Power System Modeling Tools for Sustainable Development: A Review

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***Abstract*—The green growth paradigm aims to harmonize economic growth with environmental sustainability. Electricity is essential for economic development, and if its associated carbon emissions are sufficiently low, it is a key enabler of green growth and sustainable development. Zambia, a developing country, had only 32.5% of households with access to electricity in 2022. This paper provides a comprehensive overview of power system modeling tools applicable in Zambia and evaluates the ongoing and completed power system modeling initiatives in the Zambian energy space. The study discusses the key features, applicability, and relevance of various modeling tools, including PyPSA-Earth, OSeMOSYS, MAED, MESSAGE, and WASP. Findings indicate that while many tools are available, the selection and adaptation of these tools are crucial for addressing the specific challenges in Zambia's power system. This paper aims to support the strategic planning necessary to achieve a sustainable low-carbon energy transition in Zambia.**

***Index Terms*—Sustainable Development, Low-Carbon Energy, Power System Modeling, Zambia, Energy Transition**

I. Introduction

In Zambia, the pursuit of green growth and sustainable development aligns with broader African trends. The country's forthcoming Green Growth Strategy [1] reflects this shift, aiming to balance economic expansion with environmental stewardship. Central to this strategy is the role of electricity, recognized globally as pivotal for development [2]. However, as of 2022, only 32.5% of Zambian households had electricity access [3], highlighting a critical need for electrification to fuel economic progress and meet national development objectives, such as achieving an electrification rate of 100% by 2030 [3].

This material has been produced under the Climate Compatible Growth program, which is funded by UK aid from the UK Government. However, the views expressed herein do not necessarily reflect the UK government's official policies.

Zambia's economy is significantly influenced by the mining, manufacturing, and agricultural sectors, all of which are vulnerable to climate variability and energy shortages. For instance, in 2015, Zambia's copper output fell short of targets due to low prices and power shortages, underscoring the sensitivity of its mining sector to external and internal shocks [4, 5]. Similarly, the manufacturing sector, which contributes about 7% to GDP, has seen productivity declines of 60–70% due to energy deficits caused by reduced rainfall [6, 4, 7]. The agricultural sector, employing over 60% of the population, has also suffered from erratic climatic conditions, impacting household welfare and livelihoods [8, 6, 4, 9].

The challenge of expanding electricity access involves more than simply connecting households; it necessitates strategic capacity expansion within the power system. Decisions about which power plants and transmission lines to develop, their locations, and timing are crucial for cost-effectiveness and system reliability. Optimization and power systems modeling offer a structured approach to this complex task. Beyond cost, considerations of reliability and environmental impact are paramount. Zambia's experiences with load shedding underscore the importance of a reliable power system that can overcome challenges like droughts and demand fluctuations [3]. Balancing these factors, particularly in the context of climate change, requires careful analysis and scenario planning.

This paper aims to analyze and propose the use of specific power system modeling tools to address the challenges in Zambia's power system planning, particularly in achieving 100% electrification by 2030.

The rest of the paper is structured as follows. Section II gives the literature review of the open-source power system modeling tools, including those applicable in the Zambian context. The energy modeling initiatives in Zambia are documented in Section III. Section IV provides discussions. Finally, Section V concludes the paper.

II. Literature Review

Power system modeling is essential for planning, designing, and operating electric power systems [10]. Various tools have been developed to model different aspects of power systems, including static and dynamic models, small-signal models, and tools for planning and design, operation and control, stability analysis, and protection [11] [12]. This section reviews the key features, strengths, and limitations of several power system modeling tools relevant to sustainable development in Zambia.

A. PyPSA-Earth

PyPSA-Earth is an innovative open-source global energy system model that integrates new data and functionalities for energy transition studies and policy formulation. While it offers high spatial and temporal resolution, making it useful for global and regional energy modeling, it may have limitations when applied to the specific needs of Zambia's power system. Despite being a global model, its open-source nature and adaptability make it a potential candidate for localized studies with appropriate modifications.

A representation of the PyPSA-Earth workflow can be found in Figure 1. Data is collected and processed to be then fed into the PyPSA model framework, which enables performing the desired optimization studies, such as least-cost system transition scenarios [13] [14].

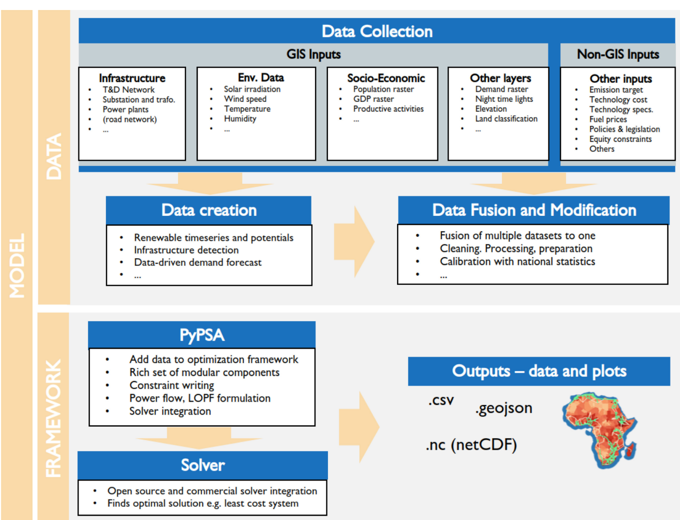

Fig. 1. PyPSA-Earth model design. Source: [13] .

B. OSeMOSYS

OSeMOSYS is a versatile tool designed for the development of energy strategies at various scales. It is known for its flexibility, open-source accessibility, and multilingual support, making it a valuable tool for capacity building and robust energy system modeling. Its ability to handle multi-resource systems and detailed power representations makes it particularly useful for countries like Zambia, where diverse energy resources need to be managed efficiently [15].

A high-level overview of OSeMOSYS Global's workflow is shown in Figure 2 below. The green boxes highlight where the user interfaces with the model, while the blue boxes highlight automated actions that run behind the scenes.

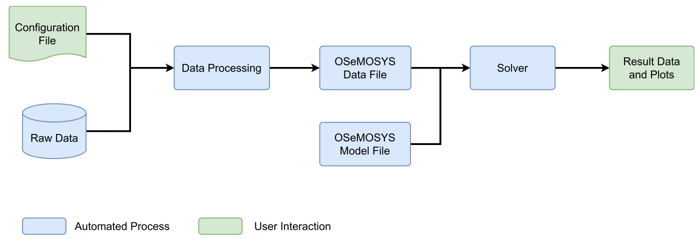

Fig. 2. OSeMOSYS Global's workflow. Source: [16].

C. Model for Analysis of Energy Demand (MAED)

MAED predicts future energy requirements based on consistent assumptions about long-term changes in a country's socioeconomic, technological, and demographic aspects. This tool is useful for forecasting energy demand across various sectors, providing valuable insights for planning and policy-making.

Figure 3 shows the major inputs and outputs of this model [17].

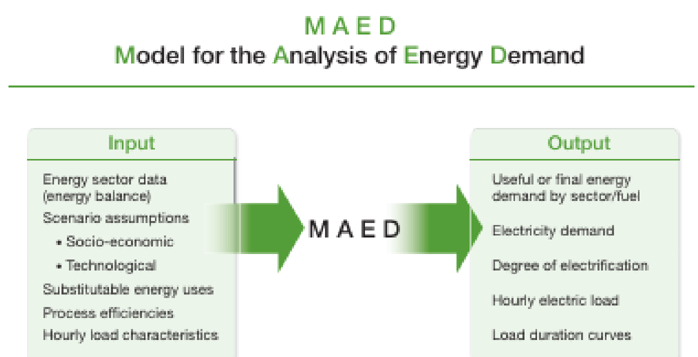

Fig. 3. Major inputs and outputs of MAED. Source: [17].

D. Wien Automatic System Planning Package (WASP)

WASP is used for planning electricity needs in developing nations. It assists in creating optimal expansion plans for generating power, considering specific local constraints such as limited fuel availability and emission regulations. WASP evaluates different capacity addition scenarios to meet demand while ensuring system reliability [18] [19].

Figure 4 shows the major inputs and outputs of this model.

E. Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE)

MESSAGE uses energy chains to map out energy flows from extraction to end-use. It is useful for long-term energy planning and policy testing, analyzing factors such as cost, investment, energy security, resource efficiency, technology adoption, and environmental limitations [20]. Figure 5 shows the major inputs and outputs of this model.

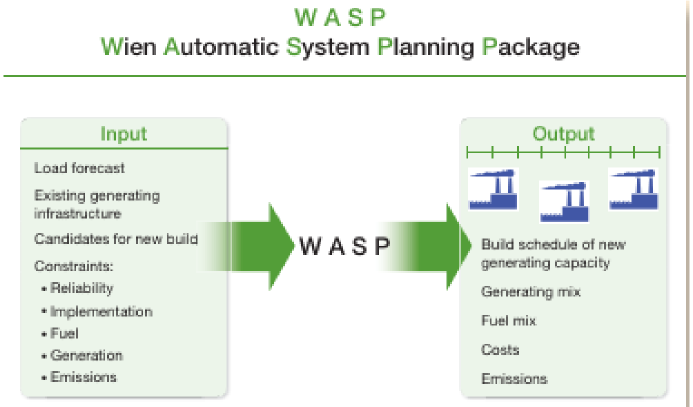

Fig. 4. Major inputs and outputs of WASP. Source: [18].

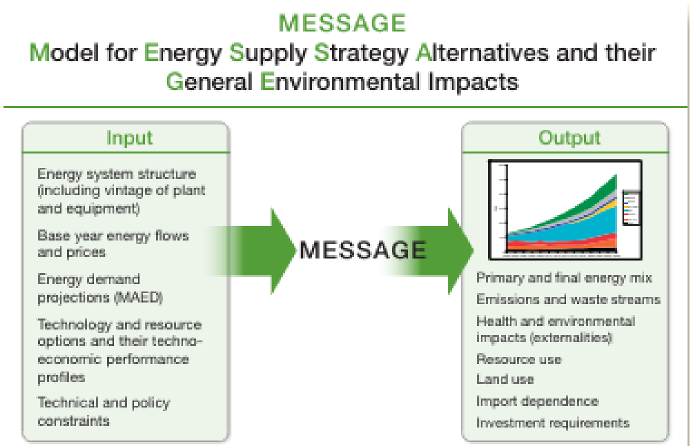

Fig. 5. Major inputs and outputs of MASSAGE. Source: [20].

F. Summary of the Key Features of the Modeling Tools

The modeling tools reviewed in this study—PyPSA-Earth, OSeMOSYS, MAED, MESSAGE, and WASP—each have unique features tailored to specific aspects of power system modeling. PyPSA-Earth focuses on power systems with high spatial and temporal resolution and is open-source, though it has a steeper learning curve. OSeMOSYS is versatile and scalable, supporting multi-energy systems (electricity, heat, gas) with both linear and non-linear options. It is also open-source and offers a user-friendly interface, making it suitable for policymakers and energy consultants.

MAED is primarily used for power systems and is well-suited for unit commitment and dispatch, though it may not handle complex system analysis well. It is partially open-source and focuses on cost minimization. MESSAGE, another open-source tool, caters to multi-energy systems and excels in long-term planning and policy analysis, though it can be computationally expensive for large systems. Lastly, WASP, which is a commercial tool, provides fast and efficient operational planning for power systems but has limited representation of power system dynamics.

In terms of data requirements, PyPSA-Earth, MAED, and WASP require high data inputs for power system components, while OSeMOSYS and MESSAGE have moderate data requirements. Typical users of these tools range from researchers and power system operators to policymakers and energy consultants, highlighting the diverse applicability and user base of these modeling tools.

Integrating advanced modeling tools such as PyPSA-Earth, OSeMOSYS, MAED, MESSAGE, and WASP can significantly enhance Zambia's ability to plan for a resilient and sustainable power system. These tools can support comprehensive scenario analysis, optimize energy resource utilization, and facilitate strategic planning to mitigate the impacts of climate variability on the economy.

III. Energy Modeling Initiatives in Zambia

This section explores the key modeling initiatives undertaken in Zambia's energy sector, examining their objectives and findings. These initiatives provide valuable insights into the country's energy transition outlook and the applicability of various modeling tools.

A. Integrated Resource Plan (IRP)

The IRP aims to transform Zambia's power sector over 30 years, focusing on diversity, resilience, financial stability, and quality service provision. It integrates demand and supply-side resources for optimal energy planning. The project, supported by UK Aid and other cooperating partners, officially launched in 2022 [21].

B. Zambia Energy Transition Study

This study explores energy transition scenarios using OSeMOSYS and FlexTool. It assesses capacity planning, cost-effective generation, emissions reduction, and system flexibility, providing valuable insights into Zambia's energy transition outlook [22].

C. Integrated Energy Demand-Supply Modeling

A model was developed to assess the impact of various scenarios on energy demand and supply in Zambia compared to a baseline (2019) scenario. This study highlights the potential for renewable integration and emission reductions, emphasizing sustainable energy planning [23].

D. Hydro–Connected Floating PV and Onshore Wind Potential

Research focuses on enhancing Zambia's hydro-dependent system resilience with floating PV and wind power. The study addresses challenges in load management strategies, particularly in light of climate change-induced droughts, emphasizing the need for diversification in the energy mix [24].

E. System Studies for Renewable Integration

A systematic approach was employed using geospatial mapping and modeling to evaluate renewable energy integration readiness. This study highlights the contribution of variable sources in meeting energy demands sustainably [25].

F. Transition Pathways Toward Inclusive Growth (TRAP-ZM)

TRAP-ZM facilitates long-term energy planning through collaborative modeling, leveraging local input and qualitative scenarios. This initiative offers valuable insights into potential energy futures [26].

G. Solar PV Performance and Financial Modeling

An analysis was conducted to assess solar PV feasibility for grid-connected homes, focusing on technical performance and financial viability. This study highlights the role of renewable energy in addressing Zambia's energy needs [27].

These initiatives showcase Zambia's proactive approach to adopting diverse strategies for sustainable energy planning and development, with each project contributing valuable insights into the country's energy transition journey.

IV. Results and Discussion

The studies reviewed indicate that Zambia is making significant strides in energy modeling and planning, with a focus on integrating renewable energy sources to achieve a sustainable low-carbon future. The key findings from the various initiatives and tools used highlight the importance of selecting appropriate modeling tools tailored to the specific needs of Zambia's power system.

A. Specific Needs of Zambia's Energy Sector

Zambia's energy sector faces unique challenges, including limited access to electricity, dependence on hydroelectric power, and vulnerability to climate change-induced droughts [28]. The reviewed tools offer various capabilities to address these issues. For example, OSeMOSYS and MESSAGE are well-suited for evaluating different energy mix scenarios, including the integration of renewable energy sources like solar and wind. PyPSA-Earth's high-resolution modeling can support detailed spatial planning, while WASP's ability to optimize power generation expansion under specific local constraints is crucial for ensuring system reliability and cost-effectiveness. MAED's capability to forecast energy demand based on socioeconomic trends is essential for planning to meet future energy needs effectively. Overall, these tools can be adapted and integrated to form a comprehensive approach to addressing Zambia's unique energy challenges.

B. Key Findings from Modeling Initiatives

The IRP highlights the need for a diverse and resilient power sector, incorporating renewable energy sources to reduce dependence on hydroelectric power and enhance system reliability [21]. The Zambia Energy Transition Study underscores the potential for significant emissions reductions and cost savings through the adoption of renewable energy technologies [29]. The Integrated Energy Demand-Supply Modeling initiative emphasizes the importance of sustainable energy planning to meet future demand while minimizing environmental impacts [23]. Research on Hydro–Connected Floating PV and Onshore Wind Potential suggests that diversifying the energy mix with solar and wind power can improve system resilience against climate change-induced droughts [27].

C. Implications for Policy and Practice

The findings from these studies have important implications for energy policy and practice in Zambia. Policymakers should prioritize the integration of renewable energy sources and the development of a resilient power infrastructure to meet the country's electrification targets. The use of advanced modeling tools can support evidence-based decision-making, enabling the development of cost-effective and sustainable energy strategies. Additionally, fostering local capacity in power system modeling and analysis is essential for the successful implementation of these strategies.

D. Recommendations for Future Research

The common trends identified in this review suggest that future research should focus on refining and adapting existing modeling tools to better address the specific needs of Zambia's energy sector. This includes developing more detailed local data inputs, enhancing the capability of models to simulate the impacts of climate change on hydropower resources, and exploring the integration of emerging technologies such as energy storage and smart grid solutions. Collaboration with international research institutions and leveraging open-source tools can further enhance the robustness and applicability of energy modeling efforts in Zambia.

V. Conclusion

In summary, this review provides a comprehensive overview of power system modeling tools and their application in Zambia's energy sector. Using power system modeling tools effectively is crucial for improving Zambia's energy security and economic resilience. These tools help address the weaknesses of key economic sectors that are affected by climate changes and energy shortages. By doing so, they support the creation of strong energy strategies that encourage sustainable growth and help reduce economic inequalities.

The analysis highlights the critical role of these tools in supporting the country's transition to a low-carbon and sustainable energy future. By leveraging the strengths of various modeling tools and addressing the specific challenges faced by Zambia's power system, policymakers and researchers can develop effective strategies to enhance energy access, reliability, and sustainability. Continued investment in modeling capabilities and data collection, along with international collaboration, will be essential for achieving Zambia's electrification and sustainability goals.

Acknowledgments

This material has been produced under the Climate Compatible Growth program, which is funded by UK aid from the UK Government. However, the views expressed herein do not necessarily reflect the UK government's official policies.

References

[1] University College London, "UCL collaborates on recommendations for Zambia's Green Growth Strategy," 2023. https://www.ucl.ac.uk/bartlett/sustainable/new

s/2023/mar/ucl-collaborates-recommendations-zambias-green-growth-strategy.

[2] The World Bank, "Access to energy is at the heart of development," 2018. https://www.worldbank.org/en/news/feature/2018/04/18/access-energy-sustainable-development-goal-7.

[3] Ministry of Energy, "Renewable energy strategy and action plan," report, Republic of Zambia, 2022.

[4] Government of the Republic of Zambia, "Annual economic report 2017," *GRZ Publications*, 2017.

[5] Ministry of Mines and Mineral Development, "Mining in Zambia 2018," report, Republic of Zambia, 2018.

[6] Ministry of National Development Planning, "Economic report 2016," *MNDP Publications*, 2016.

[7] Zambia Statistics Agency, "Labor force survey report 2020," *ZamStats Publications*, 2020.

[8] Ministry of Tourism, Environment and Natural Resources, "Environmental report 2011," *MTENR Publications*, 2011.

[9] World Bank, "Zambia economic brief: Wealth beyond mining," *World Bank Publications*, 2020.

[10] A. G. Abo-Khalil, "Digital twin real-time hybrid simulation platform for power system stability," *Case Studies in Thermal Engineering*, vol. 49, p. 103237, 2023.

[11] S. Cho, C. Li, and I. E. Grossmann, "Recent advances and challenges in optimization models for expansion planning of power systems and reliability optimization," *Computers & Chemical Engineering*, vol. 165, p. 107924, 2022.

[12] K. Mahmud, D. Soetanto, and G. E. Town, "5.6 Energy management softwares and tools," in *Comprehensive Energy Systems* (I. Dincer, ed.), pp. 202–257, Oxford: Elsevier, 2018.

[13] M. Parzen, H. Abdel-Khalek, E. Fedotova, M. Mahmood, M. M. Frysztacki, J. Hampp, L. Franken, L. Schumm, F. Neumann, D. Poli, A. Kiprakis, and D. Fioriti, "PyPSA-Earth. A new global open energy system optimization model demonstrated in Africa," *Applied Energy*, vol. 341, p. 121096, 2023.

[14] J. Hörsch, F. Hofmann, D. Schlachtberger, and T. Brown, "PyPSA-Eur: An open optimisation model of the European transmission system," *Energy Strategy Reviews*, vol. 22, pp. 207–215, 2018.

[15] M. Howells, H. Rogner, N. Strachan, C. Heaps, H. Huntington, S. Kypreos, A. Hughes, S. Silveira, J. DeCarolis, M. Bazillian, and A. Roehrl, "OSeMOSYS: The open source energy modeling system: An introduction to its ethos, structure and development," *Energy Policy*, vol. 39, no. 10, pp. 5850–5870, 2011. Sustainability of biofuels.

[16] OSeMOSYS Global, *Getting Started*, 2022. Accessed: 2024-06-28.

[17] International Atomic Energy Agency, *Model for Analysis of Energy Demand (MAED-2)*. No. 18 in Computer Manual Series, Vienna: International Atomic Energy Agency, 2006.

[18] International Atomic Energy Agency, *Wien Automatic System Planning (WASP) Package. A Computer Code for Power Generating System Expansion Planning. Version WASP-IV*. No. 16 in Computer Manual Series, Vienna: IAEA, 2001.

[19] M. Zeljko, M. Aunedi, G. Slipac, and D. Jakšić, "Applications of Wien Automatic System Planning (WASP) model to non-standard power system expansion problems," *Energies*, vol. 13, no. 6, 2020.

[20] D. Huppmann, M. Gidden, O. Fricko, P. Kolp, C. Orthofer, M. Pimmer, N. Kushin, A. Vinca, A. Mastrucci, K. Riahi, and V. Krey, "The MESSAGEix integrated assessment model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development," *Environmental Modelling & Software*, vol. 112, pp. 143–156, 2019.

[21] Ministry of Energy, "Integrated resource plan," report, Republic of Zambia, 2022.

[22] K. J. Nyoni, "The Zambian Energy Transition (ZET): A case study for OsemOSYS and FlexTool," 2022.

[23] P. P. Daka and H. Farzaneh, "Developing an integrated energy demand-supply modeling framework for scenario analysis of the low carbon emission energy system in Zambia," *Applied Sciences*, vol. 13, no. 6, 2023.

[24] K. J. Nyoni, A. Maronga, P. G. Tuohy, and A. Shane, "Hydro–connected floating pv renewable energy system and onshore wind potential in Zambia," *Energies*, vol. 14, no. 17, 2021.

[25] K. J. Nyoni, A. Kaonga, G. Muyunda, H. Phiri, and A. Mumba, "System studies to assess preparedness of the Zambian electrical grid for the energy transition through integration of large-scale variable renewable energy sources," *Journal of Electrical Electronics Engineering*, vol. 2, 2023.

[26] C. C. Growth, "Transition pathways towards inclusive climate compatible growth (TRAP-ZM)," 2023. https://climatecompatiblegrowth.com/wp-content/uploads/CCG-Transition-Pathways-for-Zambia-two-pager.pdf.

[27] U. Pal and K. Imasiku, "A solar photovoltaic performance and financial modeling solution for grid-connected homes in Zambia," *International Journal of Photoenergy*, vol. 2021, p. 8870109, 2021.

[28] E. Siankwilimba, "Effects of climate change induced electricity load shedding on small holder agricultural enterprises in Zambia: The case of five southern province districts," *IJRDO - Journal of Agriculture and Research (ISSN: 2455-7668)*, vol. 5, pp. 01–151, 09 2019.

[29] Climate Compatible Growth, "Zambia energy transition study," report, United Kingdom, 2022.