

MODELLING TOOLS FOR ENGINEERING-LEVEL PLANNING OF ENERGY COMMUNITIES: A REVIEW

I. Antoskova, A. Gavrilovs, A. Mutule*

Energy Research Centre,
Institute of Electronics and Computer Science
14 Dzerbenes St., Riga, LV-1006, LATVIA
*e-pasts: anna.mutule@edi.lv

Energy communities (EnCs) are emerging as a key mechanism for integrating distributed renewable energy resources and enhancing demand-side flexibility. Selecting appropriate modelling tools is critical for engineering-level planning of EnCs, including technology sizing and operational strategies. The paper combines a review of recent studies with a comparative analysis of selected modelling tools, outlining their capabilities, strengths, and limitations, with a focus on technical capabilities and usability. The findings reveal a growing availability of comprehensive open-source modelling tools, which are well-suited for advanced engineering-level planning of EnCs but require programming skills and expertise in energy system modelling. In contrast, commercial tools offer higher usability and are better suited for feasibility studies. Future development is expected to enhance their representation of demand-side flexibility.

Keywords: *Demand-side flexibility, distributed energy resources, energy community, energy system modelling, literature review, modelling tools, planning.*

1. INTRODUCTION

The European Union (EU) is accelerating its transition towards a decarbonised energy system, characterised by the increasing deployment of distributed renewable energy resources. Traditionally, such resources have been owned and operated individually by end users. However, this

approach faces high capital costs and spatial limitations. Moreover, the variability of renewable generation poses additional challenges for power system operation. In this context, the development of Energy Communities (EnCs) represents an important pathway to facilitate collective investment

in distributed renewable generation and potentially enhance demand-side flexibility [1], [2], increasing local self-consumption and contributing to improved economic efficiency of electricity supply.

To comprehensively evaluate the benefits of EnCs, appropriate analytical tools are required. Wide adoption of EnCs requires energy system modelling tools that go beyond approximate or conceptual assessments and are capable of supporting engineering-level planning decisions, including technology sizing, evaluation of operation strategies and interaction with the wider energy system. In this context, Bukovszki et al. highlight that design support is a key trigger for initiating EnCs [3]. Similarly, Vecchi et al. [4] emphasise that design and optimisation of effective EnCs configurations requires modelling tools capable of integrating techno-economic, environmental, and spatial evaluations.

A large and rapidly evolving number of energy system modelling tools exists, accompanied by a growing body of research. Review studies provide valuable insights in software tools and model development, but differ substantially in scope, methodological approach, and evaluation criteria. This paper does not aim to repeat or replace existing reviews of modelling

tools. Instead, it addresses the need for a structured synthesis of the review literature and its translation into an engineering-oriented tool assessment. To do so, this study addresses three questions:

- What trends and approaches emerge from existing review studies?
- What criteria should be considered when selecting modelling tools for the engineering-level planning of EnCs?
- Which existing modelling tools are best suited to support engineering-level planning of EnCs?

The main objective of this study is to focus on the selection and review of modelling tools specifically for the engineering decisions in EnCs. By doing so, it supports researchers and practitioners in choosing appropriate tools and making informed decisions for detailed planning, optimisation, and design.

The remaining part of this paper is organised as follows: Section 2 outlines the methodology, Section 3 presents a structured literature meta-review, Section 4 addresses the selection and assessment of modelling tools, and Section 5 concludes with key findings and implications for future work.

2. METHODOLOGY

The study consists of two interconnected research streams: a systematic literature review and an analysis of selected modelling tools. The literature review uncovers emerging trends in energy system modelling and underpins subsequent tool analyses. We focus on tool usability and functionality assessment rather than on mathematical approaches employed. Consequently, papers describing a single tool or

modelling algorithms without constituting a complete tool are excluded.

We limit our search to peer-reviewed publications in English published from 2020 onwards. Relevant papers are retrieved from Scopus using search string: TITLE-ABS-KEY (energy system modelling tools) AND PUBYEAR > 2019 AND PUBYEAR < 2027 AND PUBYEAR > 2019 AND PUBYEAR < 2027 AND (LIMIT-TO (LAN-

GUAGE, “English”)). Then, we refine the selection to papers reviewing and assessing energy system modelling tools. Based on full text screening, we identify studies aligned with the scope of the review, i.e., those mentioning specific tools and including at least five of them. In total, 21 publications are included in the final analysis from 9,425 identified through the first search.

Reviews on energy modelling tools vary considerably in their objectives, methodological approaches, and thematic focus. Nevertheless, we note several common trends. Some reviews explore energy system modelling from a broader perspective, while others focus on more specific questions. Many studies attempt to evaluate tools by comparing their characteristics or by applying assessment criteria or calculating indices. Following this logic, we classify the reviewed studies into four general categories: scoping reviews, thematic reviews, screening and selection, and quantitative evaluations. This help us better present the results of the literature review, analyse emerging trends, as well as align the subsequent tool analysis.

We shape four categories of literature reviews based on their primary method and purpose:

- **Scoping Review** covers a broad range of tools and aim at describing the overall land-

scape and identify common challenges;

- **Thematic Review** focuses on a specific topic or concept and aim at interpreting how that topic is addressed by the tools;
- **Screening & Selection** applies clear inclusion/exclusion criteria to select tools and aim at providing a narrative comparison of selected aspects rather than calculating scores;
- **Quantitative Evaluation** uses quantitative indicators (KPIs, indices, weighted measures) to analyse tools with specific application or idea in mind.

Some reviews employ a combination of approaches. Nevertheless, based on the main research questions and conclusions, we assign one primary category for all of the reviewed studies.

The second stream of our study comprises the selection of tools for a more detailed overview. We identify prominent tools that are frequently mentioned in the literature and apply additional criteria regarding their relevance for engineer-level studies of EnCs. These are described in Subsection 4.1. Next, we conduct a qualitative assessment of functionalities and usability of the selected tools.

Figure 1 provides a visual representation of the steps in each work stream and the interconnections between them.

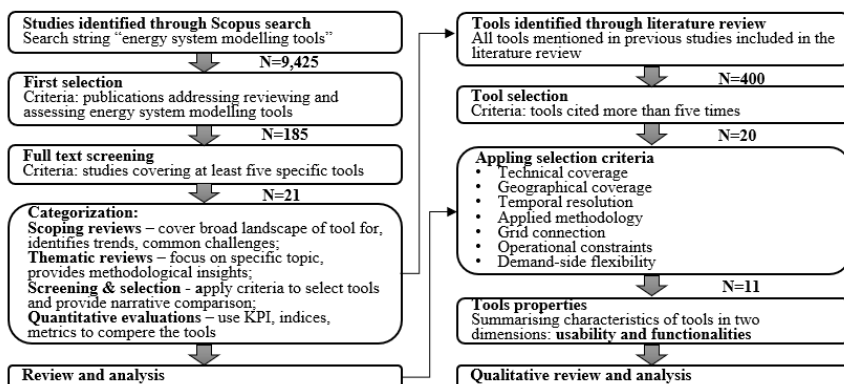


Fig. 1. The review process.

3. LITERATURE REVIEW

There is a wide body of scientific literature on energy system modelling tools. However, modern energy system planning and operation involve such a diverse range of interdisciplinary, multi-technology challenges, and specific applications that researchers continue to search for optimal solutions. To support our own study, we conducted a meta-review, i.e., a review of existing review studies, to identify rel-

evant tools and methodological approaches. In total, we identified 21 publications for inclusion in our analysis. Each publication was classified into one of four categories (scoping review, thematic review, screening & selection, or quantitative evaluation). The results show that the review landscape is relatively well balanced across these categories. Table 1 presents an overview of the selected publications.

Table 1. Selected Publications

Authors, year	Review type	Scope	Geographical scale
Prina et al. [5] 2020	Scoping review	Review of bottom-up energy system models through the challenges matrix around the concept of resolution	Different
Cuesta et al. [6], 2020	Thematic review	Evaluation of tools for hybrid renewable systems modelling focusing on a social perspective	Community
Fattahi et al. [7], 2020	Quantitative evaluation	Assessment of tools for national scale energy system modelling using multi-criteria analysis	National
Chang et al. [8], 2021	Scoping review	Review of the features and applicability of energy system modelling tools by gathering inputs from tool development teams and key users	Different
Yazdanie & Orehounig [9], 2021	Scoping review	Identification of gaps and solutions in urban energy system modelling	From project scale to city
Kazmi et al. [10], 2021	Scoping review	Review of open-source datasets and models for EnCs	Community
Heider et al. [11], 2021	Thematic review	Analysis of the representation of flexibility options in open-source modelling tools	Different
Martínez-Gordón et al. [12], 2021	Thematic review	Analysis of energy system models in terms of their level of spatial resolution and application of the findings to the North Sea region	National
Klemm & Vennemann [13], 2021	Screening and selection	Evaluation of energy modelling tools for multi-energy systems of mixed-use districts	District
Martins et al. [14], 2021	Quantitative evaluation	Assessment of modelling tools for energy efficiency in smart cities	City
Horak et al. [15], 2022	Quantitative evaluation	Assessment and comparison of urban energy modelling tools for the formulation of sustainable decarbonisation strategies	From building to municipal
Laveneziana et al. [16], 2023	Quantitative evaluation	Evaluation of the capability of energy system modelling tools for development of investment strategies at a company level	Company
Liu et al. [17], 2024	Scoping review	Reviews the landscape of simulation software for energy systems	Different

Authors, year	Review type	Scope	Geographical scale
Höffner & Glombik [18], 2024	Scoping review	Review of modelling tools for urban energy systems	City and district
Xu et al. [19], 2024	Screening and selection	Assessment and comparison of district energy system modelling tools	District
Vecchi et al. [4], 2024	Quantitative evaluation	Assessment of modelling tools for renewable EnCs by analysing capabilities in four thematic areas: technical energy-related, socio-economic, environmental, and spatial	Buildings and districts
Majidi et al. [20], 2025	Scoping review	Evaluation of energy modelling tools for smart energy system modelling	Different
Mohseni-Gharyehsafa et al. [21], 2025	Thematic review	Analysis of the functionality of software tools for energy management or flexibility enhancement in buildings	Buildings and districts
Gaugl et al. [22], 2025	Thematic review	Comparison of large-scale energy system modelling frameworks with a focus on infrastructure development planning	European
Silinto et al. [23], 2025	Screening and selection	Analysis of availability, capabilities, data requirements of tools for hybrid renewable energy systems for rural electrification in developing countries	Local
Samarasinghe et al. [24], 2025	Screening and selection	Review of capabilities modelling criteria and practical usability of large-scale energy system modelling tools	National

3.1 Landscape and Challenges of Energy System Modelling

We classify seven papers as scoping reviews. Some of these cover energy systems modelling in broad terms. For example, Liu et al. [17] review the landscape of energy simulation software in terms of capabilities, and Majidi et al. [20] explore energy modelling requirements and tools for future smart energy systems considering temporal resolution, carriers, sectors, and academic prevalence. Prina et al. [5] adopt a more targeted methodology and discuss challenges across four main fields: resolution in time, space, techno-economic detail and sector-coupling. At the same time, Chang et al. [8] analyse general trends in energy modelling based on surveys of developers and key users. Other scoping studies focus on more specific domains. For instance, Kazmi et al. [10] review datasets and tools for EnCs, and Yazdanie and Orehounig [9] and Höffner and Glombik [18]

identify gaps in urban energy system modelling tools.

The literature highlights that the evolution of the energy system and the rapid advancement of technology create a necessity for a large amount of data, which is not always available or sufficiently detailed. Chang et al. [8] conclude that representing high-resolution energy demand remains challenging across all sectors, making robust demand modelling more important than ever. Yazdanie and Orehounig [9] identify data gaps in availability and accessibility, quality and consistency, granularity, and overall data management. They distinguish two main directions for addressing these gaps: technical solutions, such as data platforms, and institutional measures, such as centralised support structures. Höffner and Glombik [18] stress the pivotal role of qualitative data input and propose that

the availability and accessibility of public datasets could be improved through the development of web interfaces or application programming interfaces (APIs). Kazmi et al. [10], focusing on both datasets and tools, point out that limited data on electric vehicles and building temperatures limit the estimation of demand flexibility potential in EnCs.

The literature indicates the trade-off between model detail and computational complexity. Yazdanie and Orehounig [9] note that large-scale models tend to sacrifice temporal and spatial granularity to maintain computational feasibility, while models designed for smaller scales or shorter time horizons can incorporate a higher level of detail. Prina et al. [5] emphasise the difficulty of achieving high resolution in time, space, techno-economic detail, and sector coupling simultaneously. Yazdanie and Orehounig [9] and Höffner and Glombik [18] note that many urban energy system modelling tools do not effectively utilise Geographic Information Systems (GIS) and the associated spatial data. Chang et al. [8] conclude that it is not possible to develop a single tool that can meet all specific modelling needs in energy systems.

Furthermore, studies draw attention to openness of the modelling tools. Prina et al. [5] discuss transparency of input and output data, documentation and software as one of key challenges in energy system modelling.

3.2 Modelling Dimensions

Thematic review studies examine particular aspects of energy system modelling tools in greater depth. Martínez-Gordón et al. [12] focus on spatial resolution, while Gaugl et al. [22] expend on resolution across technical, temporal, and spatial dimensions. Heider et al. [11] and Mohseni-Gharyehsafa et al. [21] provide a deeper examination of flexibility representation. Meanwhile,

Yazdanie and Orehounig [9] emphasise that understanding how a modelling tool is built and the mathematical logic it relies on is crucial for ensuring reproducibility and enabling thoughtful implementation of modelling results. Chang et al. [8] argue that open code enables the “out-of-the-box” usability of energy modelling tools and supports active stakeholder engagement. However, open tools still often require running additional commercial solvers, which can limit their actual accessibility [8]. In addition, tools built on open code usually require coding skills [8], [10]. However, Höffner and Glombik [18] conclude that there is a subset of open-source energy system modelling tools that offer user-friendly interfaces.

Finally, studies reveal the growing need for integrating social aspects in energy system modelling tools. Prina et al. [5] highlight that incorporating behavioural economics is important as individual preferences influence adoption of specific technologies and the potential for demand response. This is particularly critical in urban energy system modelling as discussed by Höffner and Glombik [18]. Kazmi et al. [10] also highlight the need to incorporate behavioural data when analysing EnCs.

Despite differences in scope, these studies reveal several cross-cutting issues in energy system modelling, which also emerge in the following sections.

Cuesta et al. [6] highlight the role of social aspects.

Martínez-Gordón et al. [12] analyse energy system modelling tools applied at least at national scale and assess their level of spatial resolution. The authors conclude that nowadays large-scale models allow incorporating the regional-level detail, but further increase in spatial resolution may

compromise computational feasibility. The authors propose that the advancement of clustering methods offers a way to mitigate these difficulties. These considerations are important when applying large-scale tools to long-term analyses of EnCs.

Gaugl et al. [22] provide an overview and comparison of European large-scale modelling tools from the perspective of infrastructure development. Their approach is similar to the multi-dimensional perspective of resolution used by Prina et al. [5]. The authors assess tools across three key dimensions: technological resolution (flexibility options, sector coupling, low-voltage grid effects, and stochasticity), temporal resolution (methods of time representation, planning horizons, foresight approaches, and temporal structures), and spatial resolution (the level of spatial detail applied in case studies). The authors conclude that common trends in the development of energy system modelling tools align with the evolving requirements of energy systems; however, no single tool can cover all aspects at a comparable level of quality.

Heider et al. [11] evaluate how various open-source energy system modelling tools cover five categories of flexibility options: supply side, demand side, storage, network, and sector coupling. The authors find that sector coupling is the most widely represented option, while network is the least covered. In general, many models represent specific areas better than others. Regarding

demand flexibility, which is particularly relevant for EnCs, the study finds it has the third-highest representation and is enabled in most tools. In line with these findings, Gaugl et al. [22] note a trend toward more comprehensive approaches in large-scale models, recognising that the flexibility potential often resides in lower-voltage networks.

Mohseni-Gharyehsafa et al. [21] provide a review of software tools designed for energy management in buildings and their ability to manage flexibility. The authors highlight that energy management tools at both building and district levels must be scalable to process large volumes of data. They also emphasise that standardisation and interoperability are essential to enable the necessary data exchange for flexibility services in real-life applications.

Cuesta et al. [6] assess the potential of hybrid renewable energy modelling tools to include social indicators. The authors conclude that a majority of popular tools lack mechanisms for evaluating social impacts beyond green-house gas (GHG) reductions, such as job creation or social acceptance. They identify this as an important area for further development by tool developers.

As seen from the thematic reviews above, these studies continue to deepen and broaden the same core topics. Consequently, there is a common understanding of the key challenges in the literature.

3.3 Application Contexts and Selection Criteria

Most selection and screening reviews and quantitative evaluations concentrate on tools for local applications ([4], [13]–[16], [19], [23]), except Samarasinghe et al. [24] and Fattahi et al. [7], who analyse energy system modelling tools at the national level. Consequently, most of reviews apply geographical scope as a core criterion for iden-

tifying suitable tools. Representing multiple energy sectors is another common selection requirement ([13], [23], [19], [7]), while other authors discuss sectoral coverage as a relevant tool characteristic. A similar pattern is visible for temporal resolution: some studies include it as initial selection criteria ([13], [19]), whereas others address it in

analysis. Methodological aspects, particularly the use of optimisation, are also frequently used as tool selection criteria ([13], [16], [19]). Finally, specific selection criteria are defined in line with review objectives.

As discussed earlier, the reviewed studies broadly agree on the importance of tool availability and usability. Klemm & Vennemann [13] identify closed modelling tools, limited data transparency, and the need for coding skills as major challenges for modelling multi-energy systems in mixed-use districts. Laveneziana et al. [16] similarly note that most tools suitable for company level planning are not freely available. Silinto et al. [23] expand this perspective by examining the availability of tools for hybrid renewable energy systems for rural electrification in developing countries, assessing user friendliness, required skill level, licence type and cost, and quality of documentation. In case of EnC municipalities, developers and other relevant stakeholders often have limited financial and technical resources. These findings highlight the need to balance affordable cost of modelling tools with manageable skill requirements.

4. TOOL SCREENING AND SELECTION

Energy system modelling tools are rapidly evolving: new tools continue to appear, and existing ones are regularly enhanced with new functionalities. The list compiled from the publications in our literature review contains more than 400 distinct tool

There is a consensus in the literature that no currently available tool can cover all types of tasks required in the integrated energy system analysis. Fattahi et al. [7] note that the general solution is either to expand an existing tool by adding new functionalities or to link different tools. Expanding existing tools, however, presents the challenge of maintaining mathematical transparency and computational feasibility. Vecchi et al. [4] similarly observe that, at present, there is a lack of comprehensive tools for EnCs and point out that complementary implementation of multiple tools is the most viable way forward. Samarasinghe et al. [24] explain that engineering tasks require tools with detailed geographical coverage and high temporal resolution, whereas tools with lower spatial and temporal resolution are better suited for broader socio-economic modelling. Horak et al. [15] conclude that further research is needed on effective approaches for coupling tools to support all stages of a project.

Taken together, these insights show that tool selection inherently depends on context and is shaped by trade-offs between functionalities, resolution, and usability.

names. To focus on the most prominent tools, we select those referred more than five times, resulting in a set of 20 tools. Next, we introduce the features required to support the planning stage of EnCs and define further filtering criteria.

4.1 Requirements for Modelling of EnCs

The essence of EnCs, i.e., collective, usually place-based actions centred on renewable energy generation with primarily environmental objectives, implies that

modelling tools must be capable of representing multiple renewable technologies. The geographical scope should allow modelling at the community level. Comprehen-

sive sectoral coverage is essential, including electricity and heat at minimum. This aligns with the findings of our literature review, which shows that most analyses of local-scale modelling apply similar criteria, particularly regarding geographical scope and sectoral coverage.

Kachirayil et al. [25] demonstrate that both temporal representation and the level of operational detail significantly influence planning outcomes in energy systems dominated by wind and solar power. Modelling tools for EnCs must operate at a temporal resolution of at least one hour to capture variable renewable generation and heterogeneous demand profiles, including residential, commercial, and industrial loads, thereby enabling an accurate representation of operational constraints [16]. While such temporal resolution is a necessary prerequisite for representing operational constraints, it is not sufficient on its own.

In this context, including an operational layer in planning tools allows the simulation of system dispatch, demand-side management, and energy exchanges over time. This enables the assessment of the technical feasibility, economic performance, and flexibility of EnCs ensuring that design is efficient, and investment decisions are robust for real-world grid-connected contexts.

Gjorgievski et al. [26] conclude that EnC design can rely on optimisation techniques or simulating different scenarios. Consequently, relevant modelling tools must provide an optimisation-based methodology, preferably multi-objective, to balance cost, self-consumption, emissions, and other objectives. Scenario analysis capabilities are critical for evaluating alternative strategies under varying market and policy conditions.

Emerging literature emphasises the potential of EnCs to provide demand-side

flexibility [27], [28], thereby supporting the grid in cost-efficient integration of large shares of renewable energy while also improving economic benefits for their members. Considering flexibility in EnC design requires modelling tools capable of integrating demand-side management strategies and different storage technologies [16], as well as sector coupling [29].

Finally, transparent documentation and manuals are highly desirable to ensure integration with broader planning frameworks.

Based on the above discussion, we use the criteria listed below to filter the most popular tools identified in the literature review.

- **Technical coverage:** Tools must incorporate renewable generation and storage technologies and support modelling of at least the electricity and heat sectors.
- **Geographical coverage:** Tools must support modelling at the local or community level.
- **Temporal resolution:** Modelling tools for EnCs require at least hourly resolution to capture variability in generation and demand.
- **Applied methodology:** Tools must support optimisation and related analytical methods to assess technical and economic aspects of EnCs. Inclusion of environmental aspects is recommended, while social aspects, such as user behaviour or engagement, may be considered but are not the primary focus of this study.
- **Grid connection:** Tools must support modelling of grid-connected EnCs, allowing electricity exchange with the wider power system. Tools designed solely for stand-alone or isolated microgrids are not considered suitable for this study.

- **Operational constraints:** Tools should include an operational layer (dispatch, unit commitment, and balancing) to simulate system behaviour over time, support design of control strategies, and inform investment decisions. The operational layer is considered here as part of planning simulations and does not imply real-time control.
- **Demand-side flexibility:** Tools should support demand-side flexibility, allowing the simulation of adjustable energy consumption to match system condi-

tions (e.g., load shifting, peak shaving, or flexible scheduling of appliances).

Many energy modelling tools were originally developed for specific applications, such as off-grid microgrids in HOMER, and have since been adapted to support broader planning tasks. Selecting the most appropriate tool remains a challenge, particularly when planning EnCs that integrate storage and demand flexibility [4]. Based on criteria outlined above, the following subsection presents an overview of the most relevant modelling tools.

4.2 Basic Information of the Selected Tools

Information from software vendor documentation and scientific publications was used to select the tools according to the criteria defined above. As a result, 11 modelling tools suitable for the planning and design of EnCs were identified for further analysis.

A brief description of the selected modelling tools is provided below.

- **DER-CAM** (the Distributed Energy Resources Customer Adoption Model) is a mixed-integer optimisation tool designed to support DER investment and planning decisions in a microgrid, typically by minimising total annual costs or CO₂ emissions. It is developed in the general algebraic modelling system (GAMS) and has been continuously updated by the Lawrence Berkeley National Laboratory since 2000. DER-CAM can determine the optimal mix and capacity of DERs, as well as the optimal dispatch of these resources, for a microgrid under different settings [30].
- **Calliope** is a free open-source framework for developing energy system models. It is designed to support analysis across a wide range of spatial and

temporal scales (from individual urban districts to entire countries or continents) using a scale-independent mathematical structure. There is a wide community of users around this tool. Calliope does not include a graphical user interface, and effective use of the tool requires basic programming skills. It offers both a command-line interface and a Python API, which makes it accessible to users with different levels of programming experience [31].

- **Oemof** (Open Energy Modelling Framework) is a suite of Python-based libraries developed as open-source tools modelling of renewable energy and integrated systems [32]. The community-driven nature of the oemof enables active user participation in development and promotes open science principles [33]. Majidi et al. [20] describe that originally launched as a single library to simplify the modelling of power and heat systems, it has since expanded into a modular structure with distinct packages, each designed to handle specific aspects of the energy system modelling workflow.
- **PyPSA** (Python for Power System

Analysis) is an open-source Python framework designed for the optimisation and simulation of modern power and energy systems. It supports a wide range of features, including conventional generators with unit commitment, variable renewable sources (such as wind and solar, hydroelectric generation, and inter-temporal storage), sector coupling, elastic demand modelling, and linearized power flow with loss approximations for both DC and AC networks, capacity expansion planning, and sector-coupling models [34].

- **EnergyPLAN** is a tool created by researchers from Aalborg University to support national energy planning with a particular emphasis on deploying RES. It simulates the operation of energy systems on an hourly basis, including the electricity, heating, cooling, industry, and transport sectors. The model focuses on the analysis of different regulations and market strategies [35], [36].
- **HOMER** (Hybrid Optimisation of Multiple Electric Renewables) is a commercial tool developed by the National Renewable Energy Laboratory (NREL). It can simulate and optimise stand-alone and grid-connected local energy systems consisting of PV, wind turbines, energy storage, etc. HOMER evaluates investment and operational expenses, along with techno-economic parameters and emission limitations. The tool accepts user inputs such as electrical and thermal load profiles (with resolutions as fine as one minute), technology specifications and efficiencies, operation and maintenance costs, emission constraints, and sensitivity variables. It generates outputs that include system optimisation and sensitivity analyses covering energy generation, fuel usage, emissions, and cost

metrics, presented through graphs and comprehensive data reports [37], [38].

- **urbs** is an open-source linear programming model for optimising multi-commodity energy systems, focusing on sizing, development, and utilisation [39]. It minimises system costs while meeting time-series demand for electricity, heat, or other commodities. Operating on configurable hourly time steps, urbs supports intertemporal optimisation and rapid scenario development. Built on Python, it remains lightweight yet extensible, with integrated reporting and plotting functions for streamlined analysis.
- **PLEXOS** is a powerful simulation and optimisation platform widely used for energy market analysis and system planning. Its capabilities extend beyond traditional grid modelling, making it relevant for advanced EnC applications. PLEXOS supports long-term planning, medium-term scheduling, and short-term operational simulations, enabling comprehensive lifecycle analysis for EnCs [40]. However, its complexity, cost and market-oriented focus mean that it is best suited for advanced projects.
- **EnergyPRO** is a commercial tool designed to support the economic evaluation of energy sector investment options by combining detailed simulations of technical system performance with assessments of economic impacts influenced by market dynamics, taxation, subsidies and other factors. It allows modelling participation in balancing and ancillary services, as well as sector coupling [41], [42].
- **iHOGA** (Hybrid Optimisation by Genetic Algorithms) is a robust, open-source software developed by the University of Zaragoza for simulating and optimising hybrid renewable stand-alone and grid-connected energy sys-

tems. It supports evaluating Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and Net Present Value (NPV), along with additional indicators such as the Levelized Cost of Hydrogen (LCOH), internal rate of return (IRR), and payback period. It is a powerful and flexible tool for researchers and engineers working on hybrid renewable energy systems, especially where detailed component modelling and cost optimisation are critical. [43]

- **Ficus** is an open-source Python-based

optimisation framework for energy systems, designed to model and optimise multi-carrier energy flows at building or district scale [44]. It uses linear programming to minimise costs while meeting energy demands for electricity, heat, and other carriers. Built on Pyomo and leveraging pandas for data handling, Ficus supports hourly or custom time resolutions, scenario analysis and includes integrated reporting and visualisation tools for rapid evaluation of system configurations.

4.3 Technical Capabilities and Usability of the Selected Modelling Tools for EnCs

The subsection compares modelling tools used for the planning and design of EnCs along two dimensions: technical capabilities and usability. The first dimension evolves directly from the selection criteria outlined above.

Table 2 summarises the key technical characteristics of modelling tools suitable for design of EnCs.

- **Technical coverage and networks** specify the types of renewable generation and storage technologies that the tool can represent and supported modelling energy sectors.
- **Geographical coverage** indicates the spatial scale supported, from building or microgrid to local, community, or regional levels.
- **Temporal resolution** indicates the minimum time step available for modelling variable generation and demand.
- **Planning horizon** corresponds to the period over which the tool can perform simulations or optimisation analyses, capturing both short-term and long-term planning needs.

- **Cost functions** reflects the types of system performance criteria that the tool can evaluate. These typically include economic costs, environmental impacts, and, where supported, energy efficiency or social aspects.
- **Operational layer** indicates a simplified representation of system operation included in the modelling.
- **Demand-side flexibility** indicates how adjustable energy consumption is represented in the planning model to evaluate community-scale system performance.

The second dimension, usability, considers practical aspects such as accessibility, availability of support, and overall ease of use. While technical capabilities determine the accuracy and comprehensiveness of the modelling, usability is critical for real-world application, enabling researchers, planners, and stakeholders to effectively implement the tools without excessive effort or specialised expertise.

Table 2. Technical Capabilities of the Selected Tools

Tool	Technical coverage and networks	Geo-graphical coverage	Cost function	Time resolution	Planning horizon	Operational layer	Demand-side flexibility
Calliope	Electricity (renewables, storage), heating, fossil fuels, hydrogen	User defined	Economic	User defined	User defined	Simulation of operational scenarios under predefined system configurations	Demand response
DER-CAM	Electricity (renewables, storage), heating, cooling, fossil fuels	Buildings/microgrid	Economic, environmental	15 min/30 min/ 1 h	Up to 20 years	Dispatch optimisation under operational constraints	Demand response, load shifting
Energy-PLAN	Electricity (renewables, storage), heating, fossil fuels	Local to regional	Economic, environmental, energy efficiency, social	1 h	1 year	Operational optimisation on user-defined inputs	Load shifting, operational optimisation
Energy-PRO	Electricity (renewables, storage), heating, fossil fuels	Local to regional	Economic	10 min	Multi-year	Operational dispatch optimisation with start-up/shutdown constraints and priority dispatch	Load shifting (limited demand response)
Ficus	Electricity (renewables, storage), heating, fossil fuels, hydrogen	Local to regional	Economic	User defined	User defined	Dispatch optimisation under operational constraints	Demand response
HOMER	Electricity (renewables, storage), heating, fossil fuels, hydrogen	Single site/microgrid	Economic, environmental, energy efficiency	Minutes	Yearly	Simulation of system operation; dispatch strategy modelling	Load shifting, operational optimisation
iHOGA	Electricity (renewables, storage), hydrogen, water pumping	Local/microgrid	Economic, energy efficiency	Minutes	Yearly	Simulation and control strategy optimisation	Indirect via load management, battery/grid optimisation
oemof	Electricity (renewables, storage), heating, fossil fuels, hydrogen	User defined	Economic, environmental, energy efficiency, social	User defined	User defined	Dispatch optimisation under operational constraints	Supported via demandlib and solph modules for load profiling and demand-side modelling
PLEXOS	Electricity (renewables, storage), heating, fossil fuels, hydrogen	Local to regional	Economic, environmental, energy efficiency	Minutes	Yearly	Operational optimisation; market simulation and dispatch	Demand response, load shifting
PyPSA	Electricity (renewables, storage), heating, transport sectors	Local to regional	Economic, environmental	User defined	User defined	Dispatch optimisation under operational constraints	Demand response, load shifting, elastic demand
urbs	Electricity (renewables, storage), heating, fossil fuels, hydrogen	District to continent	Economic, environmental	1 h	User defined	Dispatch optimisation under operational constraints	Demand response

Table 3 summarises the key usability characteristics of modelling tools suitable for the planning and design of EnCs. The comparison focuses on the aspects outlined below.

- **Licence type** specifies whether the tool is open-source, freeware (available at no cost the source code is not publicly accessible), or commercially licensed, and whether trial versions are available.
- **Access and installation** indicate how the tool is obtained and deployed, such as web-based access, local installation via download, or use through dedicated platforms or licences.
- **Target audience** identifies the primary user group for which the tool is designed, such as researchers, community planners, and local authorities.
- **Support and user community** reflects the availability of documentation, tutorials, and active user communities.
- **Coding requirement** indicates whether programming skills are required to use or customise the tool.
- **Graphical user interface (GUI)** specifies whether the tool provides a user-friendly graphical interface or relies primarily on script-based interaction.

Table 3. Usability of the Selected Tools

Tool	Licence type	Access	Target audience	Support and community	Coding requirement	GUI
Calliope	Open source	Download (Mamba/Conda package)	Researchers	Docs, tutorials, Gitter, GitHub	Yes (Python)	No
DER-CAM	Freeware	Browser-based	EnC planners, local authorities	Manual, videos, forums	No	Yes
Energy-PLAN	Freeware	Download	Researchers, policy makers	Manual, videos, training, online course	No	Yes
Energy-PRO	Commercial (trial available)	Purchase	EnC planners	Manual, training, contact	No	Yes
ficus	Open source	Download	Researchers, EnC planners	Docs, tutorials, forums	Yes (Python)	No
HOMER	Commercial (trial available)	Download	EnC planners	Manual, videos, forum	No	Yes
iHOGA	Commercial (trial available)	Download	EnC planners	Manual, forum, contact	No	Yes
oemof	Open source	GitHub, PyPI (Python toolbox)	Researchers, EnC planners	Docs, tutorials, forums	Yes (Python)	No
PLEXOS	Commercial	Download	EnC planners, policy makers	Manual, videos, forum	No	Yes
PyPSA	Open source	Download	Researchers, policy makers	User guide, API reference, forums with examples	Yes (Python)	No
urbs	Open source	Download	Researchers, EnC planners	Docs, tutorials, forums	Yes (Python)	No

The comparison of energy system modelling tools highlights clear trade-offs between the representation of demand-side flexibility, the operational layer, and usability. The depth of modelling for demand flexibility varies among the tools under review. Tools such as DER-CAM, Calliope, EnergyPLAN, and PLEXOS include demand-side management modules, whereas others, such as iHOGA, treat demand management indirectly, for example, through predefined demand curves.

In particular, the analysis shows that explicit demand response and advanced operational modelling are generally better represented in open-source tools (PyPSA, urbs, Calliope, and Ficus). However, their effective use requires proficiency in Python programming and a deeper understanding of model formulation and data structures. As a result, these tools are better suited for research-oriented and advanced engineering studies.

Commercial tools (PLEXOS, HOMER, EnergyPRO, and iHOGA) provide robust modelling environments and user-friendly interfaces but typically involve higher licensing costs and more limited customisation. They are generally more convenient for feasibility studies and applied assessments in professional and consultancy contexts. Among commercial tools, HOMER stands out due to its wide adoption and structured

representation of system operation. Meanwhile, PLEXOS offers an advanced representation of markets, unit commitment, and short-term dispatch, making it particularly suitable for electricity market and system operation studies. Nevertheless, adapting PLEXOS to analyse demand-side flexibility in EnCs may require substantial effort and expert knowledge.

As a compromise between modelling depth and usability, freeware tools such as DER-CAM offer a balanced solution. DER-CAM combines explicit representations of demand response at the microgrid level with a graphical user interface, enabling use without programming expertise. While its geographical scope and system scale are more limited than those of open-source planning frameworks, it provides a practical entry point for analysing EnCs.

Overall, the findings suggest that no single tool dominates across all dimensions. Open-source tools are better suited for research-oriented analyses of demand response and operational flexibility, while freeware and commercial tools provide more accessible solutions for practical planning and feasibility studies. Tool selection should therefore be guided by the research objective, required level of operational detail, and available expertise, particularly when demand-side flexibility plays a central role in the analysis.

6. CONCLUSIONS

The study has examined energy system modelling tools for engineering-level planning of EnCs. It has linked insights from meta-review of existing literature and considerations for tool selection and application.

First, we have classified existing review studies into four categories: scop-

ing reviews, thematic reviews, screening and selection, and quantitative evaluations. We have also identified common trends and challenges in energy system modelling. Then, a set of technical and functional requirements has been defined for the engineering-level planning of grid-connected EnCs. Finally, the selected modelling tools

have been compared along two key dimensions: technical capabilities and usability.

The reviewed literature has highlighted several common challenges. These include: limited availability and accessibility of reliable data, the trade-off between model detail and computational complexity, difficulties in simultaneously obtaining high level of spatial, temporal, and technological resolution, and difficulties in adequately representing demand-side flexibility. In addition, the integration of social indicators remains limited. Moreover, the need for improved interoperability and linking between modelling tools is frequently noted. Finally, literature has highlighted a trade-off between transparency and accessibility. Open-source tools offer greater transparency but often require substantial expertise, whereas commercial tools are generally more user-friendly but accessible to a limited number of users. This tension between transparency and usability is also apparent in our tool selection. Open-source tools generally allow adjustments and customisation but require programming skills and technical expertise, whereas commercial tools are more user-friendly but may incur high licensing costs.

Based on the criteria identified and careful selection to ensure relevance for engineering-level EnC planning, we have selected 11 modelling tools in total for detailed comparison: DER-CAM, Calliope, Oemof, PyPSA, EnergyPLAN, HOMER, urbs, PLEXOS, EnergyPRO, iHOGA, and Ficus. The comparison has demonstrated

a clear trend toward the increasing maturity of open-source tools. These tools are sufficiently developed to support qualified engineers and researchers in advanced engineering level studies, particularly where efficient system operation and demand-side flexibility are central objectives. Whereas commercial are better positioned for feasibility studies in professional and consultancy contexts. Further development of commercial tools could focus on improved modelling of demand response and greater transparency of operational assumptions. Such developments would increase their suitability for advanced engineering decisions in EnCs.

Importantly, the selection of tools in this study should not be interpreted as exhaustive for EnCs. Rather, it reflects a purpose-driven selection based on clearly defined criteria and study objectives. A key limitation of this study is that the selected modelling tools have not been tested or validated in real-world scenarios. Consequently, the analysis has been based on documented capabilities, rather than on practical implementation outcomes.

The findings of the study highlight the need for further evaluation of tool performance. Future work should focus on developing practical use cases and benchmark tests to facilitate the selection of appropriate modelling tools. Such efforts would help researchers, planners, and practitioners identify the most suitable tool for specific EnC applications.

ACKNOWLEDGEMENT

The research has been supported by the NextGeneration EU (Latvia's Recovery and Resilience Plan's investment "Research, Development and Consolidation Grants")

under Grant "MESVA: "Methods, Tools and Techniques for Smart Development of Energy System" (No. 5.2.1.1.i.0/2/24/I/CFLA/006).

REFERENCES

1. Cuenca, J. J., Jamil, E., & Hayes, B. (2021). State of the art in energy communities and sharing economy concepts in the electricity sector. *IEEE Transactions on Industry Applications*, 57(6), 5737–5746. doi: 10.1109/TIA.2021.3114135
2. Vernay, A. L., Sebi, C., & Arroyo, F. (2023). Energy community business models and their impact on the energy transition: Lessons learnt from France. *Energy Policy*, 175, 113473. doi: 10.1016/j.enpol.2023.113473
3. Bukovszki, V., Magyari, Á., Braun, M. K., Párdi, K., & Reith, A. (2020). Energy modelling as a trigger for energy communities: A joint socio-technical perspective. *Energies*, 13(9), 2274. doi: 10.3390/en13092274
4. Vecchi, F., Stasi, R., & Berardi, U. (2024). Modelling tools for the assessment of Renewable Energy Communities. *Energy Reports*, 11, 3941–3962. doi: 10.1016/j.egy.2024.03.048
5. Prina, M. G., Manzolini, G., Moser, D., Nastasi, B., & Sparber, W. (2020). Classification and challenges of bottom-up energy system models – A review. *Renewable and Sustainable Energy Reviews*, 129, 109917. doi: 10.1016/j.rser.2020.109917
6. Cuesta, M. A., Castillo-Calzadilla, T., & Borges, C. E. (2020). A critical analysis on hybrid renewable energy modeling tools: An emerging opportunity to include social indicators to optimise systems in small communities. *Renewable and Sustainable Energy Reviews*, 122, 109691. doi: 10.1016/j.rser.2019.109691
7. Fattahi, A., Sijm, J., & Faaij, A. (2020). A systemic approach to analyze integrated energy system modeling tools: A review of national models. *Renewable and Sustainable Energy Reviews*, 133, 110195. doi: 10.1016/j.rser.2020.110195
8. Chang, M., Thellufsen, J. Z., Zakeri, B., Pickering, B., Pfenninger, S., Lund, H., & Østergaard, P. A. (2021). Trends in tools and approaches for modelling the energy transition. *Applied Energy*, 290, 116731. doi: 10.1016/j.apenergy.2021.116731
9. Yazdanie, M., & Orehounig, K. (2021). Advancing urban energy system planning and modeling approaches: Gaps and solutions in perspective. *Renewable and Sustainable Energy Reviews*, 137, 110607. doi: 10.1016/j.rser.2020.110607
10. Kazmi, H., Munné-Collado, Í., Mehmood, F., Syed, T. A., & Driesen, J. (2021). Towards data-driven energy communities: A review of open-source datasets, models and tools. *Renewable and Sustainable Energy Reviews*, 148, 111290. doi: 10.1016/j.rser.2021.111290
11. Heider, A., Reibsch, R., Blechinger, P., Linke, A., & Hug, G. (2021). Flexibility options and their representation in open energy modelling tools. *Energy Strategy Reviews*, 38, 100737. doi: 10.1016/j.esr.2021.100737
12. Martínez-Gordón, R., Morales-España, G., Sijm, J., & Faaij, A. P. C. (2021). A review of the role of spatial resolution in energy systems modelling: Lessons learned and applicability to the North Sea region. *Renewable and Sustainable Energy Reviews*, 141, 110857. doi: 10.1016/j.rser.2021.110857
13. Klemm, C., & Vennemann, P. (2021). Modeling and optimization of multi-energy systems in mixed-use districts: A review of existing methods and approaches. *Renewable and Sustainable Energy Reviews*, 135, 110206. doi: 10.1016/j.rser.2020.110206
14. Martins, F., Patrão, C., Moura, P., & de Almeida, A. T. (2021). A review of energy modeling tools for energy efficiency in smart cities. *Smart Cities*, 4(4), 1420–1436. doi: 10.3390/smartcities4040075
15. Horak, D., Hainoun, A., Neugebauer, G., & Stoeglehner, G. (2022). A review of spatio-temporal urban energy system modeling for urban decarbonization strategy formulation. *Renewable and Sustainable Energy Reviews*, 162, 112426. doi: 10.1016/j.rser.2022.112426

16. Laveneziana, L., Prussi, M., & Chiamonti, D. (2023). Critical review of energy planning models for the sustainable development at company level. *Energy Strategy Reviews*, 49, 101136. doi: 10.1016/j.esr.2023.101136
17. Liu, Z., Luo, H., Zhang, Y., Luo, T., & Yang, X. (2024). A review of simulation software for energy systems: Design, functionality, and applications. *Thermal Science and Engineering Progress*, 53, 102760. doi: 10.1016/j.tsep.2024.102760
18. Höffner, D., & Glombik, S. (2024). Energy system planning and analysis software – A comprehensive meta-review with special attention to urban energy systems and district heating. *Energy*, 307, 132542. doi: 10.1016/j.energy.2024.132542
19. Xu, Y., Litardo, J., Del Pero, C., Leonforte, F., & Caputo, P. (2024). District energy models: A comparative assessment of features and criteria for tools selection. *Energy and Buildings*, 314, 114291. doi: 10.1016/j.enbuild.2024.114291
20. Majidi, H., Hayati, M. M., Breyer, C., Mohammadi-ivatloo, B., Honkapuro, S., Karjunen, H., ... & Sihvonon, V. (2025). Overview of energy modeling requirements and tools for future smart energy systems. *Renewable and Sustainable Energy Reviews*, 212, 115367. doi: 10.1016/j.rser.2025.115367
21. Mohseni-Gharyehsafa, B., Bampoulas, A., Finn, D., & Pallonetto, F. (2025). Energy flexibility and management software in building clusters: A comprehensive review. *Next Energy*, 8, 100250. doi: 10.1016/j.nxener.2025.100250
22. Gaugl, R., Walenta, K., & Wogrin, S. (2025). A comparative analysis of energy system modeling frameworks. *e+ i Elektrotechnik und Informationstechnik*, 1–19. doi: 10.1007/s00502-025-01345-x
23. Silinto, B. F., van der Laag Yamu, C., Zuidema, C., & Faaij, A. P. (2025). Hybrid renewable energy systems for rural electrification in developing countries: A review on energy system models and spatial explicit modelling tools. *Renewable and Sustainable Energy Reviews*, 207, 114916. doi: 10.1016/j.rser.2024.114916
24. Samarasinghe, S. L., Moghimi, M., & Kaparaju, P. (2025). A review of modelling tools for net-zero emission energy systems, based on model capabilities, modelling criteria and model availability. *Renewable Energy Focus*, 53, 100659. doi: 10.1016/j.ref.2024.100659
25. Kachirayil, F., Weinand, J. M., Scheller, F., & McKenna, R. (2022). Reviewing local and integrated energy system models: insights into flexibility and robustness challenges. *Applied Energy*, 324, 119666. doi: 10.1016/j.apenergy.2022.119666
26. Gjorgievski, V. Z., Cundeva, S., & Georghiou, G. E. (2021). Social arrangements, technical designs and impacts of energy communities: A review. *Renewable Energy*, 169, 1138–1156. doi: 10.1016/j.renene.2021.01.078
27. Honarmand, M. E., Hosseinneshad, V., Hayes, B., Shafie-Khah, M., & Siano, P. (2021). An overview of demand response: From its origins to the smart energy community. *IEEE Access*, 9, 96851–96876. doi: 10.1109/ACCESS.2021.3094090
28. Gržanić, M., Capuder, T., Zhang, N., & Huang, W. (2022). Prosumers as active market participants: A systematic review of evolution of opportunities, models and challenges. *Renewable and Sustainable Energy Reviews*, 154, 111859. doi: 10.1016/j.rser.2021.111859
29. Heliö, N., Kiviluoma, J., Morales-España, G., & O'Dwyer, C. (2021). Impact of operational details and temporal representations on investment planning in energy systems dominated by wind and solar. *Applied Energy*, 290, 116712. doi: 10.1016/j.apenergy.2021.116712
30. Lawrence Berkeley National Laboratory. (n.d.). *The Distributed Energy Resources Customer Adoption Model (DER-CAM)*. Grid Integration Group. Available at: <https://gridintegration.lbl.gov/der-cam>
31. Calliope. (n.d.). *Calliope: A multi-scale energy systems modelling framework*. Available at: <https://www.calliope.eu/>
32. Open Energy Modelling Framework. (n.d.). *Oemof: Open energy modelling framework*. Available at: <https://oemof.org/>

33. Hilpert, S., Kaldemeyer, C., Krien, U., Günther, S., Wingenbach, C., & Plessmann, G. (2018). The Open Energy Modelling Framework (oemof) – A new approach to facilitate open science in energy system modelling. *Energy Strategy Reviews*, 22, 16–25. doi: 10.1016/j.esr.2018.07.001
34. PyPSA Developers. (n.d.). *PyPSA documentation*. Available at: <https://docs.pypsa.org/latest>
35. Sustainable Energy Planning Research Group. (n.d.). *EnergyPLAN: Advanced energysystemanalysismodel*. EnergyPLAN. Available at: <https://energyplan.eu/>
36. Lund, H., & Münster, E. J. R. E. (2003). Modelling of energy systems with a high percentage of CHP and wind power. *Renewable Energy*, 28(14), 2179–2193. doi: 10.1016/S0960-1481(03)00125-3
37. HOMER Energy LLC. (n.d.). *HOMER energy modeling software*. Available at: <https://www.homerenergy.com/>
38. Bahramara, S., Moghaddam, M. P., & Haghifam, M. R. (2016). Optimal planning of hybrid renewable energy systems using HOMER: A review. *Renewable and Sustainable Energy Reviews*, 62, 609-620. doi: 10.1016/j.rser.2016.05.039
39. Technical University of Munich. (n.d.). *urbs: A linear optimisation model for distributed energy systems*. Available at: <https://urbs.readthedocs.io/en/latest>
40. Energy Exemplar. (n.d.). *PLEXOS energy market simulation software*. Available at: <https://www.energyexemplar.com/plexos>
41. EMD International A/S. (n.d.). *energyPRO software*. Available at: <https://www.emd-international.com/software/energypro>
42. Østergaard, P. A., Andersen, A. N., & Sorknæs, P. (2022). The business-economic energy system modelling tool energyPRO. *Energy*, 257, 124792. doi: 10.1016/j.energy.2022.124792
43. Universidad de Zaragoza. (n.d.). *iHOGA software*. Available at: <https://ihoga.unizar.es/en/>
44. Technische Universität München. (n.d.). *Ficus: A (mixed integer) linear optimisation model for local energy systems*. Available at: <https://ficus.readthedocs.io/en/latest/index.html>