modelled scenarios from 2019 to 2050.

3.4. Costs

3.4.1. Total Costs

In Figure 9, the total system costs for each scenario in Botswana are detailed, encompassing capital investment, variable operating, and fixed operating costs, using a discount rate of 10% added over the period from 2024 to 2050. The BAU, CPO, and FFPO had very similar emissions trajectories thus all four scenarios were combined into one line. Capital costs include the cost of planning and design, technology parts and materials, construction, and commissioning; fixed costs include worker salaries, operations and maintenance, and taxes; and variable costs largely represent the cost of fuel [25]. The Import Phase Out by 2045 (IMPPO) scenario is the most expensive at USD 147.32 billion, driven by extensive solar technology expansion. Net Zero by 2050 (NZ) follows as the second most expensive due to substantial solar investments. Both scenarios exhibit lower variable costs due to reduced reliance on fossil fuels. Fossil Fuel Phase Out (FFPO) costs slightly less than Business-As-Usual (BAU) at USD 68.04 billion vs. USD 68.35 billion, while Coal Phase Out (CPO) is USD 0.34 billion more than BAU, attributed to reduced coal power generation.

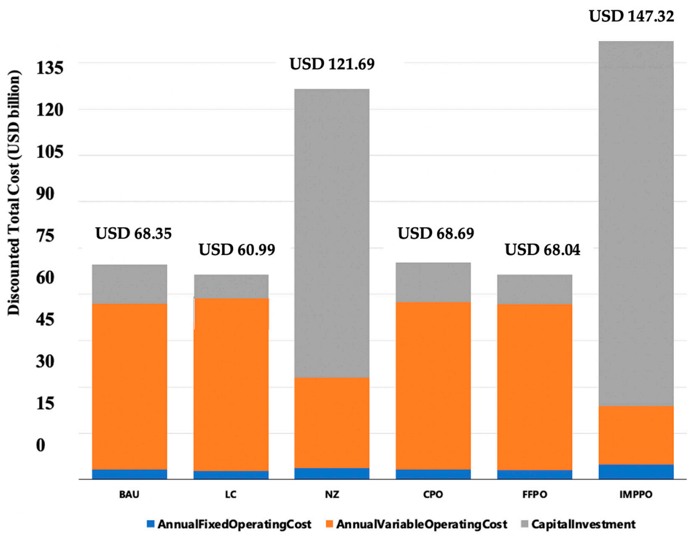
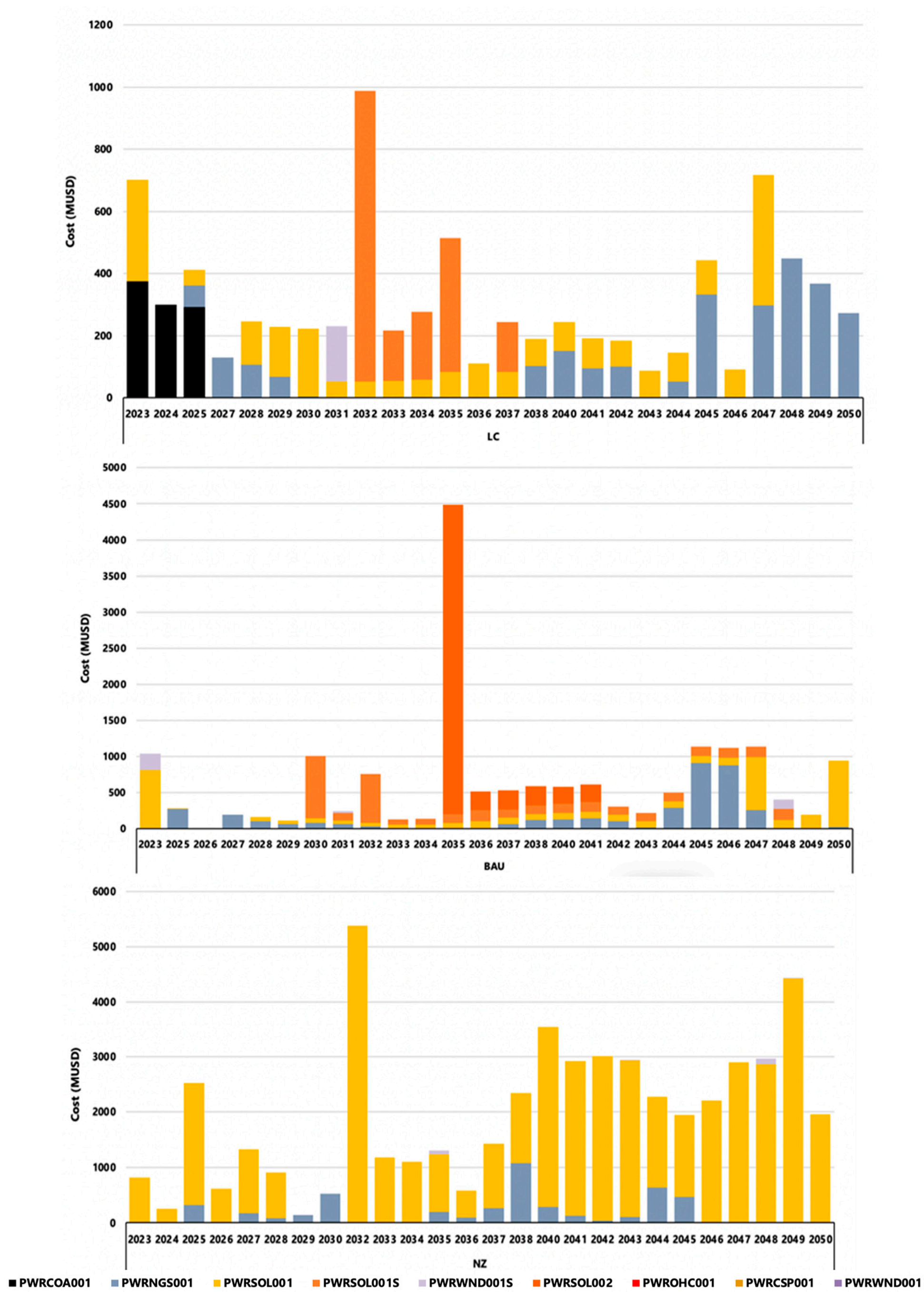


Figure 9. Total capital, fixed, and variable discounted costs of modelled scenarios in USD billion.

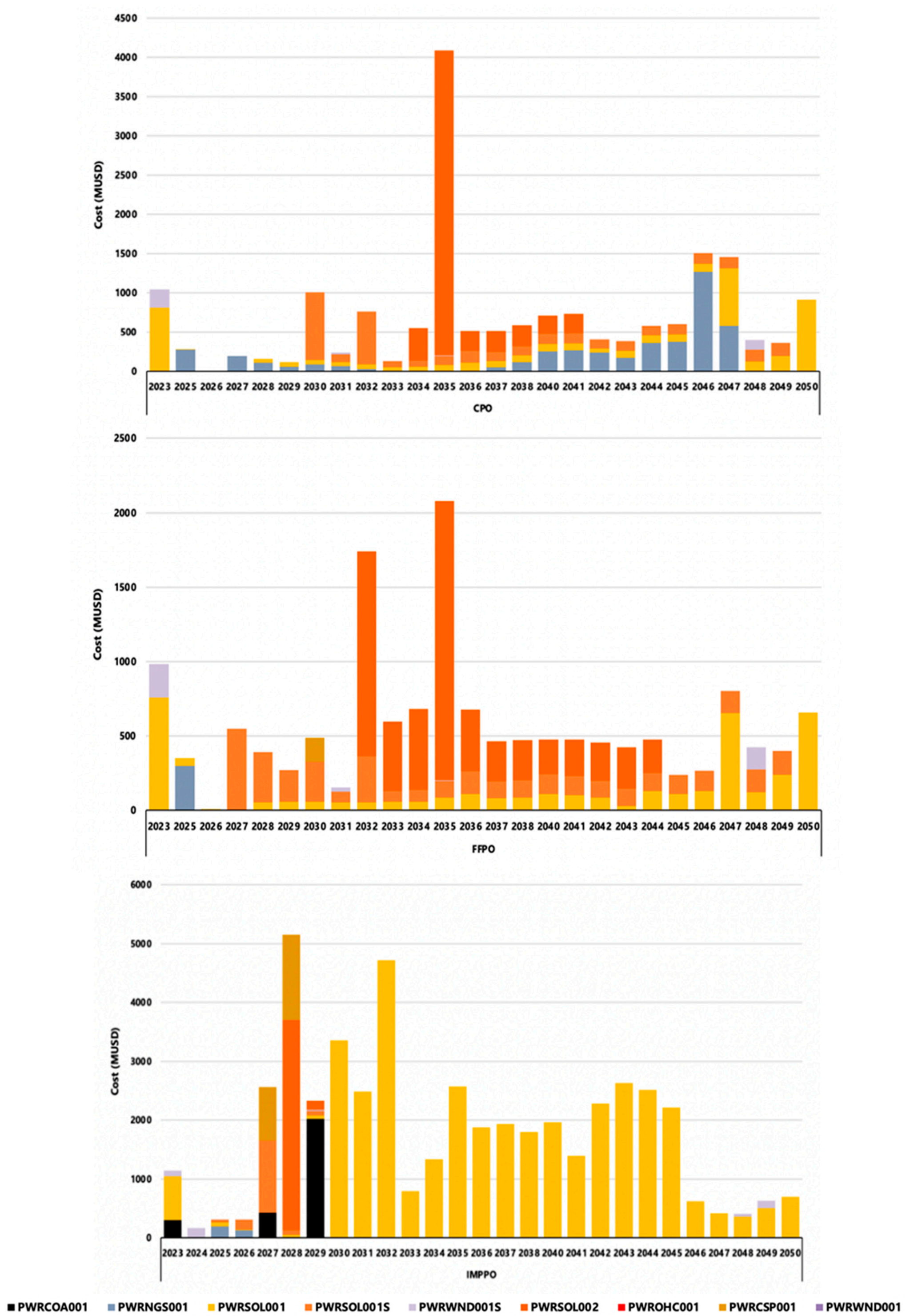
3.4.2. Capital Investment Costs

In Figure 10, capital investment costs for six scenarios in Botswana are illustrated. The Least Cost (LC) scenario has the lowest at USD 68 million, focusing on solar PV and natural gas, with no coal investment after 2025. Business-As-Usual (BAU) invests USD 14.59 billion, mainly in solar PV. Coal Phase Out (CPO) costs slightly more at USD 15.32 billion, including extra natural gas investment to replace phased-out coal. Fossil Fuel Phase Out (FFPO) is the cheapest at USD 12.54 billion, dominated by solar PV, highlighting the cost-effectiveness of renewable expansion. Net Zero by 2050 (NZ) and Import Phase Out by 2045 (IMPPO) have the highest costs, USD 43.23 billion and USD 40.77 billion, respectively, due to increased solar PV investment, while IMPPO invests more in solar PV with storage and CSP.



(**a**)

Figure 10. *Cont.*



(**b**)

Figure 10. (**a**) Annual capital investment costs for power technologies in USD billion for LC, BAU, and NZ Scenarios. (**b**) Annual capital investment costs for power technologies in USD billion for CPO, FFPO, and IMPPO scenarios.

4. Discussion

4.1. Findings from the LC and BAU Scenarios

The LC scenario defines the technologies needed to satisfy demand at the lowest cost and is dominated by natural gas, coal, and solar PV technologies. Historically, coal has dominated and continues to dominate electricity production, notably via the Morupule

B power station [26]. This power plant is highly inefficient in Botswana, with a capacity factor of 53%; therefore, the diversification of energy sources is key to ensuring a more stable supply of electricity in the country, even without considering the reduction in CO_2 emissions. The BAU scenario invests more in natural gas to achieve the emissions reductions needed in line with Botswana's NDC, as it has a lower emission factor than coal [28]. The country already has plans to expand natural gas production to reach 250 MW by 2040; however, the BAU scenario demonstrates that this expansion needs to be greater. In addition, both the LC and BAU scenarios are characterised by solar PV and solar with storage expansion at a higher rate than found in the IRP [4]. Therefore, greater investment in solar and solar storage technologies is required to achieve the NDC, in line with the findings of Baek et al. [19]. Investing in storage technologies is highly beneficial for RE systems with lots of intermittent technologies, as they aid in the stabilisation of 'power production and energy demand' [29].

4.2. Findings from the CPO and FFPO Scenarios

The CPO and FFPO findings affirm that the expansion of solar PV and solar storage technologies are crucial for fossil fuel phase out, in line with Momodu et al.'s findings [30]. The CPO scenario demonstrates that greater natural gas capacity is needed to phase out coal. Crucially, while the reduction of coal usage does increase the dependence on natural gas, it also encourages a substantial expansion of solar technologies. In 2035, there is a spike in solar PV (distributed with storage), which is attributed to the electrification of the cooking and heat sectors. The spike is more pronounced in the CPO scenario and requires a higher capital investment; therefore, the FFPO may be more economically feasible. There is also some investment in CSP in both scenarios, although only slightly in the FFPO scenario. CSP capacity increases from 200 MW to 262 MW in 2030 and remains the same for the rest of the period. As stated in their IRP, Botswana plans to install 200 MW of CSP in 2026; therefore, the model affirms the feasibility of this. However, there needs to be slightly more investment in CSP to support the phase out of fossil fuels.

4.3. Findings from the NZ and IMPPO Scenarios

The NZ and IMPPO scenarios promote the largest expansion of solar technologies relative to the other four scenarios. This is expected of the NZ scenario, given the move away from fossil fuels to achieve NZ by 2050. However, a new finding in the NZ scenario is that imports need to be reduced to reduce CO_2 emissions effectively. There were no constraints on imports in the NZ scenario, yet the model phased out imports by 2050. This demonstrates that a reduction in imports is crucial to Botswana's decarbonisation success and reaching NZ by 2050. Not only can a reduction in imports reduce CO_2 emissions, but it will also enable them to have greater energy security due to the decreased reliance on imports from South Africa that produce an unstable electricity supply.

The NZ and IMPPO scenarios are the most expensive and therefore will require high levels of financing, which is a barrier to achieving a CET in Botswana [30]. Both the NZ and IMPPO scenarios show that power generation is to solely come from solar PV, which may not be feasible from an energy security perspective. Botswana already experiences load-balancing problems, including load shedding, so they must develop a strategy for carbon-capture technologies, energy storage, and demand–response measures to mitigate these risks [26]. Nevertheless, the solar potential in Botswana is amongst the highest in the world [31]. Botswana experiences approximately 3200 h of sunshine annually, accompanied by an average Direct Normal Irradiance (DNI) of 6.83 $kWh/m^2/day$ and an average Global Horizontal Irradiance (GHI) of 6.17 $kWh/m^2/day$ [13]. The most robust solar resources are concentrated in the western and southwestern sectors of the country. Even the lowest readings in Botswana are equivalent to the most productive solar resource areas in Europe [32]. The estimated technical potential for solar in Southern Africa is 908 GW, and therefore there is a case for rapid solar expansion in Botswana, though it will require substantial investment [33].

4.4. Barriers to Botswana's Energy Transition

There are four main barriers that are likely to affect the renewable energy transition in Botswana. These include (1) the absence of policies and legal frameworks to guide RE expansion, (2) a lack of strong governance, (3) a lack of technical expertise, and (4) a lack of private sector incentives.

The primary concern regarding the successful expansion of RE is the absence of supportive policies and legal frameworks for renewable energy development in the country [34]. Despite some initiatives like the Renewable Energy Strategy of Botswana, their execution encountered inefficiencies attributed to the lack of a clear roadmap. The absence of a well-defined high-level policy roadmap creates obstacles for potential investors who hesitate to allocate funds towards energy transition endeavours due to uncertainty about the government's stance on supporting such ventures [34]. The lack of strong political commitment and urgency concerning climate change and energy transition in Botswana erodes investor confidence and assurance. Despite global commitments to reduce emissions in the energy sector, these issues do not receive the same level of attention as other government priorities. The absence of a dedicated budget for these transformations further highlights this lack of commitment. To influence change at the government level, a deliberate policy approach is required to make RE competitive, allowing solar energy to compete fairly with coal in electricity generation.

Secondly, the lack of governance in Botswana means the roles of major government actors are undefined [34]. Possessing a well-defined path or strategic blueprint outlining the key stages required to achieve the solar energy objective and desired results can aid in elucidating strategic insights among the entities driving Botswana's energy transition. Such a transformation at the higher echelons of governance can better uncover deficiencies in RE products and technologies, allowing for their rectification before they evolve into significant issues.

The third barrier is the lack of technical expertise in executing solar energy initiatives successfully. The Renewable Energy-based Rural Electrification (RERE) Programme program is frequently cited, initiated to bolster Botswana's endeavours in curtailing CO_2 emissions by promoting renewable energies and low-GHG technologies as substitutes for fossil fuels in rural regions [35]. The UNDP conducted a 'Terminal Evaluation of the RERE Programme' and concluded that both the Department of Energy and the national utility were not necessarily equipped with the essential know-how to manage such projects. The government attempts to fulfil all roles without providing other entities possessing the necessary technical capacity an opportunity to contribute to the development of RE [35].

This lack of technical expertise is linked to the fact that there is a lack of private sector investment, given the lack of incentives both on large and small scales. This is an issue as the private sector could introduce more 'innovative energy distribution models' [35]. While Botswana offers competitive electricity prices, averaging USD 0.085 per kWh for domestic consumption, these tariffs do not accurately reflect the actual costs due to government subsidies [26]. This makes it challenging for investors to negotiate equitable PPAs with BPC. Despite the 2007 amendment of the Power Supply Act to accommodate IPPs, particularly in RE generation, there has been no private investment in the generation sector. The private sector exhibited interest but faced difficulties in PPA negotiations and overcoming regulatory hurdles. A significant issue is the absence of RE feed-in tariffs (FiTs) or subsidies to facilitate the growth of solar energy projects [34]. Being a landlocked country with no domestic manufacturing of solar equipment, Botswana relies on imports, rendering solar technology expensive for service providers and consumers alike. In 2010, the government introduced the National Electricity Standard Connection Cost (NESC) scheme, which establishes a uniform fee for new household connections within network supply areas [13]. This initiative is aimed at assisting individuals in connecting to the grid and ensures uniformity in connection costs regardless of proximity to electricity infrastructure. Under the NESC scheme, households are linked to the grid at a fixed cost of approximately USD 500, with the remaining cost covered by the government through the National Electrification

Fund (NEF). However, there is no equivalent program for households seeking to connect through solar systems.

4.5. Policy Recommendations

1. Advocate and facilitate the execution of a distinct, long-term strategy for the advancement of renewable energy with a defined national budget.

Consistent growth in RE capacity necessitates a distinct vision, encapsulated in effective and executable planning. In this context, Botswana can achieve success in its adoption of RE by translating visions and roadmaps into enforceable commitments that encompass precise targets for RE technologies. Equally significant is the alignment of targets articulated in various policy and strategic documents, ensuring a unified, enduring signal to prospective investors [34].

2. Update the IRP 2030 renewables target in the IRP to 57% of total installed capacity.

The current IRP should be updated to outline more ambitious RE expansion targets. The new 2030 targets should be 31% solar PV, 18% solar PV with storage, 1% wind, 5% CSP, and 4% wind with storage. The scenario results demonstrate that a more significant expansion of solar is needed, which can aid the country in reducing its biomass and LFO imports in a move to improve its energy security.

3. Pinpoint financial and regulatory strategies to facilitate the gradual phase out of coal and natural gas production.

In conjunction with the expansion of RE objectives, Botswana must identify the strategies needed to implement a successful phase out of coal and natural gas production. The bulk of emissions originating from coal primarily reside within the electricity sector [36]. Hence, the process of phasing out coal is comparatively affordable and uncomplicated, considering the presence of readily available technologies that can serve as replacements [37].

4. Activate the operational role of the Regulatory Authority.

Botswana has taken steps towards regulatory overhaul, exemplified by the establishment of BERA in 2017. Nevertheless, BERA's operational effectiveness remains largely unfulfilled. To effectively operationalise BERA, a stable and self-sustaining budget is needed, as well as significant political autonomy and capability to ensure utilities are held accountable for their financial and operational performance [34].

5. Adapt the tariff-setting framework.

The responsibility for defining tariffs now rests with BERA; they will be established utilising a transparent methodology implemented by the Electricity Committee, incorporating a degree of performance evaluation. The existing pricing mechanism seemingly relies on a 'rate of return' approach rather than 'incentive-based' regulation, leading to apprehensions about potential inefficiencies being passed on to end-consumers in Botswana. With the BPC having attained complete cost recovery, there is an opportunity to introduce performance-oriented incentives into the methodology, encompassing factors like service quality and new policy directions (pertaining to electrification, GHG emissions, supply security, etc.). Additionally, there is potential to tailor tariffs to align with spatial or temporal consumption patterns. Moreover, the government should prioritise the completion of FiTs frameworks. Implementing FiTs is essential to incentivise the uptake of solar PV technologies and would effectively facilitate market entry for investors [13].

6. Enlarge the grid and establish a code favourable for renewable power.

With the proliferation of renewable projects, it is crucial to enlarge the grid using international financial support or government subsidies. It is imperative for BERA to develop grid codes that prioritise granting grid access to renewable-generated electricity and govern its dispatch based on marginal costs. These codes should encompass all present and future electricity generators, supplanting the existing BPC operational manual that currently oversees transmission. This shift will enhance transparency regarding the grid access granted to IPPs [13].

4.6. Limitations and Opportunities of Further Research

The model used is a simplified representation of reality, lacking consideration for climate change effects on power plants and solar cells. Integrating OSeMOSYS with the Climate, Land, Energy, and Water systems (CLEWS) model could address this. Additionally, the model does not assess the impact of increased electricity access, which can be explored using the Open-Source Spatial Electrification Tool (ONSSET), but was not within the research scope.

There is a contention that energy efficiency stands as the most potent instrument within energy policy for climate mitigation and bolstering energy security [38]. Given the sluggish pace of technological advancements in Botswana, the implementation of energy efficiency strategies and the adoption of high-efficiency industrial furnaces hold the potential to notably curtail the nation's CO_2 emissions [36]. Consequently, it is important to consider integrating energy efficiency technologies into forthcoming research.

5. Conclusions

This study explored the pathways to decarbonisation and improving energy security via the upscaling of RE technologies. A literature review was carried out to assess the current energy landscape in Botswana and its commitments to reducing CO_2 and improving energy security. The Botswana Starter Data Kit in OSeMOSYS was updated and used to create six scenarios (Least Cost, Business-As-Usual, Net Zero, Coal Phase Out, Fossil Fuel Phase Out, and Import Phase Out).

The findings indicate that a significant portion of Botswana's forthcoming RE blend will need to be contributed by solar (PV, storage, and CSP). This is especially the case in the Net Zero and Import Phase Out scenarios. Importantly, the results demonstrate that achieving Fossil Fuel Phase Out by 2045 is cheaper than the Business-As-Usual pathway by USD 31 million, and very similar to the LC pathway. In addition, investment costs are USD 2 billion lower for the Fossil Fuel Phase Out scenario than the BAU scenario; therefore, it is economically sensible for Botswana to commit to a fossil fuel phase out, as both total and investment costs are lower than if there were no fossil fuel phase out, which would be more of a stark difference if the costs of inaction were internalised. However, there are slightly greater LFO imports in the FFPO scenario relative to other scenarios, so there is likely a trade-off between a fossil fuel phase out and reducing reliance on imports. Nevertheless, the findings show that reducing imports is key to achieving better energy security and is shown to be achieved by a sizeable expansion in solar technologies. For Botswana to decarbonise and improve energy security via a reduced reliance on imports, the NZ and IMPPO pathways are more favourable. However, the NZ and IMPPO scenarios have the highest capital investment costs over the period, totalling USD 43.23 billion and USD 40.77 billion, respectively; therefore, private sector financing is needed to help support a decarbonisation pathway that does not rely on imports.

This research also assesses key barriers impacting Botswana's energy transition from coal-powered electricity to increased reliance on solar energy. These barriers include the absence of guiding policies and legal frameworks for RE expansion, inadequate governance, a lack of technical expertise, and limited private sector incentives. Furthermore, weak governance and technical expertise hinder effective implementation. To address these challenges, this study offers a series of policy recommendations. These include advocating for a clear long-term strategy for RE development, updating RE targets, phasing out coal and natural gas production, enhancing the operational role of the regulatory authority (BERA), adapting the tariff-setting framework, enlarging the grid, and establishing a favourable code for renewable power integration.

Overall, the study identifies crucial barriers and outlines actionable recommendations that could guide Botswana towards a successful transition to cleaner and more sustainable energy sources. Future work could explore the role of energy efficiency measures in reducing CO_2 emissions.

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Institutional Review Board Statement: 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 by involving stakeholders in the development of models, assumptions, scenarios, and results (Ubuntu/Community). The authors ensure that all data, source codes, and results can be easily found, accessed, downloaded, and viewed (retrievability), as well as 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).

Data Availability Statement: The data and model code used for this study are fully accessible and licensed under MIT license. The dataset is available at Zenodo repository: Saad, R. (2024) 'Techno-Economic Dataset for Long-term Energy Systems Modelling in Botswana'. Zenodo. doi: 10.5281/zenodo.10547474 (accessed on 10 October 2023).

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Appendix A.

Appendix A.1. Power Plant Technologies and Corresponding Fuels

Technologies	
Code	Description
PWRBIO001	Biomass Power Plant
PWRCOA001	Coal Power Plant
PWROHC001	Light Fuel Oil Power Plant
PWROHC002	Oil-Fired Gas Turbine (Simple Cycle Gas Turbine (SCGT))
PWRNGS001	Gas Power Plant (Combined Cycle Gas Turbine (CCGT))
PWRNGS002	Gas Power Plant (SCGT)
PWRSOL001	Solar PV (Utility)
PWRDSOL002	Solar PV (Distributed with Storage)
PWRCSP001	CSP without Storage
PWRCSP002	CSP with Storage
PWRHYD001	Large Hydropower Plant (Dam) (>100 MW)
PWRHYD002	Medium Hydropower Plant (10–100 MW)
PWRHYD003	Small Hydropower Plant (<10 MW)
PWRHYD004	Off-grid Hydropower
PWRWND001	On-shore Wind
PWRWND002	Off-shore Wind

Technologies	
PWRNUC	Nuclear Power Plant
PWRSOL001S	Utility-scale PV with 2-h Storage
PWRWND001S	Onshore Wind Power Plant with Storage
PWRGEO	Geothermal Power Plant
Commodities	
Code	Description
OIL	Crude Oil
BIO	Biomass
COA	Coal
LFO	Light Fuel Oil
NGS	Natural Gas
HFO	Heavy Fuel Oil
SOL	Solar
HYD	Hydro
WND	Wind
URN	Uranium
GEO	Geothermal
ELC001	Electricity from power plants
ELC002	Electricity after transmission
ELC003	Electricity after distribution

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