Open-Power System Modelling

A Review of Existing Methods and Models

*Philipp Sommer**

FH Muenster, Stegerwaldstraße 39, 48565 Steinfurt

Abstract

This review paper presents a short overview of current power system modelling tools especially used for analysing energy and electricity systems for the supply and demand sector. The main focus of this review lies on open source tools and models which are written and used in the programming language "Python". The modelling tools are represented in a comprehensive table with key information. Five modelling tools with an open source license can be filtered out. The modelling tool PyPSA can be considered as a high performing tool especially as the gap between power system analysis tool (PSAT) and energy system modelling tool.

Keywords: energy system modelling, grid modelling, power system modelling, open source, renewable energy

Abbreviations

ESM	energy system modelling
GHG	greenhouse gas
LP	linear programming
MILP	mixed integer programming
OPSM	open power system modelling
PSAT	power system analysis tool
RES	renewable energy sources
VRES	variable renewable energy sources

1 Introduction

The European Climate Law as part of the European Green Deal leads the path to climate neutrality by 2050. A central target is the reduction of greenhouse gas (GHG) emissions of at least 55 % until 2030 compared to 1990 levels [1]. The electricity generation from renewable energy sources (RES) is increasing in Europe, driven by ambitious targets for emission reductions set by the European Commission (EC). The EU also states that all sectors have to contribute to this reduction, but the sector with the highest potential for cutting emissions is the power sector [2]. Through increasing the share of zero-emitting RES in the electricity mix, the power sector can almost totally eliminate its emissions by 2050 [2, 3]. Energy system models can give a deep inside how our energy system can evolve. But how should we deal with that rising amount of electricity. Due to the fact that energy models were mostly proprietary and closed to the community, the interest in energy system modelling as an open source approach has renewed. There has been an increase in developing several open source tools to give new insights for these challenges and answer present questions [4]. Therefore, the aim of this research is to give an overview of current existing power modelling tools with an open source license including a specific scope for power system analysis. Furthermore, the filtered tools are shortly presented and additional information for further research is given.

*Corresponding author: philipp.sommer@fh-muenster.de

2 Review Method and Methodology

The contents of this short review were acquired through a literature research using search engines like *Google* and *Google Scholar*. The search for further literature has been expanded onto the library of the University of Applied Sciences Muenster using the search engine *FINDEX*. The main focus was to get a broad overview on review papers. After finding relevant reviews with suitable models, the research is extended by looking for additional information to define the concept of energy system modelling (ESM) in more detail. To describe the examined software in more detail e.g., websites, documentation of models is included in this research. For the research different English keywords where used e.g., *energy system modelling, open source, power system analysis tools, grid modelling*.

The energy modelling area is vast and complex. The most interesting models for this kind of research are those that consider the electricity aspect of the grid, especially for the distribution area and the interaction between the energy and power system. For this reason, models that do not meet these criteria are

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excluded. The models should have at least a purpose to analyze the power system by interacting with large shares of RES. Hereby it must be mentioned that this review does not explicitly distinguish between models or modelling tools. Some models can also be declared as frameworks[1] or tools, due to the fact that there is no data already available. However, with input data, equations and constraints a specific model can be built [3].

Given the large amount of information and publications in this area, it was not possible to cover all the information in this article. The focus lies on selected review articles. Table 1 below lists the primary articles that have already made a contribution to this topic. Other information or further models, which are not based on the main source have nevertheless a justification and are not considered only due to the scope of this work. Furthermore, other sources were consulted to cover the periphery of the paper and to provide additional information on the topic.

Tab. 1: Relevant recent reviews of energy system modelling.

Publication	Coverage
Klemm and Vennemann [5]	Modeling and optimization of MES (145 models reviewed)
Ringkjøb et al. [3]	Overview of modelling tools for energy and electricity systems (75 models)
Foley et al. [6]	Overview of electric systems models
Hall et al. [7]	Classification of 22 models (22 models)
Groissböck [4]	Open source models (31 models compared)

3 Classification of Energy System Models

According to Hiremath et al. "Energy models are, like other models, simplified representations of real systems." [8]. Therefore ESM are handy and useful to describe, optimize or even predict the assumptions by the user for the current problem. Ringkjøb et al. [3] and Klemm and Vennemann [5] give a broad overview of existing tools and categorize every model by their characteristics. They describe general characteristics, which every model has in common according to their general logic, spatiotemporal resolution and technological/economic parameters. According to the structure of Després et al. [9] and the model selection of Ringkjøb et al. [3] the reader can choose the right model by the certain criteria. In the following, these criteria are described and the process is shown in figure 1. Furthermore, this flow chart is used to expose the criteria highlighted in the table 2 and identify the appropriate tool.

[1] Frameworks include a runtime environment, libraries and a number of other components to provide the optimal basic structure

3.1 General Logic

After defining the problem statement, the reader can specify the right model by choosing the needed logic. This logic is divided into *purpose*, *approach* and *methodology* [3].

3.1.1 Purpose

Models can be categorized into four areas of application:

- **Power System Analysis Tool**: This is for the purpose to study power with high degree of detail at short scale.
- **Operation Decision Support**: For optimization of operation/dispatch in the energy/electricity at large scale.
- **Investment Decision Support**: Optimization of investment in the energy/electricity system on long-term.
- **Scenario**: Investigation of future long term scenarios and for the evaluation of several policies.

3.1.2 Approach

There are three possible approaches:

- **top-down**: It is suited for economic approach, considering macroeconomic connections and long-term changes.
- **bottom-up**: It is based on detailed technological descriptions of the energy system.
- **hybrid**: Combined approach of top-down and bottom-up method when estimating the integration variable renewable energy sources (VRES).

3.1.3 Methodology

The methodologies of all energy models can be classified into three main categories:

Simulation models: Simulation or moreover forecasting of an energy system is based on specified equations and characteristics. In most cases they follow the bottom-up approach and are best suited for testing of different topologies and investigating the impacts of these scenarios. The **Agent-based simulation** is more of a specific simulation case with

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actors (agents) included.
Optimization models: Optimization of an existing quantity of energy. Most of these models use **linear programming** (LP) as the mathematical approach where an objective function either minimized or maximized e.g., minimizing the total system cost by a set of constraints balancing the supply and demand in the grid. **Mixed-integer linear programming** (MILP) allows giving an integer value as the result of how many power plants the user should invest. **Stochastic programming** and **Artificial intelligence** are also relevant mathematical approaches in this area, but not further discussed.
Equilibrium models: These models can represent the energy sector as a part of the whole economy and their relation to it. Therefore, they serve as an evaluation of the impact of various policies on the whole economy.

3.1.4 Spatiotemporal Resolution

The spatiotemporal resolution is particularly crucial for choosing the right model and it's application. Especially, in a system with a large share of VRES it is quite important to capture the variability of solar and wind resources. The temporal resolution can vary from milliseconds to several years or decades. Also, the geographical resolution can vary from a single building or project to modeling the energy system of the whole world.

3.1.5 Technological and Economic Parameters

According to Ringkjøb et al. [3] "Measures such as grid development, energy storage and demand side management have been identified as some of the key contributors for successfully building an energy system containing large shares of VRES." Therefore, he categorized model components and properties:

Conventional Generation: Modelling each power plant individually or by combining all plants of the same technology in the region.
Renewable Generation: Renewable generation (except geothermal and tidal) is related to meteorological conditions. Due to this fact, these conditions can be modelled by meteorological data e.g., wind speed for this region by stochastic methods.
Energy Storage: Due to the variable and volatile renewable generation and the inconsistency with the demand side, energy storages are necessary. As the locations for pumped hydropower storage are limited, solutions like hydrogen, batteries or compressed-air energy become much more important. [3]
Grid: PSAT can model a detailed overview of power systems, including power flows (e.g., linear or non-linear), short-circuit calculation, detailed modelling of distribution grids.
Commodities: Many models come with a specific focus on one commodity e.g., electricity (power sector), some of them can cover multiple commodities at the same time (sector coupling) e.g., heat, electricity and hydrogen.
Demand Sector: This is where the end-user is addressed. It can be split up into the building (commercial/residential), industry (agriculture included), transport sector.
Demand Elasticity: The demand elasticity can forecast how consumption may decrease when the price of e.g., electricity increases.
Demand Side Management: Demand side management addresses the consumer (end-user) side of the energy system. Aspects like energy efficiency, energy conversion and demand response can be measured. DR is a measure for shifting certain loads when the demand is higher than the supply [10].
Costs: Costs are important for the modelling results, but very difficult to model accurately.
Market: Most models balance the supply and demand under perfect market conditions. Some models can treat the spot market (merit-order), the reserve or even the balancing market.
Emissions: Some models can represent GHG as a side product of generation e.g., CO_2, NO_x etc.. Other models treat GHG emissions as CO_2 equivalents.

3.2 Power System Modelling

Energy and power system tools are applied to model the impacts of increasing shares of variable generation at various levels of detail. Therefore long-term energy system models can analyze the evolution of the energy system on a temporal resolution over several years and include non-electricity demand sectors e.g., heat or transportation. The investment decisions e.g., monetary or reduction of emissions and policy recommendations derived from such models may serve as input for a more detailed analysis of electricity markets based on power system models. Commonly, power system models focus exclusively on electricity and the power sector, but can also include sector coupling. They model on shorter time horizons up until several years and are more detailed. On the basis of their calculations, power system models may analyze the implications of increasing shares of renewables on the grid (e.g., by assessing the resulting load flows or potential faults) [11].

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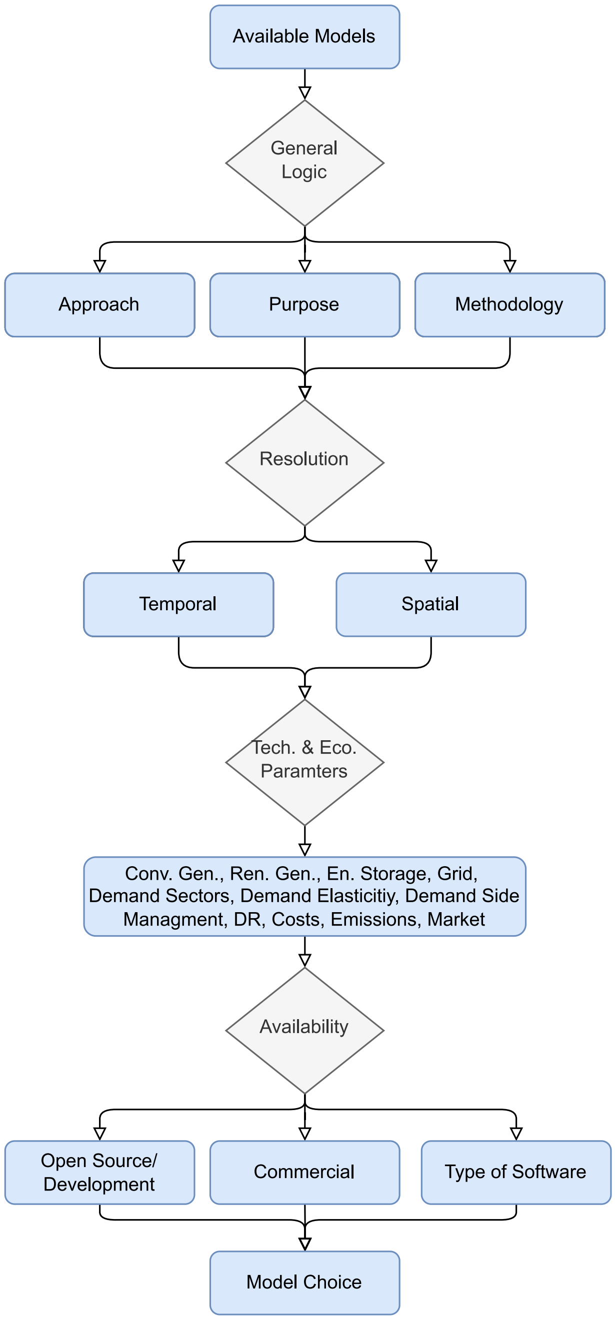

Fig. 1: Classification for model choice, adapted from Ringkjøb et al. [3]

4 Results and Filtered Models

During this research a total of five PSAT have revealed. All of them have a purpose for the analysis of the current power system. Spatialtemporal resolution and technological/economic parameters are spreaded. Also the criteria of availability e.g., programming language, open source/commercial and current development can differ. Due to this fact, a filter is applied over the mentioned criteria to highlight a few modelling tools for this area of application, following the logic of figure 1. Foremost, the model should have at least a purpose for analyzing the power system. The resolution should be at least one hour or less and for the geographical area user-defined. For the technological/economic parameters it should contain the component for considering the grid. Lastly, the availability should contain the criteria for an open source licence and should be written in the programming language "Python". After applying these filters, 16 models can be classified as PSAT. Five out of 16 models are coming with an open source licence. In table 2 are the filtered models shown. If the programming language aspect with "Python" is taken into account, **PyPSA** and **RAPSim** are the final models for this review.

5 Discussion and Conclusion

To answer the question of which is declared in the introduction, five of the reviewed existing modelling tools can be classified as power system modelling tools which has at least a purpose to analyze the electricity grid and are coming with an open source licence. The scope of this review is not a comparison or a benchmark of these tools, it rather is a selection.

Another important point in using open source is the performance of these tools. There are existing reviews for the comparison of several open source tools which are also based on Python where PyPSA is also included. Groissböck [4] compared several open source tools for energy system modelling with commercial closed source energy modelling under targeted functionality. PyPSA can be considered as a high performing tool for short-time planning and small-time steps. It can be used as a gap between load flow analysis software and energy system modelling software and has good grid modeling properties which is quite important for the integration of renewables and possible electrification of the transport and heat sector [4, 17].

In comparison to pandapower, PyPSA has more features for the economic analysis e.g., sector coupling. Pandapower provides non-linear operational power flow, short circuit calculations, state estimation, modelling of switches and three-winding transformers which is currently missing in PyPSA. [17, 18].

6 Outlook and Future Work

Several critics address that public policy energy models are insufficiently transparent. If not explicitly published, the source code and data sets should be available for peer review. This should be done to improve transparency and public acceptance. The quality of data is crucial for the electricity and energy system modelling. To overcome these challenges many models are undertaken as open-source software projects e.g., open-eGo project [19] and the Open Power System Data platform provide centralised and

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Tab. 2: Modelling tools that are suitable for power system analysis as open source. Abbreviations used in the table: **Purpose**: PSAT - Power System Analysis Tool, S - Simulation; I - Investment Decision Support, ODS - Operation Decision Support, **Approach**: BU - Bottom-Up, BBM - Bus-Branch Model; **Methodology**: ABS - Agent-based Simulation, LP - Linear Programming; **Temporal Resolution/Modelling Horizon/Geographical Coverage:**: UD - User-Defined

Tool	**GridLAB-D**	**OpenDSS**	**PyPSA**	**RAPSim**	**pandapower**
Purpose:	PSAT	PSAT	PSAT, I/ODS	PSAT	PSAT/S
Approach:	BU	BU	BU	BU	BBM (BU)
Methodology:	ABS	S	LP	S	S
Temporal resolution:	Seconds–Years	UD (1s to 1h)	Hourly	Minutes	Milliseconds
Modelling horizon:	3-5 Years	UD	1 year	days	UD
Geographical coverage:	Local-National	Community-Continental	Local-Continental	Local	UD
Reference	[12]	[13]	[14]	[15]	[16]

open data sets [20]. There is no tool that can tackle all the energy problems of the future. One solution could be a linking approach of two models. For instance, feeding the results from one model into the input of the other model. This process should ideally lead to convergence through an iterative approach [3]. There are also hard-linked models where two models are fully integrated into a single iteration product [21]. Otherwise it is a trade-off which properties and features the model should have for which application. Recently, there has been a huge development in the field of open source models and are shared via GitHub and on the openmod list [22]. The efficiency and performance of these tools heavily rely on contributions to this kind of platforms.

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