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Open-source tools for modelling energy transitions paradigm in developing countries: a compatibility assessment study

Babajide E. Shari^{1*}, Moumouni Yacouba², Ohunakin S. Olayinka^{3,4}, Saidou Madougou^{1,5}, Philipp Blechinger⁶, Nnenna C. Nwankwo¹, Mashinini Madindwa⁷ and Victor Aladesanmi⁷

*Correspondence:

Babajide E. Shari

babadjide.s@edu.wascal.org

¹West African Science Service Centre on Climate Change and Adapted Land Uses (WASCAL), Doctoral Research Program in Climate Change and Energy (DRP-CCE), Abdou Moumouni University, Niamey, Niger

²Electrical and Computer Engineering, Higher Colleges of Technology, Ras Al- Khaymah, United Arab Emirates

³Mechanical Engineering Department, The Energy and Environment Research Group (TEERG), Covenant University, Ota, Nigeria

⁴Faculty of Engineering & the Built Environment, University of Johannesburg, Johannesburg, South Africa

⁵Department of Physics, Ecole Normale Supérieure, Abdou Moumouni University, Niamey, Niger

⁶Reiner Lemoine Institut, Berlin, Germany

⁷Mechanical and Industrial Engineering Technology Department, University of Johannesburg, Johannesburg, South Africa

Abstract

Simulation models have provided reliable simulation pathways for planning the Global and national energy transition. While simulation tools have gained prominence in providing transition insights to modelling the energy paradigm of developed countries, their developing country counterparts have yet to gain a clear transition pathway. This could be due to the cost of commercial tools, technical know-how, and the complex attributes and underdevelopment of developing countries' energy systems transition paradigm. Open-source energy simulation modelling tools (OsEMT) could help developing countries gain reliable insight and understand their modern energy transition paradigm and mitigate modelling bottlenecks posed by proprietary modelling tools. The current study aims to review open-source energy models suitable for emerging economies and conduct a compatibility assessment of OsEMT for modelling the energy transitions of Developing Countries. To do this, a review of 11 OsEMT was carried out based on information and secondary data from the applications of the models and how they have captured and obtained modelling insights about 33 thematic attributes of developing countries' energy systems. A compatibility and suitability assessments were conducted for the investigation through a weighted scoring matrix and ranking. Results showed that most open-source energy models have been effectively and successfully applied to model the energy transition paradigm of developed countries. However, a few open-source models have ranked higher and are suitable for developing countries. OSeMOSYS, OEMOF and PyPSA were among the most compatible and suitable OsEMT for gaining reliable insights and modelling developing countries' energy transition pathways, although OSeMOSYS is ranked highest. Recommendations for further research and holistic support for open-source energy modelling tools were provided.

Keywords OSeMOSYS, Energy transition, Open-source energy models, Energy systems, OEMOF, PyPSA, Developing countries



1 Introduction

The energy sector, which includes electricity, transportation, heating, and cooking, accounts for approximately 73.2% of global greenhouse gas emissions [1]. The electricity sector alone contributes around 40% of worldwide carbon dioxide (CO₂) emissions [2]. In 2021, it was the largest source of global fossil fuel emissions, emitting about 14.3 GtCO₂ eq CO₂; these emissions represented roughly 38% of the world's CO₂ emissions that year. Renewable energy sources offer a sustainable alternative to decarbonize the power sector and reduce reliance on fossil fuels. Achieving renewable energy targets varies by country, with developed and developing nations responding differently to the energy transition [3]. Developed countries use policy tools such as feed-in tariffs (FIT) and carbon taxes to encourage investment in and adoption of renewable technologies [4]. Conversely, implementing such renewable energy cost initiatives is often difficult in many developing nations, whose governments are heavily burdened with subsidizing fossil energy [5]. While developing countries, especially those in Sub-Saharan Africa (SSA), contribute only a small fraction to global CO₂ emissions, they are disproportionately vulnerable to climate change impacts [6].

Many developing countries are signatories to the Paris Agreement and aim for an ambitious reduction of greenhouse gas emissions across all sectors. They have therefore developed several emissions pathways to meet their local and national reduction goals [7]. Consequently, many emerging economies focus on how to sustainably harness their existing energy resources to satisfy their growing energy demand for economic development and to lift their citizens out of poverty, while maintaining a sustainable path to a net-zero future [8]. For example, the Nigerian government planned a net-zero energy transition by utilizing both renewable energy and gas to ensure energy security for the country [9–11].

The weak strategic implementation of clean energy policies in many developing countries may be due to a poor understanding of their energy paradigm and the incompatibility of energy modelling tools to provide reliable insights for achieving a low-carbon economy driven by clean energy, which hampers meeting the 2030 targets [12]. Hence, the progress in renewable energy adoption is slower than what is required to meet international climate goals. In fact, this is a global problem affecting all countries, but it is more pronounced in developing countries, not only in Africa. To address this challenge of renewable energy adoption in developing countries, this study analysed open-access tools for energy transition modelling that can help to understand how to accelerate the deployment of renewables in developing countries [13]. Open-source energy models could enable developing countries to own their transition to clean energy by supporting a localized energy framework. Such a local energy sector would foster indigenous expertise, allowing these nations to develop tailored energy strategies aligned with their specific energy needs and resources, thereby facilitating a just transition aimed at improving energy access and ensuring economic prosperity [14–16].

Energy models are a reliable tool to investigate the plan and obtain reliable insight into a country's clean transition [17]. They are used to predict, analyze, and optimize energy consumption, helping businesses, governments, and individuals make informed decisions about energy use and efficiency [17]. Many early energy models were developed and primarily focused on the context of developed countries, reflecting their specific energy systems and priorities [18]. However, adopting energy models without adequate

compatibility assessment of the modelling tool for developing countries' energy systems may produce biased and misleading energy planning insights [19]. Many developing countries have employed several commercial energy planning modelling tools to investigate their clean energy initiatives to gain insight into their energy transition plan, and uncover the accrued benefits [20]. Such proprietary energy models might not provide transparency, collaboration, reproducibility, and reduced relevance to societal debates, and member nations may not gain full ownership of energy model codes [21]. Thus, the application of commercial energy models in emerging economies could delay achieving low-carbon targets, threaten sustainable development and lead to inconsistent policy priorities and political-economic calculations [22].

According to the Open Energy Modelling Initiative (OpenMod), there are approximately 68 energy system models with open-source licenses [23]. While open-source energy modelling tools are valuable resources for developing countries in planning low-carbon development, they don't automatically translate into sustainable energy policies [24]. Such models should be able to provide reliable insights about the country's energy system towards sustainable energy policy [25]. Evidence of the tool's use in generating insights for policy formulation is demonstrated in Costa Rica, where OSeMOSYS modelling informed the National Decarbonization Plan [24] and the latest update of the Nationally Determined Contribution (NDC) [25]. Also, Open-source models were used to investigate the long-term energy system modelling for a clean energy transition and improved energy security in Botswana's energy [26]. While open-source energy models offer valuable frameworks, they often fall short in addressing the unique techno-socio-economic realities of developing countries [20, 26]. And may not be tailored to the specific challenges and contexts of these nations, such as poverty, limited infrastructure, and diverse energy needs. A few energy models are compatible with the techno-socio-economic characteristics of developing countries. In this regard, no study has explicitly investigated the suitability and compatibility of open-source energy modelling tools to provide reliable energy policy insights to plan low-carbon development in developing countries.

This study will enhance existing knowledge of open-source energy modelling tools tailored for developing countries by examining their suitability. A few open-source models are deemed well-suited for modelling the energy systems of developing countries and capturing their techno-socio-economic characteristics. Therefore, the current study evaluates the compatibility of selected open-source energy modelling tools and how they can offer relevant policy insights into low-carbon development in developing countries. The assessment of this compatibility is important due to the numerous advantages of open-source modelling tools. Using a weighting scoring matrix approach, this suitability evaluation will inform renewable energy planners and energy system modellers in developing countries about the most appropriate open-source simulation tools to investigate and design a typical clean energy development framework based on their specific energy system features.

2 A synthesis of open-source energy planning tools in developing country energy paradigm

Open-source energy tools are computer simulation software and data made available for public use, modification, and redistribution, with publicly accessible datasets used for energy modelling and analysis [27]. These tools were developed collaboratively to ensure transparency and be used for various purposes in the energy sector, including modelling, simulation, optimization and energy transition research [28].

As energy access remains a pressing global challenge, especially in developing countries, the concept of Open Source, with its rich history of transforming various sectors, particularly in programming and information technology, has the potential to revolutionize the energy access sector [29]. Open Source, characterized by its collaborative nature and commitment to transparency, enables communities to grow around jointly maintained tools and resources for organizations to share knowledge and resources freely [30]. As such, it is capable of improving energy security and affordability, and energy efficiency, which is currently the focus of global policy attention to accelerate the transition to clean energy [31].

The initiative to support open-source energy models and open energy sector data has been on for about two decades [32]. Aside from that, the open-source energy crusade has been very active and has achieved significant and successful results within open-source communities, including applications in developed countries as well as the open-source community itself [33]. In contrast, so far, few successes have been recorded in its application and utilization in policy development in most developing countries [34]. The query of this subsection is, therefore, based on: (i) the assessment of germane attributes of the open-source model to be considered when developing energy system planning in the Developing Country context, (ii) the evaluation of important characteristics of developing countries that are essential when adopting open-source modelling tools, and (iii) how would application of open-source modelling tools translate into relevant insights for future sustainable green energy policies?

However, the lack of ownership and transparency in many commercial energy systems modelling tools limits their use in developing regions, hindering the ability to address national energy needs [24]. This is because these tools are often proprietary and opaque, making it difficult for local communities to adapt, utilize, and contribute to their development. Fortunately, open-source models seem to have more optimistic attributes despite some limitations. The United Nations Department of Economic and Social Affairs (UNDESA) and the United Nations Development Programme (UNDP) claimed that responding to national energy needs would require the following: (i) building and tailoring models to specific development contexts, (ii) strengthening government capacities to apply modelling tools to inform decision-making, (iii) communicating findings to the highest levels of government to guide policies [35].

To investigate these attributes, characteristics of selected open-source modelling tools were studied based on the guidelines prescribed by Indra Al Irsyad et al. [34]. The procedure aimed at selecting the most appropriate analytical tool. Open-sourced energy modelling tools have been widely utilized in the planning of energy transition agendas in emerging economies, with limited understanding of their application in developing countries. There are critical differences between developing and developed countries, such as energy infrastructure, energy market, and it is necessary to examine their

suitability of open-source energy models for developing countries. For example, renewable energy traditionally plays a vital role as an energy source in rural areas of developing countries. However, this is not the case in most industrialized countries, where energy models have been largely deployed [36].

To develop scenarios that investigate transition strategies in emerging nations, model ownership, transparency and a clear understanding of the modelling procedure are crucial [31]. Essentially, renewable energy planners in developing countries should be cautious about selecting analytical tools developed and largely utilized in industrialized economies. It then implies that analytical tools should be selected based on their ability to capture the energy attributes in emerging economies, including social, economic, and technical know-how of the model. Thus, considering an open-source and inexpensive computer simulation software could be preferred. It should also consider the purpose of the analysis and the issues such as energy poverty, population distribution, high level of biomass deployment, illiteracy and dearth of reliable energy database confronting and pertinent to the region.

3 Socio-economic-techno-demographic characteristics in emerging economies

Emerging economies have unique socio-economic techno characteristics that significantly interfere with their energy systems, especially in the energy end use. Such characteristics include the use of energy, energy demand, and socio-cultural attributes. The characteristics are inferred based on their peculiar Socio-techno-economic characteristics.

Many developing countries, especially in Africa, are characterized by a significant youthful population; for instance, the population of youth under the age of 30 in Nigeria is about 70% of the entire population of about 220 million people [37]. This means that around 154 million Nigerians are under 30 years old. The relatively youthful population is an indication of how energy is consumed and the country's socio-economic outlook. Also, a high proportion of young people creates future energy demand and opportunities for innovation. However, high youth unemployment can lead to social and economic instability, negatively impacting the overall economic outlook [38]. Similarly, developing countries are experiencing rapid population growth, as rapid growth increases energy demand, especially for cooking, transport, housing, and public services.

In addition, emerging economies are low to middle-income countries, characterized by limited capacity for capital-intensive clean energy investments, which often translates to high energy poverty. With little technology and energy infrastructure, many developing countries lack access to reliable, affordable energy. More so, emerging countries have a largely informal economy, making it difficult to account for energy needs (i.e., micro-enterprises), as such, making formal energy planning and demand assessment complex [39].

Furthermore, developing countries experience low technological penetration, leading to limited access to smart grids, clean energy tech and energy efficiency measures. With a high tendency of leapfrogging potential, including the possibility to skip fossil-heavy stages and adopt renewable energy technologies directly (such as solar home systems, solar mini grid/solar farms, solar street lighting). Thus, heavily dependent on weak, obsolete central utility energy infrastructure. Due to limited technological advances,

emerging economies experience limited access to energy management and financial solutions, such as the pay-as-you-go solar initiative and solar grid-tied [40].

From a social perspective, developing countries experience significant energy and gender inequality, as women and marginalized/vulnerable communities disproportionately lack energy access and are not involved in energy policies. It implies that there is a need to involve local participation for sustainable energy solutions. Besides, the region is characterized by significant political instability and governance policy inconsistencies, thus lacking investor confidence and weak policy legislation. Hence, many developing countries are known for lopsided social inclusion, which in turn discourages investment and hinders social inclusion [41]. In light of the socio-techno-economic characteristics of developing countries' energy systems, energy modelling simulation tools should be capable of providing relevant insights into a typical emerging economy by taking into consideration the socio-techno-economic attributes of such a spatial setup.

3.1 Review of open-source tools and selection criteria

Several studies have examined the relevance and application of analytical modelling tools for investigating the clean energy transition in developed countries, but fewer studies have investigated the selection criteria of those analytical tools towards adoption in developing countries. For instance, Sovacool (2013) investigated the qualitative factors responsible for the success and failure of renewable energy access programs in 10 developing countries in Asia. The study concludes by offering 10 lessons for energy analysts and development practitioners. These lessons are (i) appropriate technology, (ii) income generation, (iii) financing, (iv) political leadership, (v) capacity building, (vi) programmatic flexibility, (vii) marketing and awareness, (viii) stakeholder engagement, (ix) community ownership, and (x) technical standardization. Outcomes from the study are useful in that they provide relevant variables and factors to consider in developing countries' energy system planning. However, the study has only investigated renewable energy projects across Asia without considering what analytical tools would quantitatively provide insights into enhancing energy poverty and other relevant attributes of emerging nations' energy systems.

To overcome the bottleneck in the Sovacool study, Lyden et al. [17] explored the modelling tool selection process for identifying appropriate tools for planning community-scale energy systems, including storage and demand-side management. Lyden et al. [34] further categorized and documented modelling tools and their capabilities to inform energy modelling. The criteria for categorization included: (i) input data characteristics, (ii) supply technologies, (iii) design optimization, (iv) available outputs, (v) controls and DSM, (vi) storage, and (vii) practical considerations. While these criteria are useful, they are based on the developed and developing countries' context.

In a similar account, Bhattacharyya & Timilsina [19] critically reviewed energy models used for energy demand assessment for developing countries. Bhattacharyya & Timilsina [19] investigated the appropriateness of energy demand models on their capability to model developing countries' specific energy features. It identified poor-rich and urban-rural divides, traditional energy resources, and differentiation between commercial and non-commercial energy commodities (informal economies) are often poorly reflected in these models, and also identified huge data deficiencies in developing countries. It concludes that there is a need for further development of models to better reflect the

emerging economies' energy systems and institutionalizing the modelling paradigm as a significant requirement for investigating energy demand to deliver a holistic and reliable policy formulation.

Similarly, Indra Al Irsyad et al. [34] reviewed a few selected analytical tools for renewable energy analysis in developing Countries. The study adequately characterized the energy attributes of emerging economies and added to research knowledge of energy modelling approaches that could be considered to effectively model the energy systems of developing countries. On the one hand, the study identified systems thinking, life cycle thinking, and decision support analysis as additional approaches to modelling developing countries' energy systems. The study concluded that a few models designed for developed nations might not effectively capture relevant policy insights for developing countries. Such characteristics of the developing countries included traditional energy consumption, economic and demographic transitions, high-income inequality, and the informal economy. Also, the study did not emphasize open-source modelling tools for developing countries because little or nothing was done to address ownership and transparency issues.

Building on these few backdrops, the current study analyses selected open-source modelling tools but also applies appropriate tools to explore modelling the energy sector of a developing country, a case study of the emerging economies' power sector in the U4RIA guidelines. Outcomes would provide relevant insight for energy policy formulation that would inform model scenarios for investigating pathways to meet the region's climate goals, including net-zero emissions, and also support energy security, providing pathways to meet the electricity demand gap. An open-source modelling tool that captures pertinent characteristics of developing countries' energy sectors and provides succour to data dearth would be considered for subsequent analysis, according to [10].

3.1.1 Open-source modelling tool selection criteria

To select an open-source analytical tool for energy system modelling in developing countries, criteria based on underlying attributes of the open-source tool and patterns pertinent to developing countries based on Indra Al Irsyad et al. [34] recommendations were considered in the current study's assessment framework. The current study has employed two broad criteria (according to group A and B) as an assessment framework to investigate open-source energy tools to be suitable for the context of a developing country.

Group A: based on open-source simulation tool properties the following criteria are considered: (i) they should be user-friendly and easily comprehend by native users of energy models; (ii) there should be available of relevant and ample literature on developing country-based evidence and (iii) availability of an open learning platform, i.e., free training, open doc, certification is an important criterion.

Group B: the open-source modelling tool should be capable of providing reliable insights based on the following socio-techno-economic attributes of an emerging economy (i) informal economic and young demographic transition, (ii) high-income inequality, (iii) dynamic transition: the energy transition in an emerging economy is mainly characterized by a slow shift from the traditional energy to the modern and clean energy system, rapid urbanization with low or self/captive electricity generation, with few industrialized sectors; (iv) growing distributed energy market with transformation from

monopoly to liberal market, and an increase in energy consumption intensity, and (v) financial burden that threatens efforts to implement clean energy transition plans.

To put the selected criteria into perspective, Table 2 describes common features of open-source energy modelling tools as they apply to a developing country's energy transition context. As shown in Table 2, eleven (11) open-source energy modelling tools were selected based on their application to model the clean energy paradigm of a developing country's context. Information and attributes about the selected open-source energy modelling tools were obtained from the tools' web pages, code attributes on GitHub, a review of relevant peer-reviewed literature, and national and international reports. Also, the tools were selected based on the intended application outlined in Groups A and B, the author's experience with the use of a few models, and the Socioeconomic dynamics of developing countries' transition to clean energy.

More specifically, the evaluation of open-sourced modelling tools was based on 6 criteria and 33 sub-criteria. The major criteria include (i) purpose of analysis, (ii) spatial resolution, (iii) temporal resolution, (iv) modelling approach/methodology, (v) capacity building, and (vi) attributes based on developing countries.

- i. Analytical purpose: This explains the analytical relevance of the selected open-source tool to the modelling thematic aspects of developing countries' energy systems. The criteria are based on the tool's ability to model economic, environmental, and technological factors. It can also integrate other sectors such as heat, electricity, transport, clean cooking, and gas integration. Also, this criterion will investigate how the tool supports the high integration of renewable energy.
- ii. Spatial resolution: This investigates the ability of the tool to capture the spatial granularity of the developing country's energy framework, based on regional, municipal, or household context. More so, the global dimension of the tools must be considered.
- iii. Temporal resolution: This gives information about the model's ability to model time scales and time slices. The tool can be set to capture modelling details. Tools that can be flexible to capture specific seasons of the year and variations in the daytime, such as day and night.
- iv. Modelling methodology: This investigates the modelling methodology and approach of the tool, depending on whether it is simulation or optimization. It also investigates whether it could be regarded as a bottom-up or top-down modelling tool to analyze micro-economics or technological aspects, respectively. Also, delve into the tool's ability to use feedback systems based on system thinking or agent-based approaches, as well as the ability to compare different policy options by assessing their effects, performance, impacts, and trade-offs through multi-criteria analysis.
- v. Capacity building: This criterion assesses the availability of training and instruction materials for novice and experienced energy modellers. To further assess this criterion, sub-criteria include the availability of open online certificate courses, online assistance/ community of online users, and regional collaboration for model development and engagement. The criteria are relevant for energy modellers in developing countries because of the shortage of experienced modellers.

Developing countries attribute: this criterion aims to investigate modelling tools that consider some features that characterize an emerging country's energy sector. some

attributes of a typical developing country considered in the sub-criteria include large differences between rural and urban settlements, weak or lack of infrastructure to adequately collect and manage energy data, informal economies, as most people in developing economies are not taxed, large gaps between the poor and rich, and the willingness of developing countries to adopt and implement recommended clean energy technologies. Also, the transition experienced in development is dynamic; these transitions include a shift from traditional energy to the modern energy system, rapid urbanization, industrialization, energy market transformation from monopoly to liberal market, and an increase in energy consumption because transitions have occurred from biomass to electricity. In addition, considering the low level of illiteracy in developing countries, chances are high that there will be some level of inexperienced modellers and thus they would need hands-on training.

4 Analysis of the synthesis

Based on the outcome from the analysis of the common features of open-source energy modelling tools, as applied to the energy characteristics or attributes in developing countries energy context (see Table 2), the analysis is synthesised. The analysis of synthesis illustrates the rationale for selecting the appropriate open-source modelling tool for low-carbon energy planning in developing countries, especially in sub-Saharan Africa. This analysis would enable further insight into the application of open-source tools suitable to better understand the energy sector in developing countries.

Model assessment criteria were based on the analytical ability of the model. Open-source tools, such as AnyMOD, Genx, MESSAGEix, OEMOF, OSeMOSYS, and PyPSA, achieved all sub-criteria based on the model's ability to assess the economic, environmental, and technological impact of policy on energy planning in the developing country's energy planning paradigm (according to Table 2). On the other hand, similar tools, such as Balmerol, Calliope, ETEM, backbone and ETM, and TEMOA, in a decreasing sequence, were found to model the analytical aspect of energy planning [42].

OSeMOSYS has the highest spatial coverage to planning clean energy transition. It has been applied to modelling global, regional, national, and distributed energy systems. Specifically, it has been successfully employed to model developing countries across Africa and Asia, for energy system planning, including the power sector [43–48]. Also, OSeMOSYS has been applied to simulate the cost of energy access among village households [49], and applied across municipal household level¹. Specifically, the model has been employed to analyze ways to achieve strategic low-cost energy investment opportunities and challenges towards achieving universal access (SDG7) in about 45 African countries, including energy projection for African nations [50]. These attributed applications are included in the Energy Model Base for Africa (TEMBA) project [51].

Similarly, PyPSA developed a global open energy system optimization model and demonstrated it in a regional and national context, where a recent study examines various pathways for Africa to be net zero by 2060 [52]. However, the author is not aware of its application at the municipal spatial scale, so also MESSAGEix. Conversely, OEMOF, Backbone modelling frameworks have been applied at several spatial scales from national to municipal scales, but none of these models capture all spatial scales.

¹ Warren, Peter (23 September 2011). Incorporating behavioural complexity into the Open-Source Energy Modelling System using intangible costs and benefits. People and Buildings. London, UK.

However, the OEMOF model has been applied to the sub-Saharan region of Nigeria to investigate and design rural electrification systems based on multi-criteria methodology [53]. ETEM on the other hand is reported to have a highly detailed spatial resolution and as such could represent the municipal energy system [54].

Based on temporal resolution ETEM, OEMOF², and PyPSA were found to have the most granular time slice in the sense that they can model annual, daily, and hourly time steps [55]. ETEM can model up to four seasons time slices using typically individual days or finer [54]. Furthermore, based on the modelling approach, an optimization problem on Linear or mixed-integer programming aims to minimize electricity generation/supply cost with the use of an open-source linear and mixed-integer optimization solver [34]. Al Irsyad [34] claimed that solving an optimization problem in a bottom-up approach is the most feasible modelling approach for developing countries.

Regarding the availability of capacity building for experienced and novice modellers, all the investigated open-source modelling tools (find them in the footnote) have their codes published in open libraries or repositories. In addition, tools have their respective modelling codes readily available in the GitHub repository.^{3,4,5,6,7,8,9,10} Although not all modelling tools have channels and handles to train energy modellers to build capacities of inexperienced and gain an in-depth understanding application of the tools and enable in-country energy system models and localize/institutionalize their application. Conversely, a few open-source energy initiative and frameworks, such as PyPSA, OEMOF and MESSAGEix have structured programs or capacity training workshops for training energy modellers. As a result, hackathon materials are available for beginners and experienced modellers to exchange modelling ideas and suggestions on the same platform. On the other hand, the OSeMOSYS modelling framework has a robust and engaging training platform for energy modellers – beginners, intermediates, and experienced users. There is also an Open University course where modellers can take free energy and flexibility modelling courses based on an integrated tool - OSeMOSYS and FlexTool [56]. These courses not only combine theoretical lessons and practical exercises, but they also enable learners to gain insight into energy system investment planning, among others.

In addition, there exists a comprehensive Energy Modelling Platform (EMP) that entails capacity-building programs in energy system models, where participants are across Africa¹¹ Latin America and the Caribbean could leverage for effective energy system modelling training.¹² Additionally, trainers are not only trained for free in energy system modelling tools but also obtain a certificate upon completing all the teaching activities, certifying their expertise in the field of energy system models. Currently,

² <https://github.com/pypsa-meets-africa/pypsa-africa-archived> .

³ <https://docs.juliahub.com/AnyMOD/Dh0iA/0.1.6/> .

⁴ <http://www.balmorel.com/index.php/balmorel-documentation> .

⁵ <https://devdocs.io/backbone/> .

⁶ <https://calliope.readthedocs.io/en/stable/> .

⁷ <https://osemosys.readthedocs.io/en/latest/> .

⁸ <https://aglavic.github.io/genx/doc/> .

⁹ <https://pypsa.readthedocs.io/en/latest/> .

¹⁰ <https://docs.messageix.org/en/stable/> .

¹¹ <https://climatecompatiblegrowth.com/emp-a/#:~:text=2023,accessing%20its%20large%20resource%20base>.

¹² <https://climatecompatiblegrowth.com/energy-modelling-platform-latin-america-and-the-caribbean-emp-lac/>.

trainees are becoming trainers across continental and national scales.¹³ These efforts have fostered regional collaboration by bringing together demand-led research, energy systems modellers, academics, professionals, and providing training to support countries in the Global South in their sustainable development agenda. Additionally, the free capacity-building efforts have enabled participants to gain insight through the lens of modelling to gain relevant comprehension into their country's energy transition framework, climate goals –NDCs –, and net-zero emission strategies.

Based on this backdrop, OSeMOSYS, OEMOE, and PyPSA are identified as excellent to most effective, respectively. As they have shown to have captured relevant attributes in emerging economies previously discussed as a bane to the energy systems of developing countries. The aforementioned models have been improved upon to address the limitations found in other open-source modelling tools under investigation in the current study.

Specifically, OSeMOSYS captures thematic issues of concern in developing countries. This fact can be attributed to some improvements in the model's use. First, the introduction of a user-friendly Graphical User Interface (GUI) - the ClicSAND software based on Excel [57]. These qualities make modelling in OSeMOSYS easy, as the user does not interact with a rigorous command line during the modelling process. It is easy and fast to install, compatible with the Starter Data Kit models, and compatible with both Windows and Mac operating systems.

Second, the availability of a Country-based Starter Data Kit (CSDK), an Excel SAND Interface to input data, and access the database to import results, and also, the ease of model simulation via an OSeMOSYS Cloud platform. In this, a recent improvement on OSeMOSYS via ClicSAND and CSDK has enabled it to overcome some bottlenecks in the use of Open-source modelling tools in developing countries. Thus, this improvement will enable better rural-urban modelling, ease of data input infrastructure and availability, enable understanding of local economy and income dynamics and processes of clean technology adoption across different transition scenarios, and support for inexperienced users.

4.1 Suitability analysis

4.1.1 Weighted average ranking

The suitability analysis was conducted using a scoring matrix based on preference and ranking methodologies. A weighting average, matrix and score were developed according to Eqs. (1), (2) and (3), respectively are based on criteria and sub-criteria shown in Table 1. To do this, a weighted average of the attributes of the tools application on how effectively it has captured the 33 sub-criteria for the characteristics of an idealized developing country context.

$$Rank = \frac{\sum_i^j w_i x_j}{\sum_i^j w_i} \quad (1)$$

Where w is the weighted average and x is the rating of the open-source models from i to j . i and j represents the ranking value of the open-source energy models across their respective criteria. To do this, a weighted average and weighted scoring matrix were

¹³<https://mailchi.mp/climatecompatiblegrowth/week-121?e=d0cfd0f3e9>.

Table 1 Common features of open-source energy modelling tools as they apply to developing countries

[illegible]

Table 1 (continued)

Criteria	Sub criteria	AnyMOD	Backbone	Balmorel	Calliope	ETEM ^a	Genx	MESSAGEix ^b	OEMOF ^c	OSeMOSYS ^d	PYPsA ^e	TEMOA ^f
Dev Country attribute	Rural–urban dichotomy	✖ ^k							✖	✖		
	Available dataset									✖	✖	
	Informal economy							✖	✖	✖		
	Income inequality							✖	✖	✖		
	Willingness to adopt clean technology							✖	✖	✖	✖	
	Dynamic transition								✖	✖		
	Inexperienced users						✖			✖		

^aEnergy Technology Environment Model

^bModel for Energy Supply Strategy Alternatives and their General Environmental Impact

^cOpen Energy Modeling Framework

^dOpen-Source Energy Modeling System

^ePython for Power System Analysis

^fTools for Energy Model Optimization and Analysis

^g<https://leonardgoeke.github.io/AnyMOD.jl/stable/>

^h<https://arxiv.org/abs/2011.00895>

ⁱ<https://github.com/pypsa-meets-africa/pypsa-africa-archived>

^jhttps://en.wikipedia.org/wiki/Open_energy_system_models#cite_note-eerma-etal-2022-119

^khttps://en.wikipedia.org/wiki/Open_energy_system_models#cite_note-eerma-etal-2022-119

developed to select the relevant open-source modelling tools based on the identified criteria through the sub-criteria presented in Table 1. The following steps were considered to develop a weighted ranking according to Lamrini et al. [58].

First, each criterion was summed based on the sub-criteria of the unique characteristics of the open-source models. Numerical values were assigned to the 11 OsEMTs across 6 criteria according to the attributes in Table 1. According to Table 2, weight was assigned to each criterion; the weight was assigned to the criteria based on their relevance of the criteria to modelling energy systems in developing countries and assigning the weight was guided and informed according to Indra al Irsyad [34].

Second, the weighted average was estimated according to Eq. (1) as shown in Table 3. The total score was calculated and the weighted average was estimated using the *SUM-PRODUCT* tool in the Excel Sheet. The percentage of best was estimated using the ratio of the estimated weight score and the max weight score; from this, the rank was calculated using the *RANK* tool in Excel and the outcomes are shown in Table 3. The weighted matrix rank, in the context of decision-making, enables ranking the 11 OsEMTs based on their scores across different criteria, where each criterion was assigned a weight reflecting its relative importance and suitability in modelling developing countries' energy systems.

According to the rank shown in Table 3 where the weighted average score and ranking for the suitability assessment of 11 OsEMTs are shown. The outcome of the rank revealed the assessment of the most suitable OsEMT, where OSeMOSYS, PYPSA and OEMOF topped the rank accordingly. OSeMOSYS was ranked highest, followed by PYPSA and OEMOF. On the other hand, Callipe, Balmorel and Backbone were respectively ranked least among the suitable OsEMTs assessed. The Callipe OsEMT was ranked lowest in modelling the developing country energy systems.

The Outcome from Table 3, as shown in Fig. 1, illustrates the weighted average ranking analysis of open-source energy modelling tools; the outcome from Fig. 1 corroborates the results obtained from Table 3. The analysis was conducted based on a weighted average for the suitability assessment of open-source modelling tools to model the energy characteristics of developing countries. The weighted average in Fig. 1, described with a line trend, is aligned with the rank analysis presented in Table 3.

Furthermore, Fig. 1 revealed the analytical evidence for the suitability of open-source modelling tools to model the energy system, considering criteria based on modelling tools and the attributes of energy systems in many emerging countries. Also, Fig. 1 shows that OSeMOSYS, OEMOF, and PyPSA are, respectively, the most preferred energy modelling frameworks that could enable developing nations to gain insight into planning a low-carbon energy system. Based on the outcome from Fig. 1, OSeMOSYS' modelling tool is the most preferred.

Table 2 Weight for the criteria assessment of the OsEMTs

SN	Criteria	Weight
1	Analysis purpose	15%
2	Spatial coverage	15%
3	Temporal resolution	10%
4	Modelling methodology	24%
5	Capacity building	15%
6	Dev. country attributes	21%

Table 3 Weighted average score and ranking for the suitability assessment of 11 OsEMTs

Criteria	AnyMOD	Backbone	Balmorel	Calliope	ETEM	Genx	MESSAGEix	OEMOF	OSeMOSYS	PYPSA	TEMOA
Analysis Purpose	5	3	4	4	4	5	5	5	5	5	2
Spatial Coverage	2	3	2	1	2	2	3	3	4	2	1
Temporal Resolution	2	2	1	1	3	1	1	3	1	3	1
Modelling Methodology	2	2	2	2	2	2	2	2	3	2	2
Capacity Building	1	1	1	1	1	1	2	2	5	3	1
Dev. Country Attributes	1	0	0	0	0	0	0	1	5	7	3
Weighted Average	2.093	1.73	1.639	1.487	1.821	1.791	2.095	2.488	4	3.754	1.816
Total Score	13	11	10	9	12	11	13	16	23	22	10
Weighted Score	209.3	173	163.9	148.7	182.1	179.1	209.5	248.8	400	375.4	181.6
Percentage of Best	0.52325	0.4325	0.40975	0.37175	0.45525	0.44775	0.52375	0.622	1	0.9385	0.454
Rank	5	9	10	11	6	8	4	3	1	2	7

The suitability of OSeMOSYS as the most preferred OsEMT could largely be due to the following attributes and criteria: (i) a significant and wide range of spatial resolution up to the household level; (ii) availability of a wide range of capacity-building opportunities that will not only encourage novice modellers but also train them to becoming experienced energy model users or trainer; and (iii) capability to model an unprecedented energy characteristics in many Developing Countries, such as economy, population diversity and settlements, and level of technological advances. OSeMOSYS provides modelling support in this regard compared to the other OsEMT. Although OSeMOSYS may not fare well in aspects relating to temporal resolution, as the model might not be capable of modelling highly detailed time slices in hours or days. Hence, it is important to clarify that the relative importance of different criteria or attributes was determined and then using these weights to evaluate and rank different model options. This process is subjective, relying on literature review and preferences using data analysis. Thus, suitability rank and weights criteria were based on their perceived importance, with higher ranks receiving higher weights.

4.1.2 Weighted scoring matrix

The weighted scoring matrix is a suitability assessment method that considers preference and weight (which does not necessarily add up to 100). Instead, a weight is assigned to individual criteria based on their overall relevance. In this regard, a preference and weight were assigned to the identified criteria based on the existing 33 sub-criteria discussed earlier in Table 1.

Table 4 shows the preference and weight values assigned to the criteria of the OsEMT. The Table shows that capacity building and developing countries' attributes are top weight, with weight values 90% and 70%, respectively. Also, the preference was estimated as the sum of the sub-criteria in each criterion of the OsEMT presented, according to Table 1. Modelling methodology and developing countries attributes, respectively with 8 and 7 preference values, were considered the most preferred criteria due to the number of their sub-criteria. This is not to say that other criteria that were rated low are not important to the suitability assessment.

The weighted scoring matrix was estimated from the (i) criteria value (Table 3), (ii) reference value (Table 4) and (iii) weight (Table 4) according to Eq. (2) to (4). Equation (2) estimates the preference of modelling tools based on the assessed preference and the outcome is used to evaluate the score matrix in Eq. (3) and assessment was made across the considered modelling as i to j according to Eq. (4). Table 3 also shows estimates of the weighted average and weighted score of the open-source energy model toward its ranking. The weighted average and score are outcomes of the summation and product of the OsEMTs values and weights as expressed in equations 2 to 4. The outcome based on the weighted average and score (in bold) compares the values/weights of the OsMETs relative to one another. As shown in Table 3, OSeMOSYS had the highest weighted average, followed by PYPISA, with a weighted average of 4 and 3.754, respectively.

$$Preference\ Assessment = \frac{Criteria\ value}{Preference} \times 100\% \quad (2)$$

$$Score\ matrix = Preference\ assessment \times Weight\ value \quad (3)$$

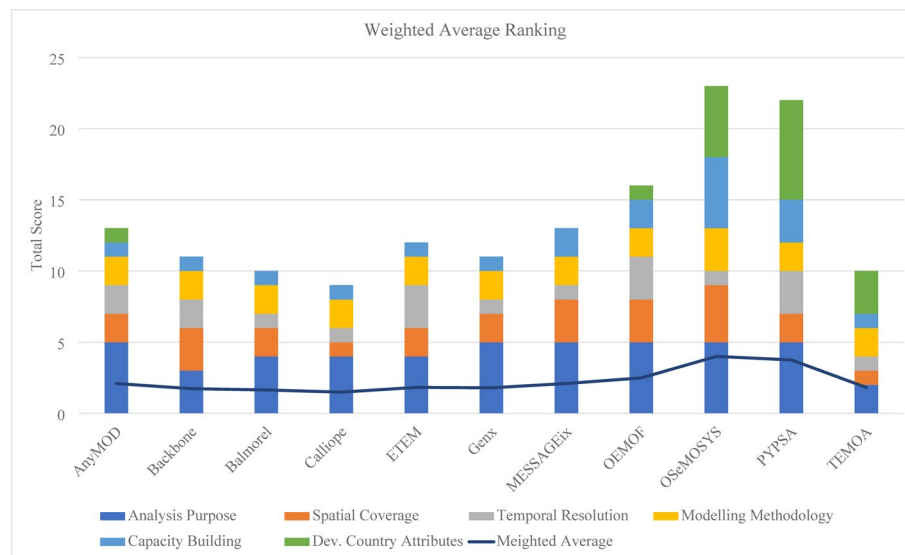


Fig. 1 Weighted average ranking analysis of open-source energy modelling tools for developing countries

Table 4 Weight and preference assigned to the weighted scoring matrix

SN	Criteria	Preference	Weight (%)
1	Analysis Purpose	5	45
2	Spatial Coverage	5	45
3	Temporal Resolution	3	40
6	Modelling Methodology	8	65
7	Capacity Building	5	70
8	Dev. Country Attributes	7	90

$$\text{Total weight scoring matrix} = \sum_i^j (\text{Score matrix}). \quad (4)$$

Equation (2) to (4) enabled the estimation of the weighted scoring matrix, outcome shown in Fig. 2. The result from Fig. 2 is similar to that obtained in Fig. 1, the weighted average ranking in that OSeMOSYS is the most preferred OsEMT to model energy system characteristics of developing countries. The Total weighted scoring rank revealed the trend implication of OsEMT selection from the 11 modelling tools. The preference rose consistently from MESSAGEix, OEMOF and sustained a peak on OSeMOSYS and PYPSA OsEMT. This suggests that the trend of analysis is concentrated across the aforementioned OsEMT.

5 Empirical case studies of selected open-source energy modelling tools

Few open-source energy modelling tools, such as OSeMOSYS, OEMOF, PYPSA, and MESSAGEix, have found significant application in gaining relevant insights about energy systems in developing countries. This section reviews a few OsEMTs that have been applied in the region. The following open-source energy modelling tools are explored: OSeMOSYS, OEMOF, PYPSA and MESSAGEix.

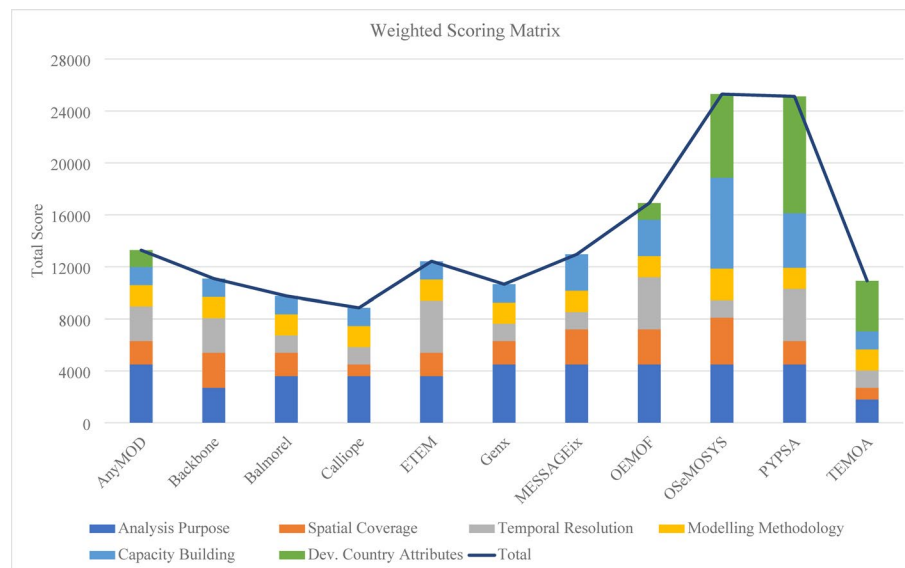


Fig. 2 Matrix scoring of the suitability of open-source energy modelling tools based on weighted score and preference

5.1 OSeMOSYS

Open-source frameworks have been instrumental in designing cost-effective energy transitions, supporting international organizations and policymakers in crafting and making decisions about energy policy, enhancing stakeholder engagement, transparency, and public acceptance [59]. The Open-Source Energy Modelling System (OSeMOSYS) stands out as a key example widely applied in energy transition and planning studies to model the sustainable development of energy systems in many developing countries, such as in Nigeria, Kenya, Ghana and Ethiopia [60] among others, as most applications of OSeMOSYS were found in Africa and Latin America, also Modelling Morocco's transition to renewable power [61], modelling the Dominican Republic energy systems [62] and a Global application [63]. The modelling tool has been applied across the energy sector, including capacity expansion, planning in the power sector, transport sector planning, and sector coupling, with a robust user manual [64] and vibrant communities of practice and users [33] and explicit documentation of the model documentation [65].

Further, the Model allows for full user flexibility in determining the time slice structure and geographic scope of the model and datasets, creating global electricity system models for an active global modelling community, with a clear research direction [48, 59]. Also, the OSeMOSYS model has been used to model granulated, i.e., hourly timesteps, in a decentralized island system and considering an integrated energy and water system [66], including climate and land [67]. OSeMOSYS has found application in modelling developing countries' energy transition plans and designing system expansion. More so, it has been used as a hybrid-integrated model across several temporal scales, with a robust community of users with a significant training platform and has gained support from international partners.

5.2 OEMOF, PYPISA and MESSAGEix

Similar to OSeMOSYS, the Open Source Energy Modelling Framework (OEMOF) has found significant application in many developing countries and aims to facilitate open

science in energy system modelling [68]. Recently, the model – OEMOF was applied to gain reliable insight into the Nigerian energy transition plan and how the country could benefit from a distributed energy system to achieve sustainable energy security [10]. In the same study by Shari et al., OEMOF has been successfully used to investigate that hydrogen fuel cells could serve as a future clean energy, while natural gas could effectively be utilized as a transition fuel in the short and medium term [10]. Also, the model has found significant application in modelling rural areas and island energy planning [69]. More so, the OEMOF is a robust open documentation of its code with an oemof-solph library, a model generator for linear and mixed-integer linear optimization of energy systems [70, 71].

Further, PYPSA was used to model the transition paradigm of Africa and used data from the Nigerian power sector to validate the model and successfully model the continent's clean energy planning [52]. PyPSA has a wide community of users and a well-documented open code [55, 72] with global coverage, integrated energy planning and high-resolution data [55]. The model's community of users is mature enough to ensure a reliable troubleshooting and hackathon platform for research initiatives to foster open data, tools and solvers, that establish a reliable modelling outcome [27, 52]. Dall-Orsoletta et al., [73] in their review study on the openness of electricity models, they identified that co-creation, co-design and crowdsourcing are relevant to modelling energy transition systems of communities, which is novel in the current energy model infrastructure. PyPSA has the aforementioned attributes of co-design and crowdsourcing, as it has a large pool of international and collaborative support [74, 75].

MESSAGEix has been widely applied to modelling the energy systems of developing countries. For instance, Tan et al. apply MESSAGEix to the prediction of energy demand in the building sector in China [76]. Also, Pohit et al. [77] investigated policy scenarios based on the imports of fossil-based electricity from other states of India, energy efficiency and economic productivity of India and Kerala using MESSAGEix in an integrated assessment framework. Awais [78], in his Thesis, used the MESSAGEix as an Integrated Assessment model (IAM) to explore the capability of the IAM to address adaptation using the Indus River Basin as an example and the adaptation of the river under socio-economic, energy, water, and land resource constraints in Zambia. The model has a training platform and has organized several training workshops to enhance the understanding of the model by novice users [79]. Including a robust global model's code documentation [80] with a model input-data management and analysis tool for the MESSAGEix model available in a Python package, referred to as d2ix [81].

5.3 Limitations

The study has explored eleven open-source energy modelling tools and investigated their suitability for gaining insights into modelling developing countries' energy systems. However, the method of assessing the OsEMT approaches is not without caveats, among other limitations. First, the study could have over or underestimated models' attributes to gain insight into characteristics of energy systems in developing countries, coupled with the dynamic changes in technology and Artificial Intelligence (AI). Also, the methodology of suitability assessment employed a subjected approach to assigning weighted values and preference values to estimate the weighted average rank and weighted scoring matrix. Second, there are limited studies on the application of open-source modelling

tools to many developing countries' cases, especially in Africa, thus underestimating the modelling attributes of a few open-source modelling tools. Also, there are a few open-source energy modelling tools that were not considered in the study, such as CLEWS, FinPlan, and OnSSET. These models were not considered because they have specified functions and are often used as hybrid tools alongside other modelling tools. Third, the data used in the assessment are purely empirical and were sourced from secondary sources, which are liable to over- or undersimplify the model's suitability framework.

6 Conclusion

There is a need to employ energy system models to gain insight into planning the energy transition in developing economies. The transition should be deliberate, as a deliberate energy transition framework will not only improve energy access but also enable developing countries to achieve their climate goals. The choice of the energy model to achieve the set goals is as important as understanding the attributes of the modelling tools capable of providing reliable transition insights for the specified region. Open-source models enable countries to take ownership of their energy future and enhance soft technology transfer from advanced countries. However, most open-source models are designed to model developed countries. If adequate caution is not taken when open-source models are applied to an emerging country's energy context, such a modelling tool might not mainstream a reliable energy policy. Thus, the current study has been conducted to assess the suitability assessment, which compares open-source models with several criteria and attributes of developing countries. Against this backdrop, a comparative and suitability assessment has been conducted on 11 open-source energy modelling tools, considering several criteria ranging from tool properties and analytical strength to characteristics of developing countries. Three open-source modelling tools, including OEMOF, PYPISA and OSeMOSYS, were found to be most suitable for gaining reliable insights into the energy systems in a developing country's transition context. The OSeMOSYS tool was preferred among all 11 modelling tools considered, this was so because the OSeMOSYS model proved to have effectively provided reliable insights, such as analytical, spatial spread, effective capacity building and training and captured emerging economies' realities. The OSeMOSYS model has scored and ranked high in the weighted score matrix among reviewed open-sourced computer simulation applications. Based on the model applications, the OSeMOSYS model has been used to gain insight into many developing countries in Africa, including Nigeria, Ghana, Kenya, Morocco, Ethiopia and Zambia, among others. The model energy system expansion, clean energy transitions and energy efficiency. More so, results from the reviewed application of the models revealed that OSeMOSYS have a wide community of users with effective troubleshooting sessions and an open training platform.

6.1 Recommendation

Compatibility and comparison analysis of selected open-source tools has been conducted. Based on the outcome of the study, a few open-source energy tools have proven to be capable of providing reliable insights into developing countries' energy systems. On this note, energy scientists and researchers, and practitioners in the energy space should embrace the use of open-sourced modelling tools to gain insight into clean energy transition pathways and evolution and make policymakers, authorities own their

energy paradigm. Also, there is a need to improvements to the modelling tool by the principal developer or other developers to capture the most relevant characteristics and attributes of developing countries' energy situation. Improving the backend codes and making the modelling tool user-friendly should be prioritized because of the low and weak data infrastructure of many developing countries. In addition, synergy between the energy modelling platform and tools is critical, as some models have specialized features that are beneficial to other models, ensuring a robust energy modelling strategy. Also, synergy between developing countries will enable healthy collaboration among model developers to know the energy situation and the asymmetrical nature of developing countries' energy systems for better model enhancement. Efforts should be put together to train and retrain model users in the form of capacity building to get more local modellers involved in national/country energy modelling activities and thus be instrumental to achieving climate goals and enhancing their clean energy transition pathways.

Author contributions

BES: conceived and drafted the work, developed the methodology, performed the data analysis, conducted data analysis and results, interpreted and drew the conclusions, conducted a literature survey, and managed communication with the journal. YM: made substantial contributions to the conception or design of the work, supervised the project, made substantial contributions to the conception or design of the work, helped develop the methodology and shape the research objective, and reviewed and edited the manuscript. OSO: supervised the project, approved the version to be published, shaped the research objective and aims, and also edited the manuscript. PB: supervised the project, reviewed and edited the manuscript, guided the project, and assisted in shaping the research objectives. SM: supervised the project, revised it critically for important intellectual content, approved the version to be published and shaped the research objective and aims. PB: guided the project. NN: shaped the research objective and aims. MM: supervised the project, shaped the research objective and aims. VA: helped in developing the methodology and also edited the manuscript. All authors gave final approval of the version to be published and agreed to be accountable for all aspects of the work, ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Data availability

The data and materials used in this study are sourced from publicly available scientific literature, research publications, and reputable online databases and have been referenced below.

Declarations

Ethics approval and consent to participate

Not applicable.

Competing interests

The authors declare no competing interests.

Consent to publish

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Clinical trial number

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