Long-term Energy System Modelling for a Clean Energy Transition and Improved Energy Security in Botswana's Energy Sector using OSeMOSYS (Open-Source Energy Modelling System)

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Abstract

Botswana currently depends on fossil fuels and imports for its electricity generation, which has given rise to issues of carbon emissions and unstable electricity supply due to conditions in neighbouring countries. Over the last few years, renewable energy penetration has grown, but not to the extent that is required to achieve decarbonisation and energy security. Conducting robust modelling analyses to explore potential and practical alternatives in the energy mix is crucial for providing essential information to key stakeholders involved in energy policy decision-making. The challenge lies in the requirement for a significant amount of data to accurately model diverse energy pathways on a national scale. Thus, this data note aims to fill the current data gap by supplying crucial information on input data and assumptions necessary for long-term energy planning in Botswana. The article details historical and/or projected data pertaining to electricity generation and consumption, electricity imports and exports, fuel prices, emissions, refineries, power transmission and distribution, electricity generation technologies, as well as renewable energy potential and reserves for the years 2015 to 2050. While the data is country-specific, it is primarily technology-based making it applicable to other countries. The article outlines various sources, assumptions, and modelling guidelines, aiming to assist in the development of new datasets. This dataset

contributes to the accessibility of energy-related information for policymakers, stakeholders, and researchers, benefiting not only Botswana but also other developing countries.

Specifications table

Subject	Energy
Specific subject area	Energy System Modelling
Data format	Raw, Analysed
Type of data	Table, Figure
Data collection	Data for this study were sourced from international organisations' websites, annual reports, databases, academic articles, and existing modelling databases. The gathering and manipulation of data were specifically tailored to meet the requirements for developing an energy system model using the linear cost-optimisation tool OSeMOSYS. It is important to emphasise that the data presented in this document is independent of the tool itself.
Data source location	Raw data sources are listed in Table 1 of this article.
Data accessibility	With this article and in a repository Repository name: Zenodo Data identification number: Direct URL to data: https://zenodo.org/doi/10.5281/zenodo.10547473
Related research article	Saad, R., Plazas-Niño, F., Cannone, C., Yeganyan, R., Howells, M., & Luscombe , H. (2024). Long-term Energy System Modelling for a Clean Energy Transition and Improved Energy Security in Botswana's Energy Sector using OSeMOSYS (Open-Source Energy Modelling System) . Cambridge Open Engage. doi:10.33774/coe-2024-0cf1p This content is a preprint and has not been peer-reviewed.

Value of the data

- Utilising these data can support the development of energy system models in Botswana, offering valuable insights for national energy investment outlooks and policy planning. The dataset enables the examination of the electricity supply system's evolution under various trajectories.
- These data serve as a valuable foundation for country analysts, policymakers, and the wider scientific community, providing a basis for model development.
- The dataset is instrumental in exploring diverse energy system pathways, offering additional insights into the evolution of Vietnam's power system.
- These open-source, country-specific data fill a gap not easily accessible in current literature, catering to the unique needs of analysts and researchers.
- The data's versatility allows for both analysing Vietnam's power system and supporting capacity-building activities.
- The integration of secondary data from multiple sources ensures analysts have comprehensive and easily accessible datasets, addressing challenges related to data inaccessibility.

1. Background

Examining potential and practical energy pathways through energy modelling analyses is pivotal for informed decision-making in energy policy, especially in the context of decarbonisation planning. The primary challenge lies in the necessity of a substantial volume of data to accurately model diverse energy pathways at a national scale. However, issues such as inaccessibility, outdatedness, inconsistency, and poor data quality can impede this process, making data collection a cumbersome and time-consuming task.

This article seeks to bridge the current data gap by furnishing essential information on input data and assumptions crucial for long-term energy planning in Botswana. The provided data can be utilised by academics, consultants, or government officials for further energy systems modelling in Botswana or the broader African context. The dataset aligns with the U4RIA goals [1], emphasizing Ubuntu, Retrievability, Reusability, Repeatability, Reconstructability, Interoperability, and Auditability. These goals underscore that "energy modelling providing policy support should not only be grounded in rigorous analytics but also in good governance principles." Furthermore, it should align with other policy actions. In summary, these goals and the data presented are crafted to elevate the quality of energy modelling in support of policy decisions.

2. Data description

This paper introduces country-specific data carefully curated for integration into the Open-Source Energy Modelling System (OSeMOSYS) tool, specifically tailored for long-term energy decarbonisation planning. However, it's important to note that the data presented in this document is not reliant on the usage of the tool itself. The information provided was gathered from publicly accessible sources, including reports from international organizations, journal articles, and existing model databases (as outlined in Table 1). This dataset encompasses historical and/or projected details pertaining to electricity generation and consumption, electricity imports and exports, fuel prices, emissions, refineries, power transmission and distribution, electricity generation technologies, as well as renewable energy potential and reserves, spanning the timeframe from 2015 to 2050.

Table 1. List of sources used in this article

Source	Reference
Government of Botswana Integrated Resource Plan 2020	Government of Botswana (2020), Integrated Resource Plan for Electricity for Botswana.
IEA Country Profile	IEA (2020) Botswana. [Online]. International Energy Agency. Available from: https://www.iea.org/countries/botswana
IRENASTAT Power Capacity and Generation	IRENASTAT. International Renewable Energy Agency. Available at: https://www.irena.org/Data/Downloads/IRENASTAT
IPCC Greenhouse Gas Emissions	IPCC (2006), Guidelines for National Greenhouse Gas Inventories, Volume 2: Energy, Table 1.3
EIA Annual Energy Outlook 2020	U.S. EIA. (2020) Assumptions to the Annual Energy Outlook 2020: International Energy Module
IRENA Renewable Energy Planning Prospects for West Africa	IRENA (2018) Planning and Prospects for Renewable Power: West Africa
European Union Energy Projections for African Countries	I. Pappis et al., "Energy projections for African countries," Luxembourg, 2019. doi:10.2760/678700
CCG Starter Data Kit Botswana	Allington, L., Cannone, C., Pappis, I. (2023). Selected 'Starter Kit' energy system modelling data for Botswana (#CCG), 04 May 2021, PREPRINT (Version 2) available at Research Square [https://doi.org/10.21203/rs.3.rs-478620/v2]
World Bank Energy Data	The World Bank (2019), energydata.info. Available at: https://energydata.info/en

2.1.Electricity demand

Historical data on Botswana's annual electricity demand from the year 2015 to 2020 is from the IEA Country Profile [2], and projected data from 2021 to 2050 is from the Government of Botswana's (GoB) Integrated Resource Plan (IRP) [3]. The electricity demands for key years are shown in Table 2. The forecast for electricity demand does not account for the potential impact of unforeseen events such as pandemics or natural disasters.

Table 2. Electricity demand for key years in PJ.

2015	2020	2025	2030	2035	2040	2045	2050
11.50	10.683	12.55	14.76	17.36	20.42	24.02	28.25

Electricity demand is categorised into sectors, namely industrial, residential, and commercial. Historical data for these sectors were sourced from the IEA Country Profiles [2], while projections were derived from the IRP [3]. The report indicates an anticipated uniform increase in energy service demands across residential, commercial, and industrial sectors. However, between 2020 and 2021, there was a significant decrease in electricity consumption due to external shocks such as Coronavirus. The sectors are shown in Table 3 and Figure 1.

Table 3. Electricity demand by sector for key years in PJ.

	2015	2020	2025	2030	2035	2040	2045	2050
Industrial	5.26	3.22	3.98	4.68	5.50	6.47	7.62	8.96
Residential	3.39	4.18	4.60	5.41	6.36	7.48	8.80	10.36
Commercial	2.85	3.28	3.97	4.67	5.49	6.46	7.60	8.94

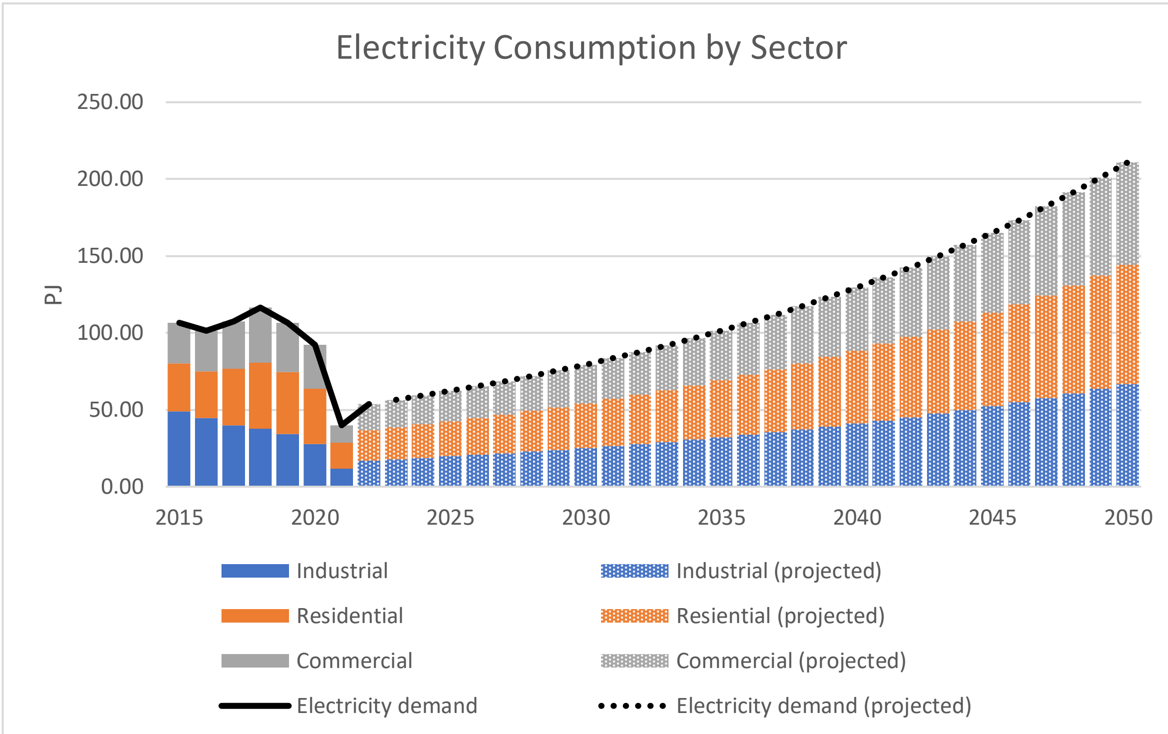

Figure 1. Electricity demand by sector

2.2. Electricity generation by source

Table 4 provides details on the yearly electricity generation spanning from 2015 to 2021. The data, sourced from the IRENASTAT database [4], was processed to illustrate generation breakdown by sub-technologies. The graphical representation of this information in Figure 2 juxtaposes it against the overall electricity generation.

Table 4. Annual electricity generation (2015-2021) by source in PJ.

Sub-technology	2015	2016	2017	2018	2019	2020	2021
Coal Power Plant	2858.6	2703	3007	3433	3227	2175	2481
Light Fuel Oil Power Plant	66	66	66	66	66	66	66
Solar Photovoltaic (PV)	1.87	1.95	1.95	1.95	1.9	1.9	2.08
Off-Grid Solar PV	1.46	3.29	3.52	4.05	4.04	4.04	4.04

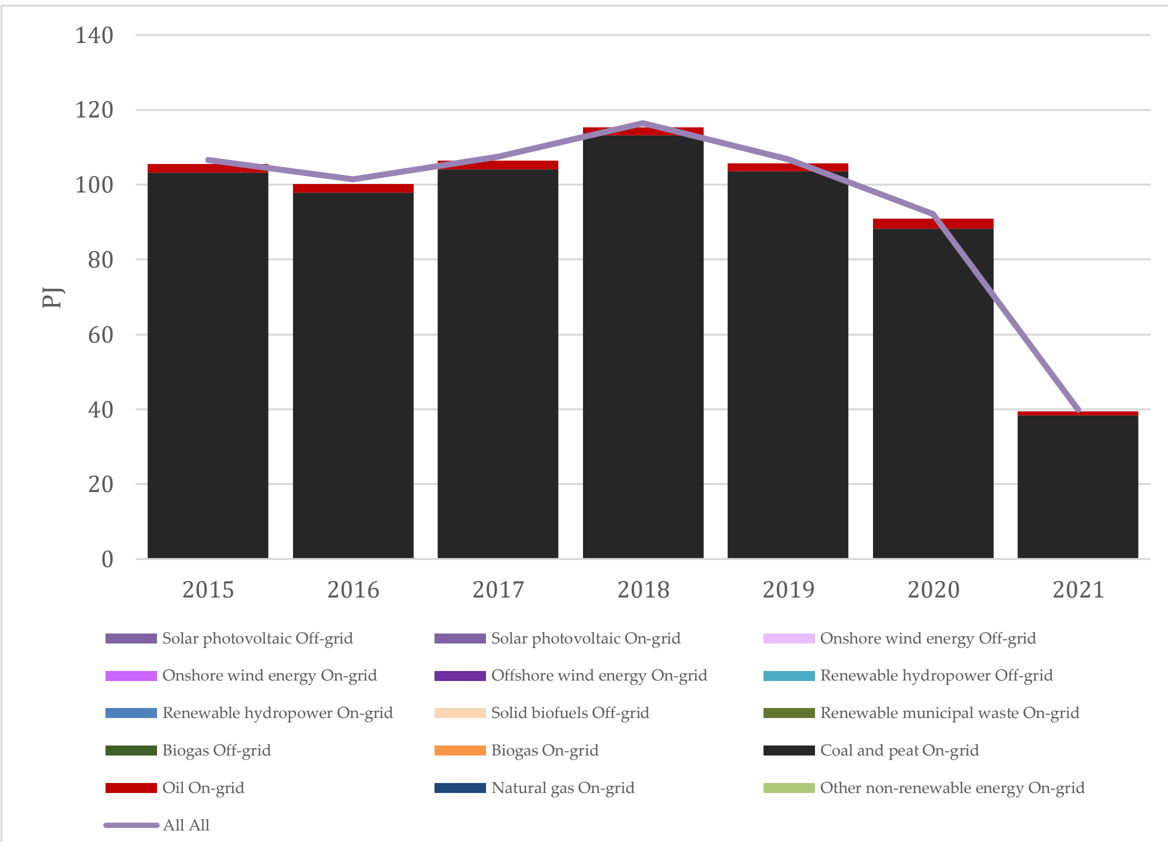

Figure 2. Annual Electricity generation by source and electricity demand.

2.3. Electricity imports and exports

Historical data on electricity imports and exports from 2015 to 2020 were extracted from the IEA Country Profile for Botswana [2] and outlined in Table 5. Due to unavailable open-source data beyond 2021, the projected values were based on the country's import ambitions outlined in the IRP [3]. Exports potential values were kept at zero as per the Botswana Starter Data Kit (SDK) [5].

Table 5. Annual electricity imports and exports (2015-2021) in PJ.

	2015	2016	2017	2018	2019	2020	2021
Imports	5.284	6.022	4.641	3.024	3.963	7.513	5.983
Exports	0	0	0.251	0.457	0.309	0.151	0.007

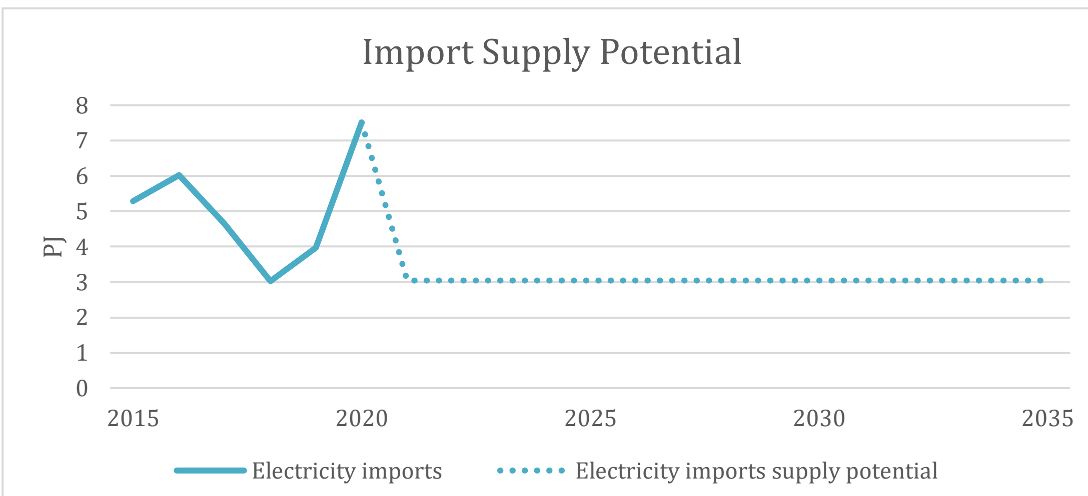

Figure 3. Electricity imports supply potential.

2.4. Fuel prices

Data regarding the price of crude oil imports and extraction were extracted from the EIA Energy Outlook 2020 [6]. Biomass, coal and natural gas import and extraction prices were compiled from the IRENA Planning Prospects for West Africa report [7]. These are consistent with the figures in the SDK [5]. Table 6 and Figure 4 display the fuel price for key dates and projections respectively.

Table 6. Fuel prices for key years in USD/GJ.

	2015	2020	2025	2030	2040	2050
Crude Oil Imports	13.1	12.2	12.8	14.3	16.9	19.5
Crude Oil Extraction	12.0	11.1	11.6	13.0	15.4	17.8
Biomass Imports	1.8	1.8	1.8	1.8	1.8	1.8
Biomass Extraction	1.6	1.6	1.6	1.6	1.6	1.6
Coal Imports	4.9	5.1	5.3	5.5	5.9	5.9
Coal Extraction	3.3	3.4	3.5	3.6	3.8	3.8
Light Fuel Oil Imports	15.9	14.7	15.4	17.3	20.4	23.6
Heavy Fuel Oil Imports	9.6	8.9	9.3	10.4	12.3	14.2
Natural Gas Imports	8.6	8.6	9.5	10.3	11.0	11.0
Natural Gas Extraction	7.1	7.1	7.8	8.5	9.9	9.9

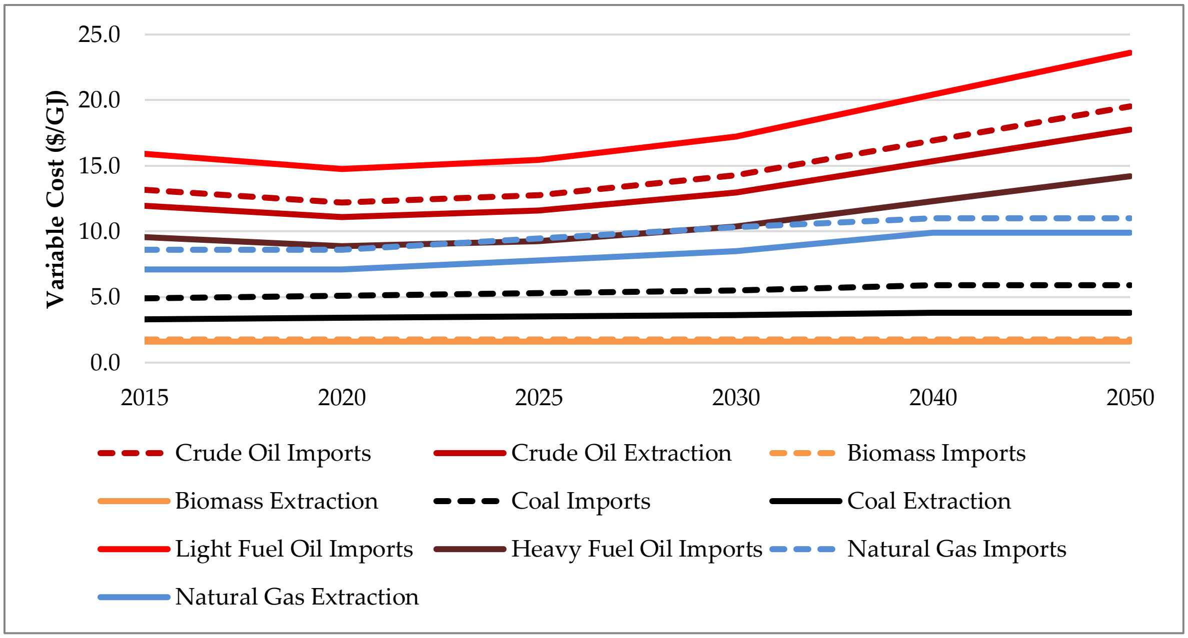

Figure 4. Fuel prices for key years in USD/GJ.

2.5. Emissions

Throughout their operational lifespan, power plants release greenhouse gases, including carbon dioxide, methane, and nitrous oxides. This study quantifies emissions in terms of carbon dioxide equivalent (CO2e), as presented in Table 7. Emission data was sourced from an IPCC annex [8].

Table 7. Emission factor of CO2e for various fuel types.

Fuel	**CO2 Emissions Factor (kg CO2/GJ)**
Crude oil	73.3
Biomass	100
Coal	94.6
Light Fuel Oil	69.3
Heavy Fuel Oil	77.4
Natural Gas	56.1

2.6.Refineries

Refinery data was collected from an African energy projections report commissioned by the European Union [9]. These values pertain to an African energy system and it is assumed that these values remain constant, as indicated in Table 8.

Table 8. Techno-economic data on refineries.

Technology	**Capital and fixed cost (USD/kW)**	**Variable cost (USD/GJ)**	**Operational life (yrs)**	**Output ratio**
Crude oil refinery option 1	24.13	0.72	35	0.9 LFO: 0.1 HFO
Crude oil refinery option 2	24.13	0.72	35	0.8 LFO: 0.2 HFO

2.7. Power transmission and distribution

The technical and economic parameters for transmission and distribution technologies were extracted from the Reference Case scenario in The Electricity Model Base for Africa (TEMBA) [10]. Based on this information, it is projected that the efficiencies of power transmission and distribution in Botswana will reach 96.0% and 86.0%, respectively, by the year 2030. Table 9 outlines the technical and economic parameters associated with the transmission and distribution network.

Table 9. Techno-economic data on the power transmission and distribution system.

Technology	Capital Cost ($/kW in 2020)	Fixed Cost ($/kW/yr in 2020)	Variable Cost ($/GJ in 2020)	Operational Life (years)	Efficiency (2020)	Efficiency (2030)	Efficiency (2050)
Electricity Transmission	365	0	0.0001	50	96%	96%	96%
Electricity Distribution	2502	0	0.0001	70	85%	86%	89%

2.8. Electricity generation technologies

Data on electricity generation technologies is obtained from the CCG Starter Kit [8] and is presented in Table 10. The assumption is made that the performance of the technologies remains constant due to a lack of available data. Additionally, global historical capital costs for renewable electricity generation technologies from 2015 to 2021 were sourced from IRENA's report on Renewable Power Generation Costs [11] and extended to projections for 2050, as detailed in Table 11 and depicted in Figure 6.

Table 10. Techno-economic data on the electricity generation technologies.

Technology	Capital Cost ($/kW in 2020)	Fixed Cost ($/kW/yr in 2020)	Operational Life (years)	Efficiency	Average Capacity Factor
Biomass Power Plant	2500	75	30	0.35	0.5
Coal Power Plant	2500	78	35	0.37	0.85
Geothermal Power Plant	4000	120	25	0.8	0.79
Oil Fired Gas Turbine (SCGT)	1450	45	25	0.35	0.8
Gas Power Plant (CCGT)	1200	35	30	0.48	0.85
Gas Power Plant (SCGT)	700	20	25	0.3	0.85
Solar PV (Utility)	1378	17.91	24	1	0.35
CSP without Storage	4058	40.58	30	1	0.45
CSP with Storage	5797	57.97	30	1	0.45
Large Hydropower Plant (Dam) (>100MW)	3000	90	50	1	0.23
Medium Hydropower Plant (10-100MW)	2500	75	50	1	0.23
Small Hydropower Plant (<10MW)	3000	90	50	1	0.23
Onshore Wind	1489	59.56	25	1	0.21
Nuclear Power Plant	6137	184.11	50	0.33	0.85
Light Fuel Oil Standalone Generator (1kW)	750	23	10	0.16	0.3
Solar PV (Distributed with Storage)	4320	86.4	24	1	0.35

Table 11. Capital cost of renewable electricity generation technologies for key years in USD/kW.

Technology	2015	2020	2025	2030	2040	2050
Geothermal Power Plant	4000	4000	4000	4000	4000	4000
Solar PV (Utility)	2165	1378	984	886	723	723
CSP without Storage	6051	4058	3269	2634	2562	2562
CSP with Storage	8645	5797	4670	3763	3660	3660
Large Hydropower Plant (Dam) (>100MW)	3000	3000	3000	3000	3000	3000
Medium Hydropower Plant (10-100MW)	2500	2500	2500	2500	2500	2500
Small Hydropower Plant (<10MW)	3000	3000	3000	3000	3000	3000
Onshore Wind	1985	1489	1191	1087	933	933
Light Fuel Oil Standalone Generator (1kW)	750	750	750	750	750	750
Solar PV (Distributed with Storage)	6840	4320	3415	2700	2091	2091

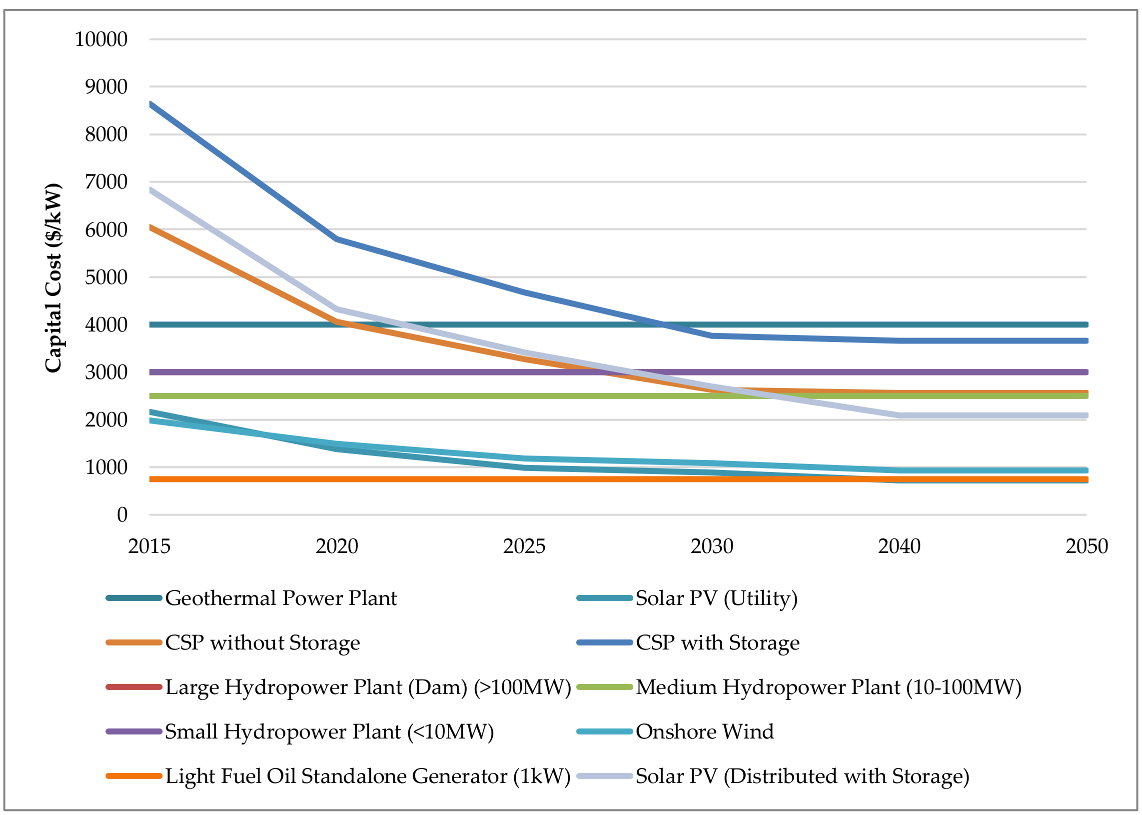

Figure 6. Capital cost of renewable electricity generation technologies.

2.9. Renewable energy supply potential and reserves

This study relies on data obtained from open reports and databases to assess the potential for domestic renewable energy supply and the reserves of fossil fuels. The renewable potentials outlined in Table 12 are taken from the Renewables Readiness Assessment conducted by IRENA [12] and are assumed to remain constant over the period. Data for fossil fuel reserves are from the World Bank energy data [13] and are displayed in Table 13.

Table 12. Renewable energy supply potential for RE technologies.

	Unit	Estimated Renewable Energy Supply Potential
Solar PV	Twh/yr	13764
CSP	Twh/yr	13070
Wind	GW	1.5
Biomass	PJ/yr	32
Small Hydropower	MW	1
Geothermal	MW	0
Hydropower	MW	0

Table 13. Fossil fuel reserves.

Fuel	Unit	Proven reserves
Coal	million tonnes	127.2
Crude oil	billion barrels	0
Natural gas	trillion cubic metres	0

3. Experimental design, materials, and methods

A comprehensive literature review was undertaken to gather data, incorporating materials from various sources such as international organisations, journal articles, databases, and media reports. The collected data underwent a thorough process of compilation, internal presentation, and discussion to achieve consensus on the main data and assumptions for use in the analysis. This section provides a detailed breakdown of the data sources and the processing methods employed for specific techno-economic parameters.

3.1.Electricity demand

Electricity consumption by sector for the years 2015 to 2020 were collected from the IEA Botswana profile [2]. The final electricity demand projection was extracted from the IRP [3]. From this source, the total demand for every 5 years was given. It is assumed that demand changes linearly between these data points. The percentage of electricity consumed per sector was calculated for the projected years using The Electricity Model Base for Africa (TEMBA) values [10].

3.2.Electricity generation by source

The electricity generation by source for the years 2015 to 2020 was first compiled from IRENASTAT [4]. As electricity generation data for 2021 was not provided from the database, the electricity generation proportion of all generation technologies, except on-grid solar photovoltaic (PV), were calculated based on the average annual growth rates from 2015 to 2020. Thus, this assumes that electricity generation by source will change based on previous growth trends. The proportion in percentage of annual electricity generated by each sub-technology was calculated and processed to align with the overall electricity generation data from the IRP [3].

3.3.Electricity imports

The historical figures for electricity imports were compiled from the Botswana IEA country profile [2]. The projected data is a constant average based on the IRP projections [3].

3.4 Fuel prices

Crude oil imports and extraction prices were extracted from the EIA Energy Outlook 2020 [6]. Biomass, coal and natural gas import and extraction prices were compiled from IRENA [7].

3.4.Power transmission and distribution

The power transmission and distribution costs and efficiencies were estimated from TEMBA, due to a lack of country-specific data for Botswana.

3.5.Capital costs of renewable technologies

The historical global capital costs of renewable electricity generation technologies spanning from 2015 to 2021 were obtained from IRENA's Renewable Power Generation Costs report [] and are presumed to be reflective of the situation in Botswana.

3.7. Renewable energy supply potential

The maximum theoretical capacity potential for RE technologies were taken from Botswana’s Renewable Readiness Assessment report [12]. These figures are assumed to stay constant over the modelling period. Fossil fuel reserves are extracted from World Bank energy data and are also assumed to stay constant over the modelling period.

Limitations

Not applicable.

Ethics Statement

Not applicable.

Credit author statement

Ranea Saad: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – Original draft preparation. Rudolf Yeganyan: Project administration, Writing- Review & Editing. Hannah Luscombe: Writing- Review & Editing. Mark Howells: Supervision. Fernando Plazas-Niño: Writing- Review & Editing.

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U4RIA compliance statement

This work follows the U4RIA guidelines which provide a set of high-level goals relating to conducting energy system analyses in countries [1]. 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).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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