International Journal of Advances in Applied Sciences (IJAAS)
Vol. 14, No. 2, June 2025, pp. 469~480
ISSN: 2252-8814, DOI: 10.11591/ijaas.v14.i2.pp469-480

A review of open-source energy system modeling tools

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Article Info

Article history:

Received Aug 6, 2024
Revised Feb 17, 2025
Accepted Apr 23, 2025

Keywords:

Energy system modeling
Energy systems
Open-source
Power system modeling
Renewable energy

ABSTRACT

Nowadays, the transition to open markets, the rapid growth of renewable energy sources like wind and solar, and the shift towards electrification in transportation and industry for decarbonization have increased the demand for advanced energy system models with detailed spatial and temporal data. This paper utilizes a comprehensive literature review and selects a representative set of open-source tools for evaluation. A comparative analysis of 17 open-source energy system modeling tools and their commercial alternatives was conducted. The paper analyzes many open-source aspects such as code commits, updates, programming languages, license details, citations, and energy system modeling features such as power flows (PFs), continuation PF, dynamic analysis, short-circuit analysis, contingency analysis, transportation model, optimal PF (OPF), multi-period OPF, unit commitment (UC), investment optimization, and graphic user interface. Based on the results, the paper suggests appropriate tools used for according power/energy system analysis objective: MATPOWER for power system analysis and Python for power system analysis (PyPSA) for energy system analysis.

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1. INTRODUCTION

In recent years, the rapid growth of renewable energy sources like wind and solar, the shift towards electrification in transportation and industry due to the need for decarbonization [1], along the growing importance of energy storage, have pushed the demand in a more sophisticated energy system models with detailed spatial and temporal data [2], [3]. Traditional power system modeling tools, developed before these trends, primarily focus on analyzing network power flows (PFs) at single points in time, which is no longer sufficient [4]. Modern grids require tools that can account for the dynamic and intermittent nature of renewable energy and the fluctuating demands of electrified transportation [5].

On the other hand, historically, energy system planning has been a closed-door affair, with research, government, and large utilities keeping their modeling methods and assumptions under wraps [6]. This approach, once acceptable due to the limited number of players in the energy sector, is now changing. The transition to open, regulated markets and the urgent need to combat climate change demands a more transparent and collaborative approach to energy planning [7].

The openness of energy system modeling has been studied in many researches [5]–[9] and shows several significant advantages. By making code and data publicly accessible, it promotes scientific rigor through transparency and reproducibility, fostering collaboration between researchers and policymakers [8]. This transparency is essential in the context of energy policy, which often faces strong public opinion and debate [8]. Open modeling can also reduce public opposition to new policies and infrastructure by providing clear explanations of the decision-making process [10]. Additionally, by reducing redundant work and facilitating collaboration, open modeling boosts productivity among researchers, allowing them to share the workload of developing and maintaining complex models and datasets [10]. Thanks to the community, there are many open data and open models published [11], [12].

Recognizing the gaps from previously published studies that primarily focus on evaluating individual tools in isolation, this work offers a novelty contribution by a comparative analysis of tools across power and energy system modeling domains, highlighting their strengths, limitations, and areas for improvement. Moreover, many aspects related to open-source performance metrics, such as the number of commits, last update time, programming language, and licenses are considered. The study also introduces tailored recommendations for different user groups, including developers, researchers, policymakers, and institutions, ensuring the practical applicability of the findings.

This paper is organized as follows. Section 2 provides an overview of the methodology used for evaluating open-source energy system modeling tools. Section 3 presents the results of the evaluation, detailing the performance, functionality, and usability of the tools across both power system and energy system modeling domains. Section 4 provides a comparison of all the tools, discussions, and some recommendations. Finally, section 5 concludes the paper.

2. METHODOLOGY

This paper utilizes a systematic review and comparative analysis to assess open-source energy system modeling tools. The methodology begins with a comprehensive literature review that investigates existing research on these tools, paying particular attention to the shift towards open-source platforms, the pressing need for decarbonization, and the integration of renewable energy. This review also explored previous work highlighting the benefits of open-source modeling, such as improved transparency, reproducibility, and collaborative potential.

Following the literature review, the authors selected a representative set of open-source tools for evaluation. The tools were chosen based on a variety of factors including their popularity, level of active development, and diversity of modeling features. Selection was guided by citation metrics, activity on GitHub, and a review of each tool's functional capabilities. Once selected, key data points were collected for each tool. This data included open-source performance metrics like GitHub stars, the number of contributors, commit frequency, programming languages used, and license details. Information was also gathered on each tool's modeling features, including power flow capabilities, short-circuit and dynamic analysis, and investment optimization techniques. Furthermore, popularity was gauged through citation indices from Google Scholar, and release history and development activity were tracked through repositories like GitHub.

The collected data was then used to categorize the tools, grouping them according to their primary focus: power system modeling tools and energy system modeling tools. Further categories distinguished tools based on the programming language used (MATLAB, Python, Julia) and the license type. With the tools categorized, a detailed comparison was conducted across several dimensions. This included comparing their functional capabilities, encompassing features like power flow analysis, contingency analysis, multi-period optimization, and the availability of graphical user interfaces (GUIs). Development activity and community support were also assessed through commit frequency and contributor count. Lastly, the licensing frameworks of each tool and their implications for usage and adaptation were examined.

Finally, a parallel comparison was made between the selected open-source tools and commercial tools such as PLEXOS and Power Factory. This comparison aimed to illuminate the existing gaps and advantages of open-source tools compared to their commercial counterparts. The findings from this analysis provide valuable insights into the trade-offs between cost, flexibility, and functionality in both types of tools.

3. RESULTS AND DISCUSSION

3.1. Energy modeling tools under review

It is necessary to distinguish between the power system model and the energy system model [7]. Power system modeling focuses on electricity, often modeling in detail the power grid in terms of electrical engineering characteristics such as voltage, current, power, phase, and harmonics. Energy system modeling often simulates energy in general with many different forms of energy (coal, oil, gas, and electricity) and is often a long-term planning model. Currently, due to the need to reduce emissions, increase clean energy, and the increasing role of electricity, these two types of models are increasingly approaching each other. In this article, both types will be referred to as energy system modeling.

The main features of the energy system analysis tools considered in this paper include, i) PF: to determine voltage, current, and power at nodes and on transmission lines in the system and ensure that components in the system are not overloaded and operate within allowable limits [13]; ii) Continuation PF: analyzes PF under variable load conditions to predict critical points, such as the peak of the power voltage curve (P-V curve) or the voltage collapse point [14]; iii) Dynamic analysis: assesses the ability of the power system to maintain stability after short-term disturbances, such as generator loss or short circuit; assesses the short-term voltage and frequency fluctuations after the disturbance [15]; iv) Short-circuit analysis: calculate short-circuit current and determine the impact of short circuit faults on the electrical system, design and select protective devices such as circuit breakers and relays [15]; v) Harmonic analysis: evaluates the impact of harmonics on the power system, which are important for protecting equipment and ensuring power quality [16]; vi) Contingency analysis: simulates and analyzes the impact of potential faults or failures of components in the grid. This analysis helps assess the system's ability to withstand faults without causing widespread disruptions or power outages [17]; vii) Transport model: model of energy transport in many forms such as transmission lines, pipelines, trucks, and ships; viii) Optimal PF (OPF): optimizes load distribution among generators to reduce generation costs; the objective function is usually the sum of generation and transmission costs; constraints on generation capacity, spinning reserves, and other requirements [18]; ix) Multi-period OPF: optimizes the operation of the energy system over multiple time periods (multi-period), instead of just in a single time period like traditional OPF [19]; x) Unit commitment (UC): the decision to start or shut down power plants to meet demand at minimum cost [20]; xi) Investment optimization: optimize the allocation of resources to achieve maximum returns, minimize risks or balancing both [21]; and xii) All energy sector: supports various energy sectors other than electricity (oil, gas, and coal).

The list of open-source energy system modeling tools studied in this paper is shown in Table 1. This list is certainly not exhaustive, but it is representative of open-source tools for energy system modeling, based on criteria such as high citation count, and active development level. The list also has a variety of modeling features for power systems and energy systems. Table 1 is arranged randomly without any preference.

Table 1. List of open-source energy and power system analysis tools in review

No.	Tool	First release	Latest version	Latest release date	Reference
1	MATPOWER	1997	v8.0	2024-05-17	[22]–[25]
2	MOST	2013	v1.3	2024-05-16	[23]
3	PYPOWER	2010	v5.1.15	2021-03-23	[22], [26]
4	pandapower	2016	2.14.9	2024-06-26	[27], [28]
5	PSAT	2002	2.1.11	2022-04-04	[29]
6	PyPSA	2015	0.21.0	2023-03-13	[30], [31]
7	Calliope	2014	0.6.10	2023-01-18	[32], [33]
8	oemof	2015	v0.5.3	2024-06-25	[34], [35]
9	OSeMOSYS	2009	V1.10	2023-01-20	[36], [37]
10	urbs	2017	V1.0.1	2019-03-13	[38]
11	GridCal	2015	v5.1.10	2024-05-31	[39]
12	Sienna	2018	v4.1.1	2024-07-03	[40], [41]
13	Power Grid Model	2022	v1.9.5	2024-07-10	[42]
14	Power Model	2018	v0.21.2	2024-07-05	[43], [44]
15	EGRET	2019	Beta	2023-04-04	[45], [46]
16	GenX	2021	v0.4.0	2024-05-07	[47]
17	LTB	2017	v1.6.2	2022-03-28	[48], [49]

3.1.1. MATPOWER and tools based on MATPOWER

MATPOWER is a package of free, open-source MATLAB-language M-files for solving steady-state power system simulation and optimization problems, such as PF, continuation PF (CPF), extensible OPF, UC, and stochastic, secure multi-interval OPF/UC [22]-[24]. It provides researchers and practitioners with a versatile and reliable toolset for academic and practical applications. MATPOWER was first released in 1997 [22], but it was not until 2017 that it was put on GitHub [25], significantly improving its accessibility and community involvement.

MATPOWER optimal scheduling tool (MOST) [23] is an extended toolkit from MATPOWER, to solve scheduling problems for power systems. MOST offers a versatile computational framework capable of addressing a spectrum of power system optimization challenges. These range from simplified deterministic economic dispatch problems within a single time period and neglecting transmission limitations, to highly complex stochastic formulations. The latter can encompass security-constrained combined UC and multi-period OPF, incorporating considerations such as locational contingencies, load-following reserves, generator ramping costs and constraints, flexible demand resources, non-ideal energy storage characteristics, and the inherent uncertainty of renewable energy generation [23].

PYPOWER [22] is a port of MATPOWER, from MATLAB to Python. PYPOWER does not fully utilize Python's object-oriented interface. Its data structure uses only NumPy arrays, making it difficult to manage the properties of components in the power grid. PYPOWER currently only solves the PF problem and optimizes the OPF. It has no functionality to deal with multi-period OF, which makes it unsuitable for UC, storage optimization, or investment optimization. PYPOWER is not actively developed anymore.

3.1.2. Power system analysis toolbox

Power system analysis toolbox (PSAT) [29] is also a MATLAB toolbox for electric power system analysis and simulation. PSAT was first released in 2002. Operational assessments are facilitated through GUIs, and a Simulink-based library offers an intuitive environment for power network design. The main features of PSAT are PF, continuation PF, OPF, small signal stability analysis, and time domain simulation [29]. PSAT is provided as a free open-source tool, but the PSAT documentation is not [50].

3.1.3. Pandapower

Pandapower builds on the data analysis pandas library [27], [28] and the PSAT PYPOWER [22]. The initial goal was to develop a user-friendly network calculation program to automate power system analysis and optimization. Starting as a convenient interface for PYPOWER, the software has matured into an independent PSAT. This evolution includes an extensive library of power system models, an enhanced power flow solver, and a wide array of additional power system analysis functionalities [27]. The pandapower network model represents electrical systems using fundamental components like lines, two- and three-winding transformers, and ideal switches. These elements are defined by their nameplate ratings and are internally represented by validated equivalent circuit models, ensuring consistency with industry standard software. The network definition relies on tabular data structures provided by the Python pandas library, facilitating straightforward manipulation of input and output parameters. Implemented in Python, pandapower offers ease of use and allows seamless integration with external Python libraries. Its capabilities encompass PF analysis, OPF, state estimation, short-circuit calculations, and the modeling of switches and three-winding transformers. However, similar to PYPOWER, pandapower currently lacks native support for multi-period OPF analysis.

3.1.4. Python for power system analysis

Python for power system analysis (PyPSA) [30], [31]. PyPSA is an open-source software package designed for the simulation and optimization of contemporary power and energy systems. It incorporates functionalities for modeling conventional generators with UC, variable renewable energy sources (wind and solar), energy storage devices, and interconnections with other energy sectors, and integrated AC/DC networks. PyPSA is engineered to handle large-scale networks and extensive time-series data efficiently. This project is actively maintained by the Department of Digital Transformation in Energy Systems at the Technical University of Berlin [31]. Based on PyPSA, many studies have been conducted, especially around the energy system in Europe [51], [52].

3.1.5. Calliope

Calliope is a framework for developing energy system models. Its primary focus is on planning energy systems at scales ranging from urban districts to entire continents. In an optional operation, it can also test a pre-defined system under different operational conditions [32]. The design of the nodes approach used in Calliope was influenced by the power nodes modeling framework [33], but Calliope is different from traditional power system modeling tools and does not provide features such as PF analysis.

3.1.6. Open Energy Modelling Framework

The open energy modelling framework (oemof) [34], which is a Python toolbox for energy system modeling and optimization. The oemof project aims to be a loose organizational frame for tools in the wide field of (energy) system modeling. oemof includes many packages for energy system modeling [34], in which, oemof-solph is a model generator for energy system modeling and optimizations (LP/MILP) [35], oemof-thermal is a tool to model thermal energy components (compression heat pumps, concentrating solar plants, thermal storages, and solar thermal collectors) as an extension of oemof-solph.

3.1.7. Open-Source energy modelling system

The open-source energy modelling system (OSeMOSYS). It is a long-term energy system planning optimization model implemented in GNU MathProg, first released in 2009 [36]. It has been employed to develop energy systems models from the scale of the globe, continents, countries, regions, and villages. It can focus on detailed power representations or multi-resource (material, financial, and all energy) systems.

3.1.8. Urbs

Urbs is a linear programming optimization model for capacity expansion planning and UC for distributed energy systems. Its name, Latin for the city, stems from its origin as a model for the optimization of urban energy systems. Since then, it has been adapted to multiple scales from neighborhoods to continents [38].

3.1.9. GridCal

GridCal is a power system planning and simulation software, written in the Python programming language. The GridCal project is divided into three packages [39]. GridCalEngine houses the database and computational logic for power system analysis. GridCalServer provides a remote application programming interface (API) to access the functionalities of GridCalEngine. GridCal itself offers a GUI that interacts with both GridCalEngine and GridCalServer. This integrated suite provides a wide array of features, including AC/DC multi-grid PF and linear OPF, AC linear analysis tools (power transfer distribution factor and line outage distribution factor), AC linear net transfer capacity calculation, AC+HVDC optimal net transfer capacity calculation, AC/DC stochastic PF, AC short circuit analysis, AC continuation PF, contingency analysis (in both PF and line outage distribution factor variations), sigma analysis (for rapid stability assessment), and investment analysis capabilities [53].

3.1.10. Sienna

Sienna is a modeling framework, developed by the National Renewable Energy Laboratory (NREL), focusing on building, solving, and analyzing the scheduling problems and dynamic simulations of quasi-static infrastructure systems [40]. Sienna consists of many packages, most of which are based on the essential package PowerSystems.jl. PowerSystems.jl provides a rigorous data model using Julia structures to enable power systems analysis and modeling. In addition to stand-alone system analysis tools and data model building, the PowerSystems.jl package is used as the foundational data container for other packages [41]. Sienna is under active development. Some features might not be available at the moment.

3.1.11. PowerGridModel

PowerGridModel is a library for steady-state distribution power system analysis. It is distributed for Python and C. The core of the library is written in C++. Currently, it supports both symmetric and asymmetric calculations for the following calculation types: PF, state estimation, short circuit [42].

3.1.12. PowerModels.jl

PowerModels.jl is a Julia package built on the JuMP optimization modeling language, specifically for steady-state power network optimization. Its primary purpose is to provide a unified platform for researchers to computationally assess new power network models and algorithms. The software architecture is intentionally designed to separate the definition of power system problems (like PF or OPF) from the mathematical formulations used to represent the network (such as AC, DC approximations, or second-order cone relaxations). This decoupling allows for the creation and comparative analysis of diverse power network formulations when applied to the same underlying problem [43], [44].

3.1.13. EGRET

EGRET is a Python-based package for electrical grid optimization based on the Pyomo optimization modeling language [45]. Its main features include the solution of unit-commitment problems and economic dispatch (OPF) problems, such as direct current OPF and alternating current OPF [46]. EGRET is particularly suited for complex modeling tasks that require flexibility and transparency in power system analysis.

3.1.14. GenX

GenX is a highly configurable, open-source electricity resource capacity expansion model [47]. GenX is a constrained linear or mixed-integer linear optimization model designed to identify the least-cost mix of investments and operational strategies for electricity generation, storage, transmission, and demand-side resources. It aims to meet electricity demand over one or more future planning years while adhering to a range of power system operational constraints, resource availability limitations, and externally imposed environmental, market design, and policy requirements.

GenX can be tailored to address different planning questions by adjusting the model's resolution and scope in several key areas. These include the temporal resolution of time series inputs like electricity demand and renewable resource availability, the level of detail in power system operations including UC constraints, and the geospatial resolution and representation of the transmission network. The model supports a comprehensive range of electricity resources, encompassing both conventional and emerging technologies such as thermal power plants, variable renewable sources like wind and solar, run-of-river and reservoir-based hydro, pumped-storage hydropower, energy storage systems, demand-side flexibility, demand response, and advanced technologies including long-duration energy storage [47].

3.1.15. CURENT large-scale testbed

The CURENT large-scale testbed (LTB) is a research facility designed for rapid prototyping of power systems [48]. It is a tightly integrated, closed-loop platform consisting of four major independent packages: ANDES for dynamic simulation, AMS for dispatch simulation, AGVis for grid visualization, and DiME for distributed messaging environment [49]. These LTB packages can be used individually or in a federated manner, making it a versatile and comprehensive platform for power system research and development.

3.2. Comparison of open-source performance and citations

The open-source tools in the paper are evaluated according to the following criteria: modeling features, open-source performance metrics, and number of citations. Modeling functions are the features described in the previous section. Typically, each energy system modeling tool usually focuses on some of them. Open-source performance metrics are retrieved from the toolkit's performance indicators on GitHub [54]. Citation indices are retrieved from Google Scholar [55].

Open-source performance metrics of interest encompass several key indices that help evaluate the popularity, development activity, and usability of a tool. One such metric is the number of stars on GitHub, which reflects the level of community interest in the project. Another important metric is the number of contributors on GitHub, indicating how many developers actively participate in the tool's development. Additionally, the number of commits in the last month, or the date of the most recent commit if no activity occurred in the past month, demonstrates the tool's ongoing development and activeness. The programming language used by the tool and its associated ecosystem also plays a crucial role. These factors impact the scalability of the tool and the level of support available from the development community. In addition, the study also looked at the number of citations for each tool. The number of citations was retrieved from Google Scholar.

Finally, the type of license under which the software is released is essential, as it dictates how the tool can be used, modified, and distributed. Open-source licenses generally fall into three broad categories [56]. Permissive licenses, such as Massachusetts Institute of Technology (MIT), Apache, and Berkeley software distribution (BSD), are flexible and impose minimal restrictions, allowing the software to be freely used, modified, and distributed, even in proprietary applications. Copyleft licenses, such as General Public License (GPL), Lesser General Public License (LGPL), and Affero General Public License (AGPL), require that any derivative works be distributed under the same license, ensuring that the software remains open source. Lastly, hybrid licenses, like Mozilla Public License (MPL), combine elements of both permissive and copyleft licenses to address specific use cases. The comparison results of open-source performance and citations are shown in Table 2. All the performance indicators were recorded in July 2024.

Table 2 shows that there are 3 main programming languages: MATLAB, Python, and Julia. MATLAB is a popular language for scientific computing tools in the 2000s. The dependence on MATLAB, which is a powerful tool but high cost, limits access to the tools. In the 2010s, Python-based tools are developed to replace MATLAB language because of the many advantages of the language and cost [57]. In recent years, the Julia language has received much attention for application in scientific and technical computing due to its open source, high-level, high-performance characteristics for technical computing [58].

MATPOWER, PSAT, and OSeMOSYS are the three oldest tools and also have the largest number of citations. MATPOWER in particular has more than 7,200 citations since 1997, far surpassing other tools. In terms of development speed, some of the most actively developed tools are GridCal, Sienna, and PowerGridModel with monthly commits ranging from 100-250. For the least actively developed tools, the last update may even be a year ago. PSAT alone does not provide code on version control sites like GitHub, but only provides the final version as a zip file, so it has the slowest development speed (the latest version from 2022). Most of the open-source tools use MIT, Apache, and BSD licenses, which are flexible licenses that allow for free use, distribution, and even commercial, closed-source code. Some use GPL, and LGPL, which require that developments based on them be open source.

Table 2. Comparison of open-source performance and citations

No.	Tool	Programming language	Stars	Contributors	Commit	License	Cites
1	MATPOWER	MATLAB 99.2%; TeX 0.8%;	403	14	12	BSD	7,240
2	MOST	MATLAB	31	N/A	May 2024	BSD	232
3	PYPOWER	Python	323	17	Mar 2023	BSD	N/A
4	pandapower	Python 86.0%; Jupyter Notebook 13.5%; Other 0.5%	805	103	47	BSD	918
5	PSAT	MATLAB/Simulink	-	-	-	-	1,273
6	PyPSA	Python	1,200	72	58	MIT	581
7	Calliope	Python	277	15	33	Apache	217
8	oemof	Python	283	48	54	-	299
9	OSeMOSYS	GNU MathProg, GAMS, Python	151	11	June 2023	Apache-2.0	1,004
10	urbs	Python	177	22	Mar 2024	GPL-3.0	N/A
11	GridCal	MATLAB 50.0%; Python 49.6%; Other 0.4%	399	29	252	LGPL 3.0	417
12	Sienna	Julia 99.8%; Python 0.2%	271	27	123	BSD	84
13	Power Grid Model	C++ 73.3%; Python 20.8%; C 4.9%; Other 1.0%	135	18	135	MPL-2.0	2
14	Power Model	Julia 93.4%; MATLAB 6.6%	377	28	14	BSD	118
15	EGRET	Python 99.9%; MATLAB 0.1%	127	14	Nov. 2023	BSD	165
16	GenX	Julia 100%	256	28	May 2024	GPL v2	N/A
17	LTB	Python 98.4%; Shell 1.6%	208	17	Mar 2024	GPL v3	27

3.3. Comparison of energy modeling features

The energy system modeling features of each open-source tool are compared in Table 3. The GUI is also considered in the comparison. In addition, some commercial tools for energy system modeling are also included in the comparison. Regarding the graphical interface, only a few open-source tools have a graphical interface: PSAT (based on Simulink) and GridCal, while all commercial tools have a graphical interface.

Table 3. Comparison of energy modeling features of open-source and commercial energy/power system analysis tools

No.	Tool	GUI	PF	CPF	Dynamic	Short-circuit	Harmonic	Contingency analysis	Transport model	Linear OPF	Non-linear OPF	Multi-period OPF	Unit commitment	Investment Opt.	All energy sectors
	Open-source power system analysis tools														
1	MATPOWER		x	x				x	x	x					
2	MOST		x	x					x	x		x	x		
3	PYPOWER		x					x	x	x					
4	pandapower		x					x	x	x	x				
5	PSAT	x	x	x	x			x		x	x	x	x		
6	PyPSA		x					x	x	x		x	x	x	x
7	Calliope								x			x		x	x
8	oemof								x			x	x	x	x
9	OSeMOSYS								x			x		x	x
10	urbs								x			x	x	x	x
11	GridCal	x	x	x	x	x		x		x				x	
12	Sienna		x		x					x	x	x	x		x
13	PowerGridModel		x		x	x		x							
14	Power Model		x							x	x				
15	EGRET									x		x	x		
16	GenX									x		x	x	x	
17	LTB		x		x					x		x	x		x
	Commercial power system analysis tools														
1	NEPLAN	x	x		x	x	x	x	x	x	x				x
2	PowerFactory	x	x	x	x	x	x	x		x	x				
3	PowerWorld	x	x	x	x	x		x	x	x	x				
4	PSS/E	x	x	x	x	x		x		x	x				
5	PSS/SINCAL	x	x	x	x	x	x	x			x				x
6	PLEXOS	x							x	x		x	x	x	x

Energy system modeling can be categorized into two distinct groups based on their primary functions. The first group focuses on power system modeling, which involves tools designed to analyze and simulate the behavior of electrical power systems. Open-source tools in this category include MATPOWER, PYPOWER, pandapower, PSAT, GridCal, and PowerGridModel. Additionally, there are several commercial tools widely used for power system modeling, such as NEPLAN, PowerFactory, PowerWorld, PSS/E, and PSS/SINCAL. The second group pertains to energy system modeling, which addresses broader energy system dynamics, including generation, distribution, and optimization of energy resources. Notable open-source tools in this category include PyPSA, Calliope, oemof, OSeMOSYS, urbs, PowerModel, EGRET, GenX, and LTB. Among the commercial tools, PLEXOS is a prominent option for comprehensive energy system modeling.

Comparing open source and commercial tools, it can be seen that commercial tools are easier to use (all have graphical interfaces), full of features, and professionally supported. However, open-source tools are developing very quickly by the community and are approaching commercial tools. For example, OSeMOSYS is mature enough to be used in regional power system planning [59]; GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit) also uses PyPSA for many studies on renewable energy integration and energy system transition in Thailand [60], Vietnam [61], and Brazil [62].

3.4. Discussion

The energy system tools are evolving. Open-source tools are increasingly popular due to transparency, reproducibility, and collaborative opportunities. They challenge the traditional dominance of proprietary tools by offering comparable functionality at no cost. Python-based tools like PyPSA and pandapower exhibit significant progress in usability and community support, while Julia-based tools such as Sienna are emerging as high-performance options. With the strength of the community, open-source tools can be actively under development. The vitality of development communities, as shown by metrics like GitHub commits and contributors, significantly impacts the tools' advancement. GridCal and Sienna lead in active development. However, there are still many gaps and limitations of open-source tools. Many open-source tools lack comprehensive GUIs, limiting their appeal to users unfamiliar with programming. Some tools focus on niche functionalities (e.g., long-term energy planning vs. detailed power flow) without fully addressing the needs of integrated energy systems. Transitioning from MATLAB to Python or Julia involves retraining and overcoming institutional inertia, especially for longstanding users of MATLAB-based tools like MATPOWER and PSAT.

Based on the comparisons presented, the paper would like to propose recommendations for different types of users of open-source energy system modeling tools. For developers, it is suggested to prioritize improving user experience by creating intuitive graphical interfaces or dashboards that enhance accessibility for a broader audience. Additionally, developers are encouraged to expand tool functionality to support integrated energy system features, bridging the gap between power system modeling and broader energy system applications. For researchers and policymakers, Python-based tools like PyPSA are recommended for energy system modeling due to their versatility and the strong support of an active community. For applications that demand high performance and scalability, Julia-based tools such as Sienna are suggested as a viable alternative. For institutions, it is recommended to organize training programs to facilitate the transition from MATLAB-based tools to open-source solutions, emphasizing the benefits of cost-effectiveness and flexibility. Institutions are also encouraged to collaborate with open-source communities to ensure that tool development aligns with regional energy planning needs.

4. CONCLUSION

In this paper, a list of popular open-source energy system modeling tools has been reviewed and compared on aspects such as code commits, updates, programming languages, supported energy system modeling features, and citations. Among the tools, MATPOWER has the longest development history, leading in the number of citations, and is still actively developed. Although MATPOWER lacks the function of calculating multi-period OPF, since version 6.0 there has been an extension called MOST based on MATPOWER, supporting this ability. The weakness of MATPOWER is its dependence on MATLAB tools and language, so there are some limitations in terms of cost and ecosystem compared to Python. Among the Python-based tools, PyPSA has the best open-source performance and citation metrics. The number of functions PyPSA supports is also quite large, but its focus shifts towards energy system modeling, lacking the ability to analyze dynamic processes and power system faults. There are a number of Julia-based tools that are also being actively developed, such as Sienna, Power Model, and GenX. However, the Julia ecosystem is still quite small compared to Python’s. Unlike commercial tools, open-source tools often do not have a graphical interface, which also limits their accessibility to the research community. In the review list of the paper, only GridCal and PSAT have a graphical interface. In general, depending on the research objectives, the appropriate tool should be selected. Some recommendations for each type of user have been proposed in the discussion section. For the two most frequent-use aspects (power system analysis and energy system analysis), the paper suggests using MATPOWER for power system analysis and PyPSA for energy system analysis.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
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Va : **Va**lidation
Fo : **Fo**rmal analysis
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R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
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CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [NPL], upon reasonable request.

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