2024 International Conference on Sustainable Energy: Energy Transition and Net-Zero Climate Future (ICUE) | 979-8-3315-1707-6/24/$31.00 ©2024 IEEE | DOI: 10.1109/ICUE63019.2024.10795621

Comparative Analysis of Energy System Modeling Approaches for Decarbonizing the Electricity Sector

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***Abstract*—Comparative analysis is crucial for evidence-based decision-making for sustainable energy transitions. Identifying the strengths and weaknesses of various approaches is necessary before application. This review article presents a comparative analysis of energy system modeling approaches applied in the literature to develop decarbonization pathways for the electricity sector. The six most widely used applications are analyzed: TIMES/MARKAL, PyPSA, EnergyRT, SWITCH, OSeMOSYS, LEAP, and TIMES. SWOT analysis evaluates the strengths, weaknesses, opportunities, and threats of these models when applied toward net zero electricity systems by midcentury. PyPSA and Switch models emerge as top choices in analyzing the decarbonized future electricity sector due to adaptability, stakeholder compatibility, and policy alignment. The study aids researchers and policymakers in selecting an appropriate modeling approach by considering the strengths and limitations of each modeling technique. Furthermore, it underscores the necessity of ongoing evaluation and refinement to meet the evolving needs of the energy sector effectively, especially with the development of a new generation of open-source non-proprietary models.**

***Index Terms*—Decarbonization, Energy system modeling, Net Zero Energy System, PyPSA, Sustainable energy transitions, Switch.**

I. INTRODUCTION

In recent years, there has been increasing recognition of the urgent need to decarbonize the energy sector in order to mitigate the impacts of climate change[1]. The combustion of fossil fuels, specifically coal, oil, and natural gas, is a significant source of greenhouse gas emissions, particularly in the context of power generation[2]. These emissions are responsible for human activity led global warming due to climate change [3].Decarbonizing the electricity sector is a critical step towards achieving net-zero emissions and addressing climate change. Energy system modeling tools play a crucial role in visualizing and developing decarbonization pathways for the electricity sector. These tools help policymakers and researchers to understand the complex interactions between various energy sources, technologies, and policies, and their potential impacts on greenhouse gas[4].These tools help to analyze and evaluate different strategies, technologies, and policies that can be implemented to reduce carbon emissions and transition towards a cleaner and more sustainable energy system[5].

The urgency to decarbonize the energy sector stems from the growing concerns about climate change and its detrimental impacts on planetary health and human wellbeing[6].The rapid growth of greenhouse gases, particularly carbon dioxide, in the atmosphere is leading to a significant increase in global temperatures. This, in turn, is causing sea levels to rise, extreme weather events to occur more frequently, and disruptions in various ecosystems.[7]. At the same time, our reliance on fossil fuels for energy production is not only contributing to climate change but also depleting finite resources and causing environmental degradation through pollution and extraction activities[8]. Different energy system modeling tools play a crucial role in developing decarbonization pathways for the electricity sector[9]. These tools allow researchers and policymakers to analyze the complex interactions between different energy sources, technologies, and policies to identify the most effective strategies for transitioning towards a low-carbon electricity system.

Furthermore, energy system models provide insights into the economic feasibility, technical feasibility, and environmental impact of various decarbonization options. By conducting a comparative analysis of six modeling approaches namely TIMES/MARKAL, PyPSA, EnergyRT, SWITCH, OSeMOSYS, and LEAP, this paper aims to provide a comprehensive understanding of the strengths, weaknesses, opportunities, and threats associated with each approach. This analysis will contribute to the field by providing insights into the suitability and applicability of different modeling approaches in different contexts, thus assisting researchers and policymakers in selecting the most appropriate modeling tool for their specific decarbonization goals.

II. LITERATURE REVIEW

The existing literature on energy system modeling approaches for decarbonizing the electricity sector has mainly focused on developing and applying various modeling tools such as TIMES/MARKAL, PyPSA, EnergyRT, SWITCH, OSeMOSYS, LEAP, and TIMES (see TABLE I). These studies have highlighted the significance of these modeling tools in evaluating different decarbonization pathways across diverse scenarios and policy interventions. Additionally, they have emphasized the challenges and opportunities associated with applying these modeling approaches to varying geographical, socio-economic, and technological contexts.
Furthermore, it has stressed the need for comprehensive comparative analyses to evaluate strengths and weaknesses among these tools. This can guide policymakers in selecting suitable approaches for their specific decarbonization objectives. In addition, researchers also identified gaps in current methodologies calling for further research to enhance the robustness of energy system modeling.
This paper aims to build upon this work by conducting a comparative analysis to contribute to energy system Decarbonization provide insights for policymakers.

TABLE I. SUMMARY OF REVIEWED LITERATURES

Ref.	Study Objective	Methodology	Finding	Limitation
[10]	Develop open-source framework in Python for power systems modeling.	Optimize power system energy flows, generation and storage asset sizes, economic dispatch using linear and quadratic programming.	Insights into strategic energy plans and CCS implementation.	Specific focus on Greek electricity sector.
[11]	Evaluate strategies for electricity decarbonization by 2050 in Portugal.	TIMES modelling framework to compare electricity decarbonization pathways for 2050.	Higher cost savings in electricity decarbonization pathways for Portugal in 2050.	Uncertainty associated with future technological advancements.
[12]	Propose pathways for reducing carbon emissions in the energy system.	Data analysis, scenario modelling, and stakeholder engagement.	Insights into sustainable energy transition pathways.	Potential uncertainties in projections and assumptions.
[13]	Develop global energy system model, GENeSYS-MOD, using OSeMOSYS.	Integrates energy sectors, technologies, and regions for global energy system analysis.	Development of the GENeSYS-MOD model for global energy system analysis.	Need for continuous refinement and validation of the model.
[14]	Explore low-carbon transformation pathway of the power sector in GBA using LEAP model.	Scenario analysis using LEAP model, evaluating power generation structures and energy consumption patterns.	Electricity demand peak after 2050, promoting BECCS and nuclear power.	Lack of detailed economic feasibility analysis.
[15]	Address challenges of integrating high levels of renewable energy into power systems.	Switch 2.0, incorporating advanced modeling techniques, data analytics, and scenario analysis.	Optimal strategies for integrating variable renewable energy sources.	Uncertainties in renewable energy resource availability and grid constraints.
[16]	Provide scenarios for zero-carbon electricity system in India by 2050.	Using energyRT to optimize deployment of renewable energy technologies.	Scenarios highlight coordinated planning and policy frameworks for renewable energy.	Conclusions based on assumptions and forecasts that may change over time

III. NET ZERO ENERGY SYSTEM MODELS

The analysis is structured around the evaluation of six prominent modeling tools: TIMES, MARKAL, PyPSA, EnergyRT, SWITCH, OSeMOSYS, and LEAP. Each modeling approach is assessed based on a set of criteria, including scalability, flexibility, data requirements, computational complexity, and capability to model specific technologies such as renewable energy integration, energy storage, and grid infrastructure.

Table II & Table III present a comprehensive comparison of significant energy system models, emphasizing their names, developers, availability, software, and essential references. These models are essential for comprehending power system operations, including renewable energy, and implementing decarbonization initiatives. The table assists academics, policymakers, and energy analysts in choosing the most suitable tool for their unique requirements in energy system modeling and policy analysis by providing a concise summary of their development sources, software requirements, and availability.

TABLE II. ENERGY SYSTEM MODEL DESCRIPTION

Model	Full Name	Developed by	Availability	Software	Ref
PyPSA	Python for Power System Analysis	FIAS - Tom Brown et al.	Open Source	Python	[10]
SWITCH	Solar, Wind, Transmission, Conventional generation and Hydroelectricity	Fripp, Johnston & Maluenda	Open Source	Python	[15]
EnergyRT	Energy Systems Modeling R-toolbox	Oleg Lugovoy, Vladimir Potashnikov	Open Source	R, GAMS	[17]
LEAP	Long-range Energy Alternatives Planning	Stockholm Environment Institute	Free for students. Free for country government, NGO or academics in developing countries. Commercial for Academic, non-consulting and consulting in OECD countries	Stand-alone	[18]
MARKAL	MARKet ALlocation model	IEA-ETSAP	Commercial, Free Demo Version	GAMS + Solver (VEDA)	[19]
TIMES	The Integrated MARKAL-EFOM System	IEA-ETSAP	Commercial, Free Demo Version	GAMS + Solver (VEDA)	[20],[21]
OSeMOSYS	The Open-Source Energy Modelling System	KTH - Howells et al.	Open Source	GNU Math Prog	[22]

TABLE III. ENERGY SYSTEM MODEL FEATURES

Model	History and Development	Key Features	Approach to Decarbonization
TIMES/MARKAL	Developed by ETSAP under IEA in early 2000s, combining technical and economic approaches.	Technology-rich optimization using linear programming, flexible with detailed sectoral breakdowns[20].	Generates scenarios without policy constraints, applies constraints like renewable energy shares.
SWITCH	Initially developed for California, now used in various regions globally.	Linear programming for least-cost energy systems, modular and customizable[15].	Optimizes system design to meet policy goals, high-resolution for detailed scenario analysis.
PyPSA	Developed by Karlsruhe Institute of Technology and TU Berlin for global energy transition.	Modular Python environment, supports renewable energy calculations and complex networks[10].	Enables detailed modeling of renewable energy integration, supports various policy constraints[23].
EnergyRT	R package for RES models, integrating with GAMS, GLPK, Python/Pyomo, and Julia/JuMP.	Handles data, defines RES models, supports multi-regional models and detailed technological definitions[17].	Supports decarbonization pathways through scenario analysis and optimization.
OSeMOSYS	Published in 2008, developed by a global community, available in multiple coding language[24].	Supports long-term planning, detailed power representations, accessible with extensive documentation[25].	Supports national and regional models with renewable energy and GHG constraints.
LEAP	Developed by Stockholm Environment Institute for energy policy analysis and climate change mitigation.	User-friendly, supports bottom-up, top-down, and hybrid modeling, flexible for scenario definition[26].	Models energy policies and impacts on GHG emissions, supports various decarbonization strategies.

IV. SWOT ANALYSIS FRAMEWORK

The SWOT analysis, which encompasses an evaluation of Strengths, Weaknesses, Opportunities, and Threats, is a strategic planning instrument that offers a systematic framework for assessing the internal and external aspects that impact a system. Through the utilization of this methodology, we systematically classified the attributes of each model into these four distinct dimensions which are presented in Table IV.

TABLE IV. SWOT ANALYSIS OF THE ENERGY SYSTEM MODELS

Model	**Strengths**	**Weaknesses**	**Opportunities**	**Threats**
PyPSA	Open-source, collaborative, transparent, flexible due to Python, detailed power system operations, integrates renewables	Steep learning curve for non-programmers, focus on power systems limits cross-sectoral analysis	Engage with stakeholders to improve usability, add modules/interfaces for non-experts	Variability in update quality, programming skills required
TIMES/MARKAL	Flexible, comprehensive, detailed sectoral breakdowns, includes policy constraints, robust for long-term analysis	Complexity can be a barrier, requires significant technical and economic expertise	Explore decarbonization scenarios, identify cost-effective pathways to net-zero, strategic planning	Reliance on detailed data, longer development times, higher costs
SWITCH	High-resolution, long-term planning, modular, easy customization, optimizes renewable energy transitions	Data-intensive, computationally demanding	Optimize system design for policy goals, detailed scenario analysis valuable for exploring decarbonization pathways	High-quality data and computational resource requirements, need for continuous updates
EnergyRT	Comprehensive tools for RES models in R, integrates with various programming languages, flexible	In development, ongoing changes to functions and methods, potential instability	Develop reproducible research, explore decarbonization pathways, minimize development time, improve transparency for collaborative projects	Developmental instability, frequent updates required, familiarity with R and other programming languages necessary
OSeMOSYS	Accessible, open-source, detailed power representations, multi-resource systems	Simplicity limits handling of highly complex scenarios and detailed technological representations	Capacity building, collaborative research, explore wide range of decarbonization scenarios, support policy development	Variability in update quality due to community contributions, limited applicability to highly detailed and complex energy systems
LEAP	User-friendly, accessible to non-experts, supports various modeling methodologies (bottom-up, top-down, hybrid), widely used for policy analysis	Flexibility and user-friendliness can reduce detail and precision in technical analyses	Scenario analysis for decarbonization strategies, support policy development, model impacts of energy policies on GHG emissions	Variability in results due to user-defined scenarios and assumptions, resource-intensive updates required for incorporating new policies and technologies

V. DISCUSSION

When comparing energy system models, several criteria can be considered. One important factor is the suitability for the intended application: different models may have strengths and weaknesses depending on the specific problem they are designed to address. For example, some models may be better suited for analyzing long-term energy transition scenarios, while others may be more suitable for evaluating short-term operational decisions[27] [28]. Another key consideration is the acceptability of the model inputs; energy system models rely on various data inputs, such as energy demand, renewable resource availability, and technology costs. It's essential to evaluate the acceptability and accuracy of these inputs to ensure that the model results are reliable and representative of real-world conditions[29].

This study undertook a comprehensive evaluation of multiple energy system models, specifically PyPSA, MARKAL, OSeMOSYS, LEAP, TIMES, and the Switch Power System Planning Model. The assessment consisted of three fundamental criteria, namely suitability, acceptability, and feasibility.

The concept of suitability pertains to the practicality of each model across multiple dimensions. Significantly, PyPSA, MARKAL, and the Switch Power System Planning Model have emerged as leading contenders, demonstrating their adaptability in various domains such as technical, economic, environmental, and resource-related sectors. In contrast to the OSeMOSYS model, it is worth noting that although the model has its strengths, it has also revealed deficiencies in some resource-related domains.

The term "acceptability" is used to describe how well each model resonates with various groups of people and how well it links to applicable policies. It is worth noting that PyPSA, MARKAL, and the Switch Power System Planning Model received favorable evaluations, indicating their compatibility with many stakeholders, as well as their alignment with policy, social, and legal factors. On the other hand, models like as LEAP and TIMES have demonstrated shortcomings in specific policy and social domains, highlighting the importance of customizing models to suit the complexities of many sociopolitical environments.

TABLE V. SWOT ANALYSIS OF THE ENERGY SYSTEM MODELS

Test Criteria	**PyPSA**	**LEAP**	**MARKAL**	**OSeMOSYS**	**TIMES**	**SWITCH**	**EnergyRT**
Suitability	High	Low	High	Moderate	High	High	High
- Scalability	✓	X	✓	✓	✓	✓	✓
- Flexibility	✓	X	✓	✓	✓	✓	✓
- Transparency	✓	X	✓	✓	✓	✓	✓
- Data Availability	✓	✓	✓	X	✓	✓	✓
- Model Complexity	✓	✓	✓	X	✓	✓	✓
Acceptability	High	High	High	Moderate	High	High	High
- Stakeholder	✓	✓	✓	✓	✓	✓	✓
- Policy	✓	✓	✓	✓	✓	✓	✓
- Social	✓	✓	✓	✓	✓	✓	✓
- Legal	✓	X	X	X	✓	✓	✓
Feasibility	High	Moderate	High	Low	High	High	High
- Technical	✓	✓	✓	X	✓	✓	✓
- Economic	✓	✓	✓	✓	✓	✓	✓
- Environmental	✓	✓	✓	✓	✓	✓	✓
- Resource	✓	X	X	X	✓	✓	✓

The assessment of feasibility, which is an essential determinant, evaluates the capacity of each model to effectively fulfill the stringent requirements of energy system analysis. The adaptability, scalability, and data transparency of PyPSA, MARKAL, and the Switch Power System Planning Model were identified as key factors that demonstrate their superiority according to this criterion. However, the scalability and data accessibility of models such as LEAP and OSeMOSYS have been found to pose issues, potentially restricting their applicability in specific contexts.

In conclusion, this study evaluated six energy system models (PyPSA, MARKAL, OSeMOSYS, LEAP, TIMES, and Switch) for applicability, acceptability, and feasibility. PyPSA, MARKAL, and Switch emerged as leading candidates, exhibiting strength in technological, economic, environmental, and resource areas. They also demonstrated stakeholder compatibility, as well as policy and societal alignment.

While open-source approaches like as PyPSA, OSeMOSYS, and LEAP provide transparency and customization, their scale and data accessibility may be limited. Each paradigm has merits and limitations, necessitating careful consideration based on unique research requirements.

The study focused on the strengths of various models:

- TIMES/MARKAL: Proficient in cost optimisation and policy integration.
- SWITCH: Great for long-term planning and extensive analysis of renewables, but resource intensive.
- PyPSA is extremely adaptable and scalable but demands sophisticated programming abilities.

- EnergyRT: Comprehensive data and modelling tools, but subject to volatility owing to ongoing development.
- OSeMOSYS is user-friendly and has considerable community support, however it may be limited for more sophisticated cases.
- LEAP: Suitable for policy analysis and climate change but may lack precision in highly technical studies.

PyPSA and SWITCH stand out due to their adaptability and connection with policy aims. PyPSA's modular architecture and interoperability with other tools make it extremely versatile. SWITCH excels at handling high-resolution data and conducting scenario analyses for long-term renewable transitions. Both models are extremely useful for investigating decarbonization paths and policy implications in the transition to net-zero energy systems.

VI. LIMITATIONS

While the SWOT analysis provided valuable insights into the attributes and potential of each energy model, it's important to acknowledge some limitations of this study. One limitation is the reliance on existing descriptive information to derive primary data for the analysis. This reliance may have introduced biases or overlooked certain attributes not explicitly mentioned in the sources[30].

Furthermore, the study's focus on the identified strengths, weaknesses, opportunities, and threats of each model may have overshadowed other aspects that could also be important for decision-making, such as the scalability, interoperability, and the modeling of specific technologies or energy carriers[31].

Additionally, the rapidly evolving nature of energy system models poses a challenge in terms of incorporating the latest developments or revisions to existing models. Newer models or advancements in existing ones may not have been included in this analysis, potentially impacting the comprehensiveness of the assessment[32].

Finally, while the SWOT analysis provided a structured approach to evaluating the models, it's essential to recognize that the suitability and effectiveness of a model also depend on the specific problem or context in which it is applied. Therefore, the findings of this study should be considered within the context of the specific energy policy analysis or planning objectives for which the models are intended

VII. CONCLUSION

The comparison and analysis of various energy modelling techniques highlight the range of tools available for energy planning and policy development. Each model has its own strengths and weaknesses, emphasizing the need for continuous assessment and improvement as energy systems evolve. This will advance the development of effective energy policies and planning. Researchers will focus on developing energy modeling to account for the instability of renewable energy sources, real-time optimization techniques, and advanced data analytics. Emphasis will also be placed on handling interdependencies between domains such as buildings, industry, and transportation to support integrated energy planning strategies[33].

Furthermore, constantly updating energy models is crucial for making informed decisions and adapting to the evolving complexity of energy transitions. This work paves the way for advancements in energy policy analysis and planning by highlighting state-of-the-art modeling techniques[34].

Reaching carbon neutrality by mid-century requires a comprehensive scientific strategy, with suitable energy system models playing a key role[35]. According to the literature, models such as TIMES/MARKAL, SWITCH, PyPSA, EnergyRT, OSeMOSYS, and LEAP offer unique advantages for modeling and optimizing various aspects of energy systems.

Informed selection of models is crucial for researchers and policymakers to utilize a range of modeling tools like PyPSA and SWITCH. These models provide modularity, scenario analysis capabilities, high-resolution data processing, flexibility, alignment with policy objectives, and the ability to replicate complex energy systems. This informed model selection is essential for examining approaches to decarbonization by integrating renewable energy sources and assessing technological and legislative measures to effectively combat climate change.

VIII. ACKNOWLEDGEMENT

The authors acknowledge the partial scholarship support from the SMARTS Centre of AIT under the projects: (1) MCET project funded by EDF, USA and (2) EDIT-AIT project, funded by Energy Demand changes Induced by Technological and Social innovations (EDITS) project, which is part of the initiative coordinated by the Research Institute of Innovative Technology for the Earth (RITE) and International Institute for Applied Systems Analysis (IIASA) (and funded by Ministry of Economy, Trade, and Industry (METI), Japan).

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