The Transition towards Affordable Electricity: Tools and Methods

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1. Introduction

In an effort to counteract climate change, the electric grid is subjected to significant transformations, such as the integration of renewable generators, demand-side flexibility, and new electrified transportation. These changing paradigms highlight the importance of research into new methods and tools, which can equip the power system stakeholders to plan and operate the electric grid of the future. The electric grid has been divided into three major subsystems: (1) generation, (2) transmission, and (3) distribution. For the analysis of the electric grid, modeling each subsystem in full detail may not be feasible in terms of complexity management and computational requirements. Instead, different modeling methodologies and software tools exist for the analysis of each subsystem. At the same time, the advancement of computational technology and the increasing interdependency between different subsystems is pushing the boundaries of these software frameworks. For example, (1) demand response techniques can activate demand-side control of the load to match generation, (2) battery charge/discharge can mimic both load/generator, (3) microgrids can act as small independent grid operators, and (4) renewable energies are considered as zero-variable-cost resources, which are highly variable and uncertain in nature.

To manage the diverse modeling requirements in this context, the research community is continuously developing open-source software tools for electric grid analysis. The open-source aspect allows greater control for researchers to extend and customize modeling workflows to match the requirements of particular studies, which ensures a broad adoption of such tools alongside the more conventional commercial power system tools. An exemplary set of open-source tools for electric grid analysis includes (1) OpenDSS and GridLAB-D for distribution grid analysis, (2) GRIDAPPS-D as a platform to standardize distribution grid interoperability with respect to modeling and data exchange, (3) TESP as a co-simulation platform that integrates multiple open-source tools, (4) MESMO for operational optimization of DER dispatch in the distribution grid, (5) MATPOWER for large-scale system integration studies, and (6) URBS for planning optimization of renewable energy deployment in the generation mix.

This chapter examines the landscape of open-source tools for electric grid analysis to identify the suitability and applicability of various tools for specific problem types in this domain. As a representative set of software frameworks, the following tools are considered: (1) MATPOWER, (2) GridLAB-D, (3) MESMO, and (4) URBS. The first part of this chapter begins with an introduction to the requirements of different problem types and a feature comparison of the software tools in order to differentiate the purpose for each of the different tools. This is complemented with a brief introduction to each of the four frameworks. Furthermore, to characterize the requirements for test case preparation, as well as for results post-processing, input/output specifications are compared for the four tools. In this context, the model conversion and co-simulation platforms GridAPPS-D and TESP are introduced to highlight possible workflows for test case preparation. In the second part of the chapter, the key capabilities of each tool are demonstrated for a district-scale test case based in Singapore. The test case considers a synthetic electric grid model, thermal building demand models, EV charging models, and photovoltaic (PV) generation potentials. The key results are discussed to highlight the core analyses that the different software tools can support. Eventually, the discussion section serves as a guideline for the choice of open-source tools for different electric grid modeling and analysis tasks.

Existing reviews for open-source tools energy system modeling and optimization, e.g., Després et al. (2015); Kriechbaum et al. (2018); Ringkjøb et al. (2018); van Beuzekom et al. (2015), focus on providing a classification of the tools by mathematical model types, as well as temporal, geographical, and sector coverage. Studies in Ringkjøb et al. (2018); van Beuzekom et al. (2015) provide a detailed comparison for a large number of tools across these dimensions. Another study (Després et al. 2015) compares a smaller number of tools in a similar fashion. Lastly, Kriechbaum et al. (2018) seeks to identify current challenges associated with the available tools. In contrast to these methodical reviews, the core objective of this chapter is to differentiate key use cases for the presented software tools and to enable the reader to pick the best tool for their problem. The chapter points out specific features and application examples for each tool, such that choosing the right tool for a specific study is made easy. Since the presented tools only represent a small fraction of the available open-source frameworks, possible alternatives for each tool are indicated in Section 2.1.

2. Software Frameworks

2.1. Overview and Features

Software tools for distribution system analysis typically cater to specific problem types and stakeholders of the electric grid. Therefore, the features of these software frameworks are driven by the requirements arising from different problem types. To begin with, the following problem types for energy system analysis can be generalized based on Ringkjøb et al. (2018) (Section 2.2.1) and Klemm and Vennemann (2021) (Section 3.1):

- Operational problems, which describe the analysis of the system at an operational timescale with the purpose of providing operation decision support. Examples for this category are unit commitment problems, optimal control/model predictive control problems, and market-clearing problems. Operational problems can be cast into simulation problems and optimization problems depending on the application. For example, market-clearing problems would be expressed as optimization problems, whereas simulation is more suited for studying the nominal behavior of the distribution system with regard to a known set of control variables.
- Planning problems, which characterize design decisions for the energy system, i.e., at a planning timescale, with the goal of providing investment decision support. These studies can be addressed in terms of simulation-based scenario analysis or optimal planning problems. The simulation-based approach captures a conventional method for district-scale energy system design, whereas optimal planning seeks to determine optimal values for the design decision variables, e.g., component sizing and placement.

Essentially, problem type governs the temporal scale and resolution of the mathematical model as well as the selection of decision variables. Independent of the problem type, the solution method can be categorized into (1) simulation and (2) optimization. Simulation or forecasting tools calculate the state variables of the energy system based on fixed inputs for control and disturbance variables, whereas optimization tools determine state and control variables that optimize some objective subject to operational constraints.

The different problem types rely on casting a mathematical model for the electric grid into the particular solution logic. Mathematical models for the electric grid are essentially obtained by aggregating the models of its subsystems, i.e., generators, transmission systems, distribution systems, and DERs. To this end, complexity management is an important aspect of electric grid modeling in managing model formulation effort, model parameter data requirements, and computational limitations. In line with this, different software tools for electric analysis typically focus on a limited subset of features. To compare the capabilities of the selected software tools, the following features are considered in Table 1:

- Power flow simulation describes the ability to solve the nonlinear steady-state electric power flow;
- Power flow optimization refers to the ability to solve an optimization problem based on the electric power flow;
- Balanced AC model highlights whether steady-state properties, i.e., voltage, branch flow, and losses, can be represented for single-phase electric grids;
- Multi-phase AC model highlights whether steady-state properties, i.e., voltage, branch flow, and losses, can be modeled for multi-phase unbalanced electric grids;
- Transient dynamics model describes the ability to model transient properties of the electric grid, in addition to steady-state properties;
- Convex electric grid model denotes whether the electric grid model can be obtained in a convex form;
- DER simulation describes the ability to simulate the system dynamics and behavior of DERs assuming fixed control inputs;
- DER optimization describes the ability to solve an optimization problem considering system dynamics and behavior of DERs;
- Convex DER model notes whether the DER model can be obtained in a convex form;
- Operational problems indicate the ability to express operational problems as outlined above;
- Planning problems denote the capability to model planning problems as described above;
- Simulation-based solution highlights whether the tool is suited for simulation-based analysis, in which control or decision variables are provided as an input;
- Optimization-based solution describes the inclusion of interfaces to numerical optimization solvers, such that optimization problems can be modeled and solved, where decision variables are obtained as outputs from the optimal solution;

- Multi-period modeling refers to the ability to consider multiple time steps and capture inter-temporal linkages during simulation/optimization.

Table 1 reviews these features for a selected set of open-source tools. For the sake of brevity, only the following four representative software frameworks are included in the discussions:

- MATPOWER is an open-source software tool for power system analysis in MATLAB or GNU Octave (Zimmerman et al. 2011). It originated as a tool for balanced AC power flow solutions but has since been extended for optimal power flow (OPF) and optimal scheduling applications (Murillo-Sanchez et al. 2013). Similar tools are available for other language platforms, e.g., pandapower (Thurner et al. 2018), PYPOWER (Lincoln 2021), and PowerModels.jl (Coffrin et al. 2018).
- GridLAB-D is a software tool that connects distribution system simulation and DER simulation (Chassin et al. 2008). Its core capability is to coordinate the simulation of various subsystems in an agent-based fashion, where each subsystem model can be implemented independently. Through a modular approach, GridLAB-D supports studies ranging from classical power flow analysis to integrated energy market simulation with detailed models for the behavior of individual DERs. A similar tool in this category is OpenDSS (Dugan and McDermott 2011).
- MESMO is a Python-based framework for Multi-Energy System Modeling and Optimization, which enables the convex optimization of district-scale energy system operational problems. A similar feature set is provided by the software platform OPEN (Morstyn et al. 2020).
- URBS is an open-source software tool for energy system optimization (Dorfner et al. 2019), with a focus on capacity expansion planning and unit commitment of DERs. The sibling project FICUS provides an extension for modeling multi-commodity energy systems in factories (Atabay 2017). Similar open-source frameworks are Calliope (Pfenninger and Pickering 2018), oemof (Hilpert et al. 2018), and Temoa (Hunter et al. 2013).

Table 1. Differentiating components under each scenario.

Feature	MATPOWER	GridLAB-D	MESMO	URBS
Electric grid modeling				
Power flow simulation	✓	✓	✓	
Power flow optimization	✓		✓	✓ [a]
Balanced AC model	✓	✓	✓	
Multi-phase AC model		✓	✓	
Transient dynamics model		✓		
Convex electric grid model			✓	✓ [a]
DER modeling				
DER simulation		✓	✓	
DER optimization			✓	✓
Convex DER model			✓	✓
Problem types and solution methods				
Operational problems	✓	✓	✓	✓
Planning problems				✓
Simulation-based solution	✓	✓	✓	
Optimization-based solution	✓		✓	✓
Multi-period modeling	✓ [b]	✓	✓	✓

[a] URBS implements a simplified nodal flow balance model for the electric grid. [b] Requires using the MATPOWER Optimal Scheduling Tool (MOST) extension. Source: Table by authors.

2.2. MATPOWER

MATPOWER (Zimmerman et al. 2011) is a MATLAB package that solves the nonlinear power flow, as well as OPF. Among other tools that are able to solve power flow and OPF problems, MATPOWER stands out due to its computational efficiency and extension capability, particularly in dealing with large-scale system operation and optimization problems. Researchers across the globe have relied on the MATPOWER extension capability to solve a broad spectrum of power system operation and planning problems.

For OPF problems, MATPOWER implements multiple state-of-the-art methods including the primal-dual interior-point method (Wang et al. 2007), the trust-region-based augmented Lagrangian method and relaxation-based convexified OPF models. Furthermore, MATPOWER and its underlying modules are suitable for electricity market applications. For example, MATPOWER Optimal Scheduling Tool (MOST) (Murillo-Sanchez et al. 2013) is able to solve problems as simple as a deterministic, single-period economic dispatch problem or as complex as a stochastic, security-constrained, combined unit-commitment and multi-period OPF problem with locational contingency and load-following reserve, e.g., in Cho et al. (2019); Murillo-Sanchez et al. (2013). Further studies have adopted MATPOWER in distribution network analysis and market applications (Hanif et al. 2019).

The basic features of MATPOWER are summarized in the following:

1. Modeling capabilities
   - AC and DC single-phase electric grid models;
   - Nonlinear OPF models;
   - Relaxation-based convexified OPF models.
2. OPF problems types
   - AC- and DC-OPFs;
   - Co-optimize energy and reserves;
   - Unit commitment problems;
   - Stochastic and contingency-constrained OPF problems;
   - Parallelizable OPF formulations.

2.3. GridLAB-D

As a mature open-source simulation tool, GridLAB-D (Chassin et al. 2008, 2014) combines traditional power flow simulation capabilities with advanced DER modeling and control. Its event-driven solution logic is able to simulate various interacting DERs of the electric grid, e.g., the room temperature evolution within buildings is simulated, along with the resulting load flow in the electric grid. Apart from its traditional simulation features, the recent new capabilities of GridLAB-D can be summarized as follows:

- End-use models, including thermostatically coupled and non-coupled appliances and equipment models (Pratt and Taylor 1994; Taylor et al. 2008);
- Event-driven agent-based simulation environment to allow for behavioral decision modeling;

- Module to simulate market-based control, e.g., retail market modeling tools, including contract selection, business and operations simulation tools, models of SCADA controls, and metering technologies;
- Extension to high-level languages such as MATLAB and Python through programming interfaces;
- Possibility to run parallel power flows for large-scale system simulation.

GridLAB-D's thermal end-use models consist of commercial and residential end uses, implemented using the equivalent thermal parameters model (Pratt and Taylor 1994). The innovation in these models is that they solve differential equations of their end uses such that state changes can trigger an event for the power flow base simulator to stop and sync with the end-use models. Currently, advanced models such as heat pumps, resistance heating, electric hot water heaters, washer and dryers, cooking appliances (range and microwave), electronic plugs, and lights are captured in the model.

2.4. Multi-Energy System Modeling and Optimization (MESMO)

The Multi-Energy System Modeling and Optimization (MESMO) is a Python-based software tool for optimal operation problems of electric and thermal distribution grids along with distributed energy resources (DERs), such as flexible building loads, electric vehicle (EV) chargers, distributed generators (DGs), and energy storage systems (ESS). It implements convex modeling techniques for electric grids, thermal grids, and DERs, along with a set of optimization-focused utilities. Essentially, MESMO is a software framework for defining and solving numerical optimization problems in the electric/thermal grid context, such as OPF, distributed market clearing with network constraints, strategic offering, or multi-energy system dispatch problems. Additionally, the tool also includes classical steady-state nonlinear power flow models for electric and thermal grids.

The need for its development stems from the observation that numerical-optimization-based studies of district-level energy systems often require significant upfront implementation effort, due to domain-specific models being implemented in different software tools. Additionally, applications such as distribution locational marginal pricing and distributed/decentralized market clearing further require the underlying mathematical models to be implemented in a convex manner, which often necessitates the implementation of custom mathematical formulations. To improve this workflow, MESMO implements interoperational convex modeling techniques for electric grids, thermal grids, and DERs, along with a set of optimization-focused utilities.

MESMO is intended to complement the existing software in the domain of district-level energy system simulation and optimization. Therefore, it combines (1) convex multi-energy system modeling for (2) optimization-focused studies on the operational timescale with a focus on (3) market-clearing and distribution locational marginal price (DLMP) mechanisms. Essentially, MESMO is developed as a software framework for defining and solving numerical optimization problems for multi-energy system operation. It implements convex models for electric grids, thermal grids, and DERs, along with a set of optimization-focused utilities. To this end, the feature set of MESMO can be summarized as follows:

1. Electric grid modeling
    - Obtain nodal/branch admittance matrices and incidence matrices for the electric grid;
    - Obtain steady-state power flow solution for nodal voltage/branch flows/losses via fixed-point algorithm;
    - Obtain sensitivity matrices of global/local linear approximate grid model;
    - All electric grid modeling is fully enabled for unbalanced/multi-phase grid configuration.
2. Thermal grid modeling
    - Obtain nodal/branch incidence matrices and friction factors;
    - Obtain thermal power flow solution for nodal head/branch flows/pumping losses;
    - Obtain sensitivity matrices of global linear approximate grid model.
3. Distributed energy resource (DER) modeling
    - Obtain time series models for fixed DERs;
    - Obtain state-space models for flexible DERs;
    - Enable detailed flexible building modeling with the Control-Oriented Thermal Building Model (CoBMo) (Troitzsch and Hamacher 2020).
4. Multi-energy system operation
    - Obtain and solve nominal operation problems, i.e., steady-state simulations, of electric/thermal grids with DERs, i.e., multi-energy systems;
    - Define and solve numerical optimization problems for combined optimal operation for electric/thermal grids with DERs, i.e., multi-energy systems;

- Obtain DLMPs for the electric/thermal grids.

Figure 1 depicts a contextual view for the software architecture of MESMO, i.e., a high-level overview of the most important components and the interaction between the software system and its stakeholders, based on the C4 model (Brown 2015) for representing software architecture.

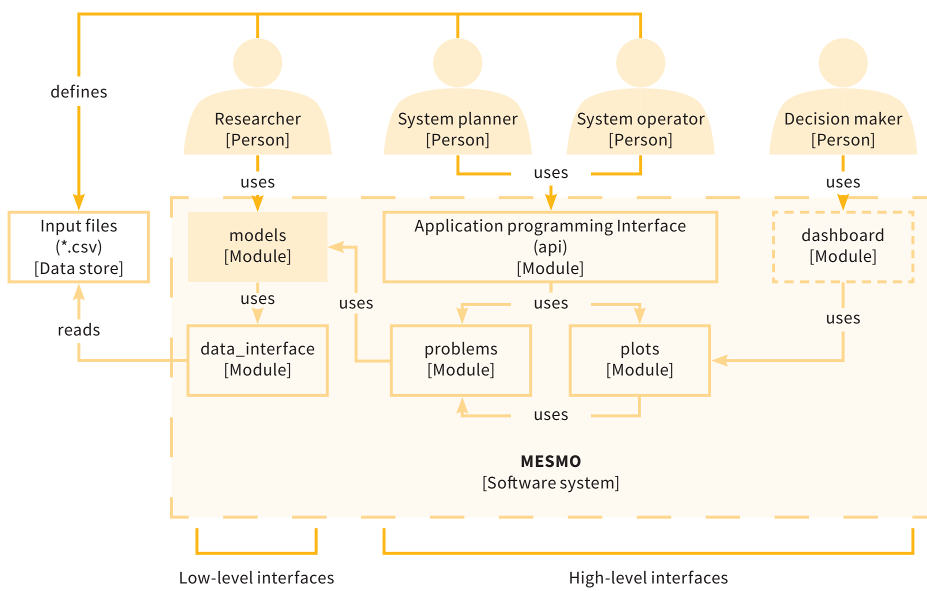

Figure 1. Software architecture of MESMO depicted as a contextual view based on the C4 model (Brown 2015). Source: Graphic by authors.

The user interfaces can be distinguished into high-level interfaces, i.e., the `api` module and the `dashboard` module, as well as low-level interfaces, i.e., the `models` modules. To this end, the `api` module and `models` modules describe programming interfaces, whereas the dashboard refers to a graphical user interface (GUI). Researchers primarily interface MESMO directly through the `models` modules, because they require highly granular access and modifiability of the modeled objects for custom workflows. System planners and system operators interface MESMO through the `api` module, which provides convenient access to the most common workflows, i.e., running of planning/operation problems and producing results plots. Decision makers interface MESMO through the GUI of the `dashboard` module. Note that the `dashboard` module has not yet been implemented at the time of writing.

Scenario and model data definitions are enabled through a standardized CSV-based input file format, which is referred to in Figure 1 as "Input files (*.csv)". The input files are expected to be defined by researchers, system planners, and system operators, where decision makers would rely on these actors to define appropriate scenarios for their review.

Internally, the `api` module implements API functions that rely on the `problem` module and `plots` module. The `dashboard` module implements the GUI framework but relies on the `plots` module to generate individual plots. The `problems` module implements the main workflows for setup and solution of different problem types, for which it uses the mathematical models defined in the `models` modules. The `problems` module also implements a standardized results object across all problem types, which is used by the `plots` module. The `models` modules further rely on the `data_interface` module to obtain the model data definitions from the input files.

MESMO has been utilized for a small number of studies focusing on multi-energy systems modeling and operation in Kleinschmidt et al. (2021); Schelo et al. (2021) as well as the design of market mechanisms for distribution-level energy systems in Troitzsch et al. (2020, 2021). The initial software architecture iteration of MESMO was developed as the Flexible Distribution Grid Demonstrator (FLEDGE) in Troitzsch et al. (2019).

2.5. URBS

URBS is an open-source linear energy system model (Dorfner et al. 2019). It is time-step based, with the default time-step size being 1 h. URBS sets up an optimization problem in which the objective is the minimization of costs or emissions in scenarios specified by the user. It is implemented in Python using Pyomo for the formulation of the optimization problem. Various numerical optimization solvers can be connected to URBS. The user can define various sites (e.g., countries or districts) and specify the following input data for each site:

- Sites (e.g., countries or districts);
- Commodities (e.g., gas, coal, electricity) and their market prices;
- Processes (i.e., power generators) and their characteristics such as installed capacity, minimum load factor, efficiency, and costs;
- Transmission and storage capacities, and costs;
- Time series of demand and intermittent generation;
- Demand-side management capacities.

Moreover, buying and selling prices for electricity and limits for costs and emissions can be specified, among others. Within the boundaries specified by the user, URBS determines which generators to use and to what capacity in order to satisfy the demand in each time step. URBS also decides whether to change the installed capacity of the given generators within the set boundaries. The user can also specify which outputs to be generated in the form of spreadsheets and plots. For each scenario, the output of URBS comprises emissions; prices and costs; installed, added, and retired capacities; transmission and storage for each site.

URBS has mostly been used for studies on transmission networks, e.g., in Europe (Schaber et al. 2012) or the Asia-Pacific region (Huber et al. 2015; Ramachandran et al. 2021; Stich et al. 2014; Stich and Massier 2015). However, it has also been used for smaller networks (Fleischhacker et al. 2019; Zwickl-Bernhard and Auer 2021) or specific applications such as managing the integration of intermittent sources of energy or electric vehicles (Massier et al. 2018), with some modifications. Due to its open-source availability, URBS can easily be modified and extended. Recently, uncertainty modeling has been integrated (Stüber and Odersky 2020), and first efforts to combine it with life cycle assessment have been made (Ramachandran et al. 2021).

3. Workflows for Test Case Preparation

3.1. Input/Output Specification

Inputs and outputs for different electric grid analysis software are typically governed by the underlying mathematical model specifications that are implemented within each tool. Therefore, each tool usually defines custom input and output formats in line with its internal data models. In this context, inputs refer to the technical system and problem parameters that define the test case, i.e., the subject of the study. Outputs are the results that are obtained after a successful solution of the simulation or optimization within the software tool. Tables 2 and 3 outline the different input and output data items for the presented software tools.

Input definitions can be provided either as (1) file-based input in text-based and table-based format or (2) script-based input. The file-based input is often the default avenue, as it allows encoding the complete test case into a single data container. At the same time, the script-based input allows for a more flexible way of defining and modifying models during runtime. This is an important capability for studies in which custom problem definitions or model coupling is desired. For example, MATPOWER can be utilized to iteratively obtain power flow (PF) solutions through continuous modification of model parameters, thereby extending beyond

MATPOWER's base functionality. In order to document their functionality, to allow for benchmarking, and to serve as tutorials, most software tools provide a bundled set of input data definitions for selected test cases. For the presented tools, the available test cases are summarized in Table 4.

Table 2. Input specifications.

	MATPOWER	GridLAB-D	MESMO	URBS
Input	MATLAB-based format	Text-based format [b]	CSV-based format [a]	XLS-based format
Electric grid parameters	• Nodes: Nominal voltage. • Lines: Node connections, resistance/reactance/ capacitance, rated current limit. • Transformers: Node connections, phases, ratio, angles, rated power, resistance/reactance parameters.	• Nodes: Nominal voltage, phases. • Lines: Node connections, phases, resistance/ reactance/ capacitance matrices, rated current limit. • Transformers: Node connections, phases, connection scheme (wye/delta), rated power, resistance/ reactance parameters. • Line and transformer parameters are encapsulated into line type and transformer type definitions.	• Nodes: Nominal voltage, phases. • Lines: Node connections, phases, resistance/reactance/ capacitance matrices, rated current limit. • Transformers: Node connections, phases, connection scheme (wye/delta), rated power, resistance/ reactance parameters. • Line and transformer parameters are encapsulated into line type and transformer type definitions.	• Lines: Node connections, efficiency, reactance, voltage angle, base voltage, installed capacity, and minimum and maximum permitted capacity for expansion planning.
DER parameters	• N.A.	• Connection: Node, phases, connection scheme (wye/delta), nominal active/reactive power. • Fixed DERs: Dispatch time series. • Flexible DERs: Equivalent thermal parameters inputs such as thermal resistance and thermal capacitance of thermal electric loads; Battery model parameters such as inverter ratings, operation strategy.	• Connection: Node, phases, connection scheme (wye/delta), nominal active/reactive power. • Fixed DERs: Dispatch time series. • Flexible DERs: Detailed state-space model parameters, e.g., thermal building parameters, battery model parameters, EV charger efficiencies, generator model parameters.	• Connection: DERs are aggregated in the sites they are located in. • Time series: Fixed for each site (demand and intermittent supply). • Demand-side management: Can be specified for each commodity.
Cost parameters	• Operation costs: Price value. • Customizable cost functions.	• Tariff type based on customer class.	• Operation costs: Energy price time series, price sensitivity.	• Investment, fixed, variable, and fuel costs of processes, storage, transmission, weighted average cost of capital, depreciation periods, CO_2 abatement costs.

[a] MESMO input data reference: https://purl.org/mesmo/docs/0.5.0/data_reference.html (accessed on 25 August 2021). [b] Base script format is .glm, whereas additional input files could be .txt, .csv, etc. For an introduction to input/output of GridLAB-D refer to: http://gridlab-d.shoutwiki.com/wiki/GridLAB-D_Wiki:GridLAB-D_Tutorial_Chapter_4_-_Data_Input_and_Output (accessed on 25 August 2021). [c] For more information on DER parameters refer to: http://gridlab-d.shoutwiki.com/wiki/Residential_module_user%27s_guide (accessed on 25 August 2021). Source: Table by authors.

Table 3. Output specifications.

	MATPOWER	GridLAB-D	MESMO	URBS
Input			CSV-based format	XLS-based format
Electric grid results	• State variables: Nodal voltage magnitude, nodal voltage angles, branch power flow, total losses, single-branch losses.	• State variables: Per-phase voltage magnitude, nodal voltage angles, branch power flow, total losses, single-branch losses, and reactive power flows.	• State variables time series: Per-phase nodal voltage, branch power flow, total losses.	• Capacities: Initial and newly installed (processes, transmission, storage, etc.). • Time series of import and export (i.e., transmission between sites) of electricity.
DER results	• N.A.	• Temperature evolution and dispatch time series of thermostatically controlled loads and active/reactive power injection by batteries.	• Fixed DERs: Dispatch time series. • Flexible DERs: Dispatch time series, detailed state/control variable time series.	• Time series of electricity generation by process per time step, emissions by generator per time step, storage utilization, demand-side management, etc.)
Cost results	• System-level costs. • DLMP values.	• Billing results of customers with different classes, energy costs etc.	• System-level / DER-level operation costs. • DLMP time series, decomposed into congestion, voltage, loss, and energy components.	• Costs: Total investment, fixed and variable costs of processes, storage, transmission, fuel costs. • Emissions: Total emissions (CO_2 and others if specified).

Source: Table by authors.

Table 4. Included test cases.

	MATPOWER [a]	GridLAB-D [b]	MESMO	URBS
Available test cases	• Small Transmission System Test Cases • Small Distribution System Test Cases • Synthetic Grid Test Cases • European System Test Cases • French System Test Cases	• Small-scale distribution system test cases (e.g., IEEE 4-Node and IEEE 37-Node systems) • A medium-scale test system with residential models to test DER modeling capabilities • IEEE 8500-Node test system	• Small-scale distribution test cases (e.g., IEEE 4-Node, Singapore 6-Node) • Medium-scale distribution test case (Singapore Geylang, see Section 4) • Multi-energy system test case (Singapore Tanjong Pagar)	• Fictitious three-region example (Dorfner et al. 2019) • The 16 states of Germany connected to a few other regions (Dorfner et al. 2019) • HVDC connection between Australia and Singapore (Siala 2021b) • Mekong region (Siala 2021a) • Southeast Asia (Siala et al. 2021)

[a] Refer to Zimmerman and Murillo-Sánchez (2019) for more information for individual test cases. [b] MESMO test cases are currently located in the `data` directory of the MESMO repository https://purl.org/mesmo/repository (accessed on 25 August 2021). Source: Table by authors.

Outputs can similarly be obtained either as (1) file-based format or (2) runtime objects. The former can include basic, text-based and table-based outputs, as well as more sophisticated data visualization in image-based formats, e.g., through the integrated plotting capabilities of MESMO and URBS. Runtime objects are data containers that cater to custom post-processing workflows of the user and enable coupling with other software tools. Such workflows for software coupling are further discussed in the context of TESP in Section 3.3.

Since each software typically defines custom data formats, the user eventually ends up preparing dedicated pre-processing and post-processing workflows for each tool. In order to reduce the upfront effort for test case input data preparation, conversion between common data formats may be possible through third-party translation tool chains, e.g., by means of GridAPPS-D, according to Section 3.2. In the long term, input/output data are foreseen to converge towards the Common Interface Model (CIM), i.e., the standardized format for electric grid models according to IEC 61970/61968.

3.2. Model Conversion via GridAPPS-D

GridAPPS-D (Melton et al. 2017; Pacific Northwest National Laboratory 2021a) is a software tool that handles model input and output conversions, which enables utilizing multiple models to build new application workflows; see Figure 2.

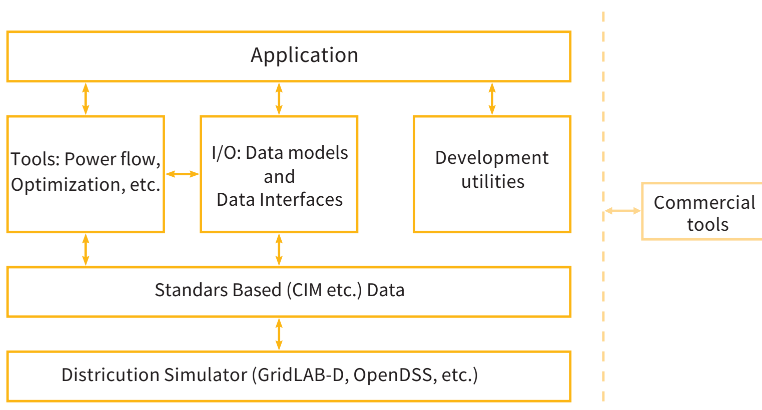

Figure 2. Overview of the software architecture of GridAPPS-D. Source: Graphic by authors, information adapted from (Melton et al. 2019).

For the test case preparation of this chapter, we utilized the Common Information Model Hub (CIMHub) to demonstrate one of the key capabilities of GridAPPS-D, i.e., the transformation of grid models across various data formats. CIMHub, as shown in Figure 3, is a module of GridAPPS-D that translates power distribution network models between different tools using the IEC 61970/61968 Common Interface Model (CIM) as a hub. CIMHub can convert models from commercial tools such as CYMDist to open-source research-grade tools such as OpenDSS and GridLAB-D. The supported inputs are CYMDist, CIM XML, OpenDSS, and Synergi Electric for distribution networks. The supported output formats are OpenDSS, GridLAB-D, and comma-separated value (CSV) for distribution systems. CIMHub can also be used to develop and propose extensions to the CIM standard.

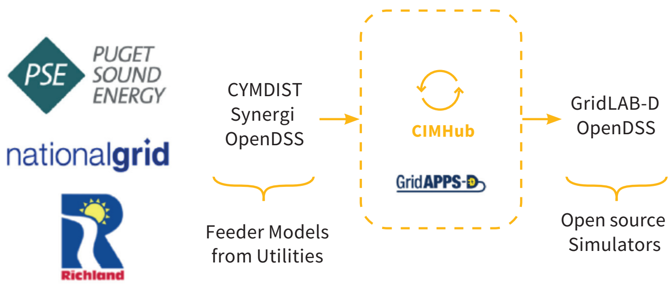

Figure 3. Power distribution network model conversion workflow via CIMHub.
Source: Graphic by authors.

One goal of the GridAPPS-D program is to encourage CIM adoption by many tool vendors, lowering the burden of model conversion and other costs of integration. Details describing the overall project and the CIM transformer model can be found in Melton et al. (2017), whereas CIM unbalanced line model and database are explained in McDermott et al. (2018). CIMHub is open source under the Berkeley Software Distribution (BSD) license.

3.3. Co-Simulation via TESP

With the utilities developed to bring models from CIM to common distribution grid analysis software, a co-simulation platform can be utilized to run legacy software in an integrated fashion (Huang et al. 2018). An example of such a co-simulation platform is given in Figure 4, called the Transactive Energy Simulation Platform (TESP). Summarizing the functionality of TESP briefly, various utilities are utilized to translate the passive distribution grid into an active one by adding interactive DERs in the GridLAB-D distribution grid model, e.g., using the `feederGenerator.py` (Pacific Northwest National Laboratory 2021b). The `feederGenerator.py` script provides a systematic way of changing the distribution grid passive loads to responsive buildings, modeled using an equivalent thermal parameter approach from Taylor et al. (2008). This is important, as this makes the distribution grid load responsive to the events occurring external to it, e.g., weather impacts, outages, and wholesale market price changes.

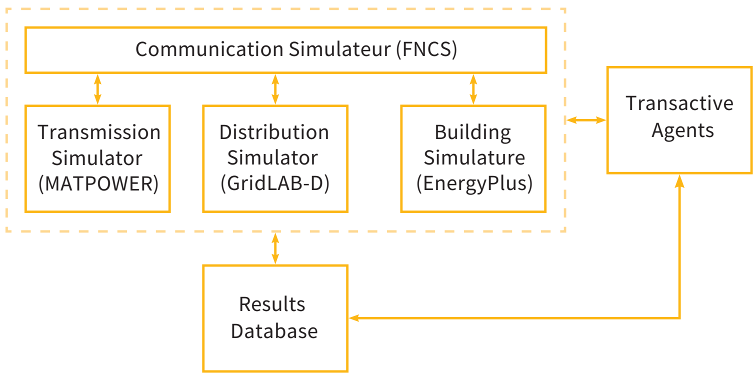

Figure 4. Co-Simulation via the Transactive Energy Simulation Platform (TESP). Source: Graphic by authors, information adapted from Huang et al. (2018).

4. Test Case

4.1. Electric Grid

The synthetic electric grid model from Trpovski (2021) was used in this test case to demonstrate the district-scale modeling capabilities of the selected tools. The following serves as a brief overview of the methodology that was applied for the preparation of the grid model, but the interested reader is referred to Trpovski (2021) for more detail. An overview of the synthetic grid layout for the Geylang District is provided in Figure 5, where 66/22 kV substations are depicted with larger nodes and 22/0.4 kV substations with smaller nodes. Note that, although depicted as direct connections between nodes, the grid lines are assumed to follow the street layout, i.e., the layout laid as underground cables.

Figure 5. Synthetic grid layout for the Geylang District in Singapore. Source: Graphic by authors.

The synthetic grid was derived based on information for (1) postal-code-clustered demand estimates and (2) 66/22 kV substation locations. Since every building block in Singapore is assigned an individual postal code, this served as a relatively detailed input for generating the 22 kV load clusters. A power system planning approach was devised to obtain the mapping and line layout between 66/22 kV substations and 22/0.4 kV substations, i.e., transformers at 22 kV load clusters. For the presented test case, the substation rating was assumed to be in 100 MVA units for 66/22 kV transformers and 1 MVA units for 22/0.4 kV transformers. This means that the minimum transformer rating for 22/0.4 kV was

1 MVA, and an appropriate integer value of transformers was deployed depending on the aggregate peak load at each 22/0.4 kV substation, where maximum utilization of 0.9, i.e., a safety factor of 1.11, was assumed for the transformer rating. The baseload time series was homogeneously defined for all 22 kV load clusters based on a representative load shape from the aggregate demand data for Singapore, which is published, along with price data, by the EMC at Energy Market Company (2021).

The final test case for the Singapore Geylang District comprised 4 subnetworks of the 22 kV distribution grid, where each subnetwork was connected to exactly one 66/22 kV substation. The total network consisted of 391 nodes and 387 lines. The lines of the synthetic grid were characterized by two line types, which defined electric parameters and current-carrying capacity, as documented in Table 5. Both line types represented underground cables, and their parameter values were based on cable supplier information, as outlined in Trpovski (2021).

Table 5. Electric line types.

Line Type	Max. Current	Resistance	Reactance
Type A	585 A	$0.23\,\Omega\,\mathrm{km}^{-1}$	$0.325\,\Omega\,\mathrm{km}^{-1}$
Type B	455 A	$0.39\,\Omega\,\mathrm{km}^{-1}$	$0.325\,\Omega\,\mathrm{km}^{-1}$

Source: Table by authors.

4.2. Building Models

The overview of the inputs, methods, and outputs for processing the feeder to attach flexible DERs to the passive loads is given in Figure 6. From the provided inputs, the stages to change the passive loads to an active one, i.e., loads that can dynamically change response based on external (weather) and internal (temperature) variables are shown. The workflow is as follows:

1. First, back-bone feeders with information on substations, lines, and loads were inputted in GLM format.
2. The module used the `networkx` Python package to perform graph-based capacity analysis and upgrades relevant protection equipment such as fuses, transformers, and lines to serve the expected load. For example, transformers can be oversized with a margin of 20%, and the circuit breaker to the air conditioner can be rated 2 times the nominal electrical load.
3. Each load was then changed to contain ZIP load, plug loads schedules, and thermostatically controlled load, as intended with the percentage population.

For example, 40% thermostatically controlled load penetration would result in convergence of only 40% load to thermodynamic models, and the rest would be left as fixed loads with a time series, which could be modified to change their load shape.

4. For each thermostatically controlled load, the equivalent thermal properties parameter (Taylor et al. 2008) were randomized to represent a certain population of devices.

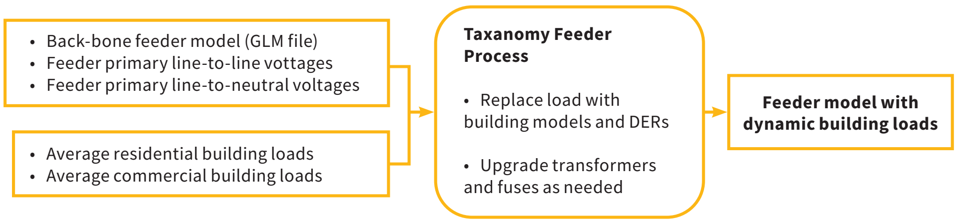

Figure 6. Building model generation workflow with `feederGenerator.py`. Source: Graphic by authors, information adapted from Pacific Northwest National Laboratory (2021b).

4.3. EV Chargers

Figure 7 highlights the main steps for the derivation of the EV charger models for private EV charging. First, historical car park availability data was used to derive representative vehicle inflow and outflow time series for existing car parks in the study area through probabilistic modeling. Second, a car park charging simulation was computed based on the representative vehicle inflow, outflow, EV penetration, and EV/charger parameters. This served to obtain the required input time series for the definition of fixed EV chargers and flexible EV chargers in MESMO.

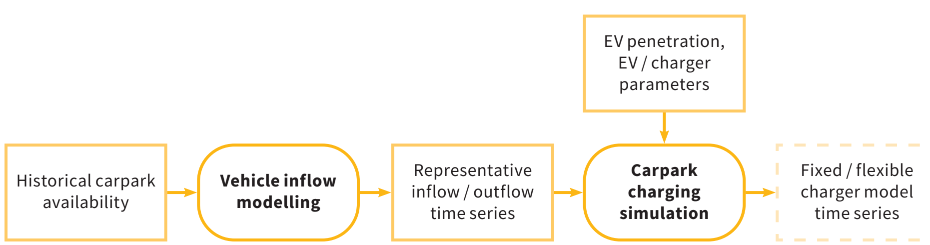

Figure 7. Workflow for EV charger demand modeling. Source: Graphic by authors.

The main input data items for the synthetic EV charger demand modeling were (1) the historical car park availability and (2) car park capacity. Both inputs were obtained from the LTA Datamall API (Land Transport Authority 2021b), which contains a selection of public residential, commercial, and mixed-use car parks in Singapore, particularly at public housing developments, government-operated general public car parks, and large-scale mixed-use developments, e.g., malls with attached office blocks. The input data was recorded at 10 min intervals between September 2018 and March 2020. Additional technical model parameters for EVs and chargers are defined in Table 6. In this test case, four EV penetration scenarios were considered: 0% (baseline scenario), 25%, 75%, and 100%.

Table 6. Electric line types.

Parameter	Value	Source
Private car population (Singapore)	520,000	(Land Transport Authority 2020a, 2020b)
Vehicle driving distance (Singapore), mean value	$48\,\mathrm{km\,d^{-1}}$	(Land Transport Authority 2021a)
Vehicle driving distance (Singapore), standard deviation	$16\,\mathrm{km\,d^{-1}}$	Assumed
EV energy consumption	$170\,\mathrm{W\,h\,km^{-1}}$	(EV Database 2021)
Charger efficiency	95%	Assumed
Charger power factor	0.95	Assumed
Slow charger active power	7.4 kW	Assumed
Slow charger share	75%	Assumed
Fast charger active power	50 kW	Assumed
Fast charger share	25%	Assumed

Source: Table by authors.

4.4. Photovoltaic Generators

Photovoltaic (PV) generation potentials were estimated for this test case to demonstrate the ability of URBS for determining the cost-optimal deployment of renewable generators. To this end, PV generators were not directly modeled, but instead, the generation potential was estimated for each node of the electric grid. Importantly, PV deployment was assumed only at building surfaces, as the considered test case was based in an urban environment. Therefore, in the first step, the horizontal building surfaces were obtained from geographical information system (GIS) data for the building polygons in the test case area. In the second step, the PV generation potential at individual buildings was estimated from the available surface area and historical solar irradiation data for Singapore. Third and last, the PV generation potential of each building was mapped to the corresponding node of the synthetic electric grid. Input data items for this workflow were (1) the GIS data for building polygons and (2) the historical solar irradiation time series for Singapore. The former was obtained from Open Street Map through the Overpass API, based on the data in August 2021. The total installable PV capacity in the study area amounts to 2023 MW. Half-hourly time series of solar irradiance in Singapore were used.

Costs for rooftop PV system installations in Singapore were taken from Solar Energy Research Institute of Singapore (SERIS) (2020). For a high-efficiency system of more than 1 MW_p, a cost of ca. SGD 0.92 per W (USD 0.68 per W) was reported for 2021. For smaller systems (below 600 kW_p), the reported cost was USD 0.74 per W, and for below 300 kW_p, it was USD 0.95 per W.

4.5. Other Generators and Demand

Information on electricity generation capacity by generator type in Singapore was taken from Energy Market Authority (2020a). The installed capacity of the different generator types is listed in Table 7. These do not include the potential PV capacity in Geylang. Cost efficiencies of power plants in Singapore were obtained from Lacal Arantegui et al. (2014). They are given in Table 8.

The half-hourly electricity demand of Singapore was taken from Energy Market Authority (2020b), which is made available under the terms of the Singapore Open Data Licence version 1.0[1]

Table 7. Installed capacity of existing generators in Singapore.

Generator	Installed Capacity (GW)	Efficiency (%)
Gas (CCGT)	10.50	59
Gas (OCGT)	0.18	40
Gas (steam turbine)	2.06	38
Oil	0.49	38
Waste-to-energy	0.26	28
PV	0.17	16

Source: Table by authors, values based on Energy Market Authority (2020a).

[1] https://www.ema.gov.sg/Terms_of_use.aspx (accessed on 25 August 2021).

Table 8. Fuel prices.

Fuel	Price (USD/MWh)
Gas	31
Oil	40
Waste	12
Biomass	6

Source: Table by authors, values based on Lacal Arantegui et al. (2014).

5. Results

5.1. MATPOWER

This part of the study utilizes the load flow analysis from MATPOWER to study the impact on the electrical grid from different EV penetration levels. The result is shown in Figure 8, where the indicators are the branch losses and voltage profile at 22 kV distribution lines in the Geylang test case. It is worth noting that the voltage drop increases linearly to the additional peak demand from EV charging power, whereas losses increase exponentially to the additional EV charging demand.

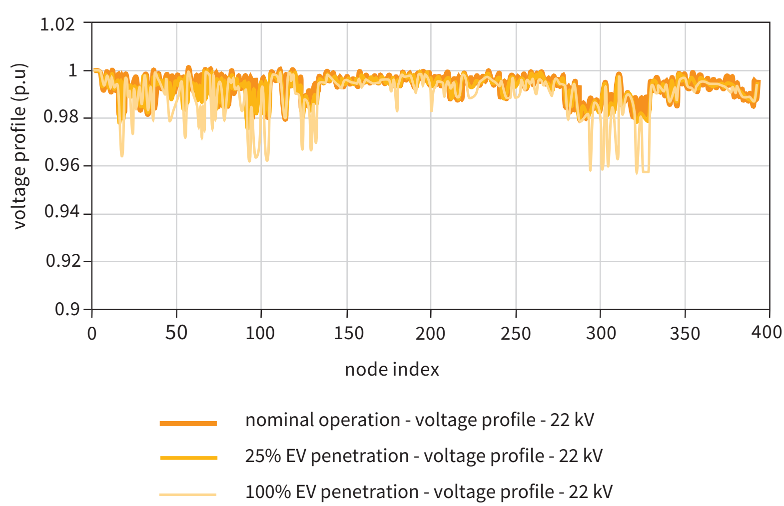

Figure 8. *Cont.*

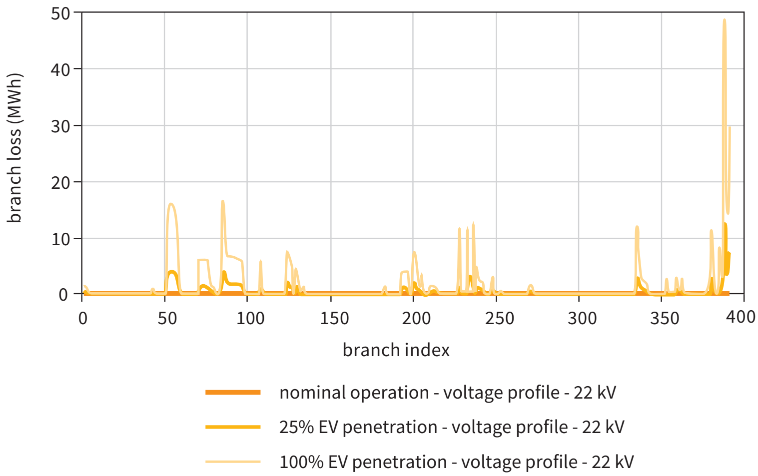

Figure 8. Voltage profile and branch losses for different scenarios from MATPOWER. Source: Graphic by authors.

5.2. GridLAB-D

Figure 9 shows the feeder load profile of the grid, which has been shown to contain thermostatically controlled loads. For the sake of simulation, we populated 525 houses with an average 3 kW load. We can observe the capability of the disaggregating contribution of thermostatically controlled load from the total load of the feeder.

Furthermore, one can select one of the thermostatically controlled loads from the population and plot its internal variables, such as temperature evolution, setpoints, and load; see Figure 10. Note that in Figure 10, the cooling of two buildings is shown by plotting the aggregated temperature of the room. For both buildings, note that aggregated temperature decreases with an increase in consumption, showing the powering of the air-conditioner and staying close to its set point.

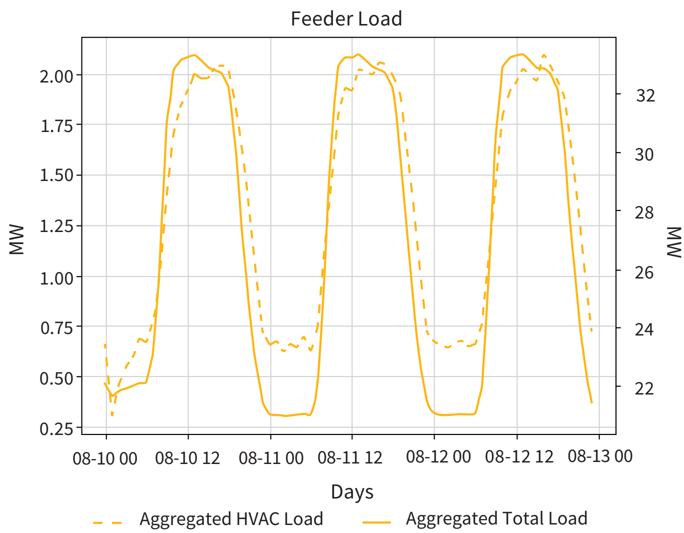

Figure 9. Feeder load profile—averaged over 5 min. Source: Graphic by authors.

Figure 10. Building temperature and consumption—averaged over 5 min. Source: Graphic by authors.

5.3. MESMO

For the uncontrolled charging scenario, Figure 11, in its lower portion, depicts the cumulative distribution of substation transformer utilization in the test case area. The upper portion of Figure 11 describes the distribution of the transformer utilization with a box plot. The utilization level is calculated as the ratio of peak loading to the rated loading of the transformers. Recall from Section 4.1 that 22/0.4 kV transformers are assumed to occur in 1 MVA units. To this end, a large proportion, i.e., as much as 85% of transformers experience between 0.1 and 0.3 utilization in the baseline scenario (0% EVs) because load clusters can be significantly smaller than 1 MVA in the synthetic grid. In the baseline scenario, nearly 100% of substations are loaded below 0.9, where the median utilization occurs at approx. 0.11 and the mean utilization at approx. 0.21. With increasing EV penetration, the share of substation transformers loaded below 0.9 falls to approx. 94% for 25% EVs and below 90% for both 75% and 100% EVs. The median substation utilization increases to approx. 0.15 and remains constant across the higher penetration levels, since the substations with allocated charging demand occur consistently above the median level. The mean utilization increases proportionally to the EV penetration level, i.e., up to approx. 0.5. Note that the plot is truncated at the utilization level 1.0 for consistency, although higher-level EV penetration scenarios can cause significant overloading of selected transformers due to the highly localized nature of these loads.

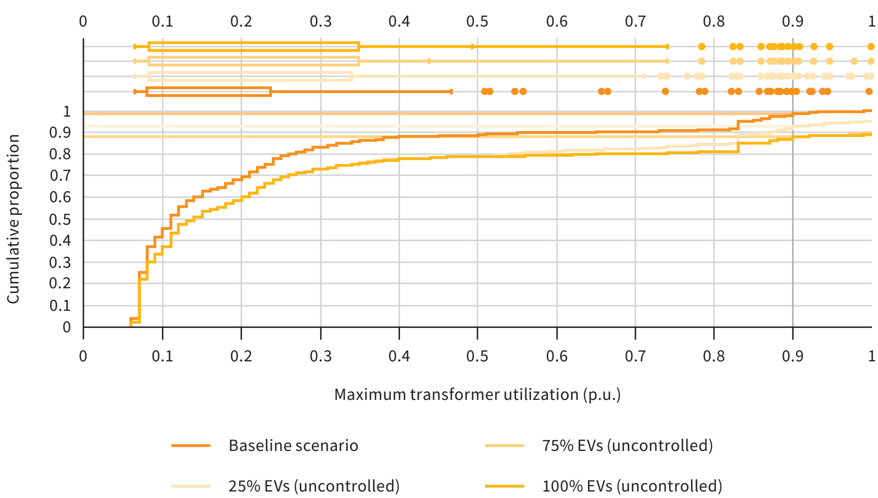

Figure 11. Substation transformer utilization for uncontrolled charging. Source: Graphic by authors.

Figure 12 depicts a comparison of the substation utilization for smart charging and uncontrolled charging across the different EV penetration levels. For 25% EVs, the smart charging increases the share of transformers loaded below 0.9 from approx. 94% to approx. 99%, and the mean utilization is decreased by approx. 0.08. For higher penetration levels, the benefit of smart charging reduces proportionally. At 100% EVs, the share of transformers loaded below 0.9 only increases by approx. 1%, although mean utilization decreases by approx. 0.08, i.e., similar to 25% EVs and 75% EVs. This behavior is due to the very high peak load at local substations, i.e., even a significant flattening of demand peaks still leads to highly overloaded substations in the 100% EV penetration scenario.

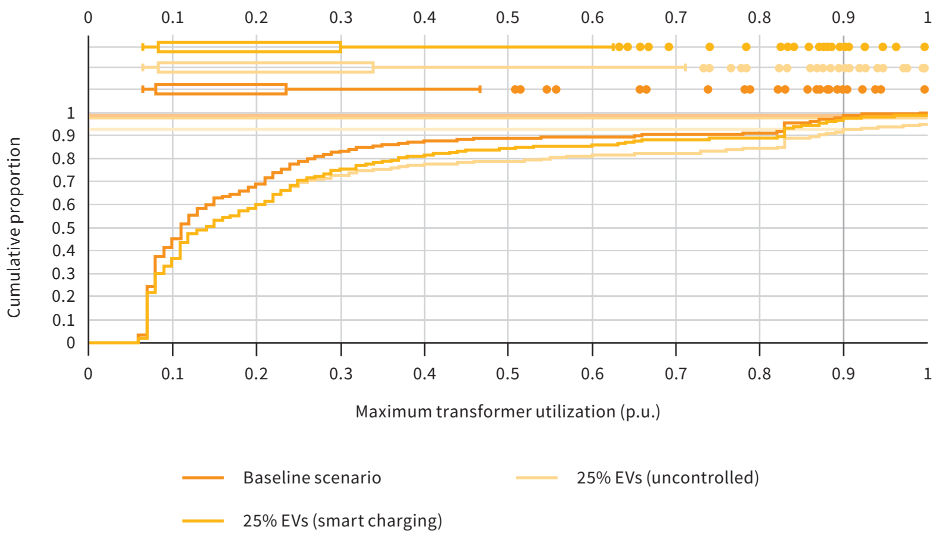

Figure 12. *Cont.*

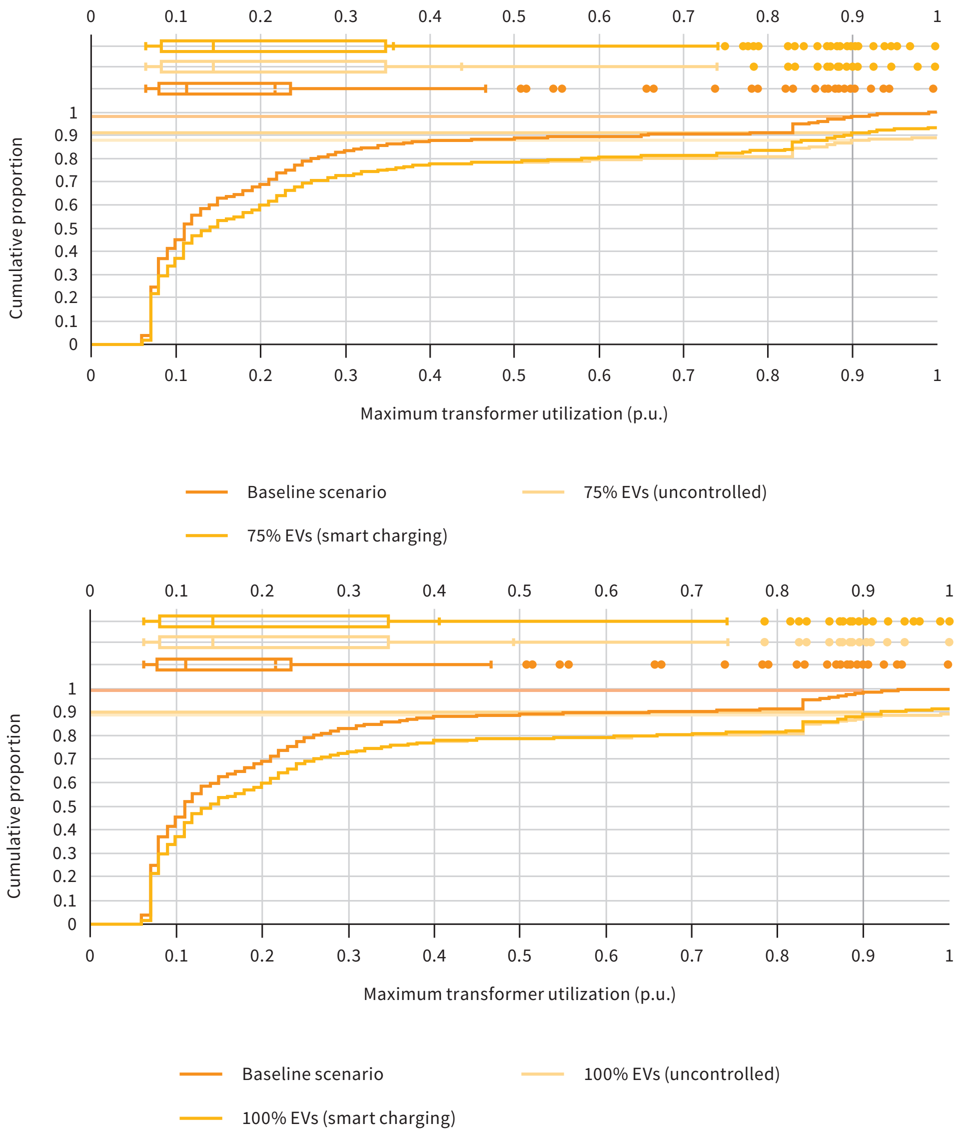

Figure 12. Substation transformer utilization for smart charging. Source: Graphic by authors.

5.4. URBS

For URBS, we set up a model with the parameters defined in Sections 4.4 and 4.5. The model consisted of the grid defined in Section 4.1 plus one additional node representing the “rest of Singapore”, with its demand and its fossil generators. Each of the four 66/22-kV substations was connected to this additional node since the grid of the test case was divided into four isolated subgrids. Electricity can be transmitted both ways between Geylang and the rest of Singapore. The transmission capacity of the lines between the four entry points to the Geylang grid and the rest of Singapore was set sufficiently high to allow for unrestricted power exchange, which is realistic given the high robustness of Singapore’s grid.

In this case study, PV and electric vehicle chargers could be installed in Geylang only. URBS could decide to increase the transmission capacity of the existing grid lines in the Geylang network if needed. We defined four scenarios with regard to PV and EV chargers to be deployed in Geylang, with Scenario 1 being the reference scenario. See Table 9.

Table 9. Scenarios in URBS. Scenario 1 is the reference scenario.

Scenario	PV	EV Chargers
1	no	no
2	yes	no
3	no	yes
4	yes	yes

Source: Table by authors.

The reference scenario was to test the feasibility of the model, i.e., whether the demand could be satisfied in every time step and whether the existing distribution capacity was sufficient. The costs and emissions of the system were determined as well.

For scenarios 2 and 4, we analyzed how much PV power and additional line capacity URBS decided to install for different costs of PV systems ranging from USD 0.70 per W to USD 0.85 per W. In these scenarios, all PV must be integrated. The results are displayed as subscenarios a, b, c, and d. A typical day regarding the solar insolation profile in Singapore with an average irradiance of 363 W m^{-2} during daytime and a maximum irradiance of 815 W m^{-2} was chosen for the study. URBS determines the cost-optimal solution taking into account costs of fossil generation, PV installations, and grid upgrades. The lower the price, the higher the installed PV and additional installed distribution capacity.

For scenarios 3 and 4, we chose the fixed EV charging case with and EV penetration of 100%.

In the reference scenario, no additional transmission lines were built. Hence, the test case is feasible. The amount of installed PV and additional transmission capacity for all other scenarios, as well as resulting cost and emission reduction, compared with the reference scenario, are shown in Table 10. For the lowest PV price, the model installs more than 1700 MW of the maximum possible amount of 2023 MW of PV. The new install grid capacity is up to almost 4200 MW for the highest value of installed PV capacity. This number does not depend significantly on the EV penetration of 0 or 100% with fixed charging. Note that in scenario 3, without PV, an additional 150 MW of grid capacity is installed in order to supply the EV charging demand, while the difference of installed grid capacity between cases 2 and 4 is lower than that, which means that some of the PV power can be used directly to charge EVs.

Table 10. URBS scenarios showing installed PV capacity and additional grid capacity for different prices of PV systems and EV penetration levels of 0 or 100%.

Scen.	PV Inst. Cost	EV Penetr.	Inst. PV Cap.	New Grid Cap.	Cost. Red.	Em. Red.
—	(USD/W)	(%)	(MW)	(MW)	(%)	(%)
1	—	0	0	0	0	0
2a	0.85	0	970	780	0.16	2.75
2b	0.80	0	1290	1820	0.30	3.62
2c	0.75	0	1580	2640	0.47	4.14
2d	0.70	0	1710	4170	0.67	4.77
3	—	100	0	150	−0.59	−0.59
4a	0.85	100	1020	870	−0.40	2.31
4b	0.80	100	1340	1900	−0.26	3.17
4c	0.75	100	1510	2690	−0.08	3.63
4d	0.70	100	1720	4060	0.12	4.22

Source: Table by authors.

Cost savings are marginal. When PV is installed, fuel costs decrease since less power from fossil fuels is required, but investment and fixed cost of PV and new gridlines are about as high as the savings. For scenarios 3, 4a, 4b, and 4c, a slight cost increase can be observed. Overall CO_2 emission reduction in Singapore's power generation is up to almost 5%, depending on the amount of PV installed. Due to the additional demand caused by EVs, the emission reduction is lower in scenario 4 and negative in scenario 3, where installation of PV is not allowed.

Figure 13 shows the demand and PV generation in Geylang for one day without and with EV charging. The pattern under the blue demand curve depicts the demand covered by fossil fuels. The white part is covered by PV. The pattern under the red PV curve depicts the amount of PV exported to the rest of Singapore. For both with and without EV charging, the curves appear similar. During the day, when power is generated by PV, the share of demand in Geylang covered by PV is 88% without EV charging and 88% with EV charging. EV chargers are only connected at 43 nodes, while URBS decided to install PV at 302 nodes, such that PV supply and EV charging demand are not necessarily matched, and installing additional grid capacity is costly.

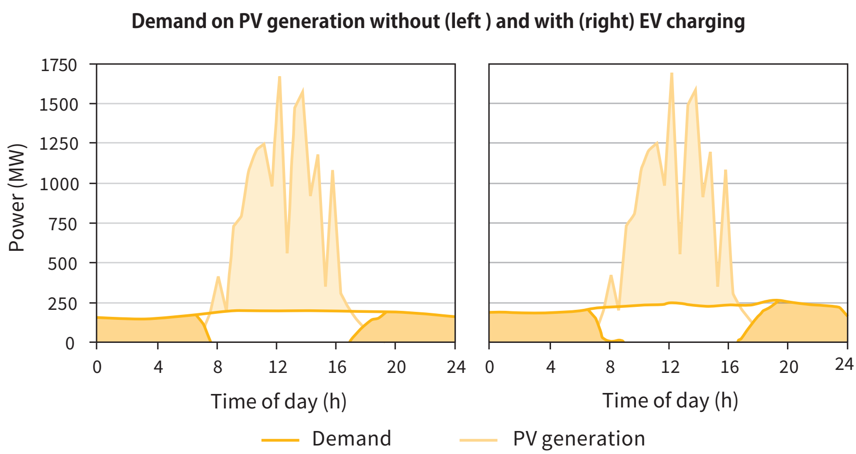

Figure 13. Demand (dark orange) and PV generation (light orange) in Geylang without (**left**) and with (**right**) EV charging. The dark orange area depicts the share of the demand that has to be supplied from Singapore's fossil fuel power plants, while the white area under the dark orange curve represents the amount supplied by PV. The light orange pattern depicts the amount of solar PV that is exported to the rest of Singapore where it replaces fossil generation. Source: Graphic by authors.

6. Discussion

The presented results underline the key capabilities of each of the software tools. For district-scale electric grids, these capabilities can be summarized as follows:

- MATPOWER primarily supports the study of operational problems for the electric grid, with capabilities for both simulation-based and optimization-based analysis. This tool caters to the need for a highly accessible power flow simulation tool with the convenience of scripting directly through MATLAB. While MATPOWER is limited to balanced AC power simulations, this is often sufficient for an initial assessment of grid hosting capabilities upon deployment of renewable generators or additional loads, as demonstrated in Section 5.1. In this regard, the tool is also suitable for the scenario-based study of planning problems in the electric grid. While the MATPOWER's focus was originally on a single-step power flow solution, it has been extended with an ecosystem of optimization-based and multi-period analysis, e.g., through the OPF or MOST interfaces.
- GridLAB-D is a software framework focused on the simulation-based analysis of operational problems for the district-scale electric grid and DERs. The tool enables the utilization of highly detailed models for each subsystem of the district-scale energy system. This is demonstrated in Section 5.2 in terms of the detailed modeling of HVAC loads of the buildings in the synthetic grid. GridLAB-D benefits from the rich ecosystem of tools for model preparation and co-simulation, which were presented in Sections 3.2 and 3.3. Since GridLAB-D caters mainly to simulation-based electric grid analysis, it does not directly enable optimization-based solutions to electric grid operation problems. Yet, an optimization-based control system can indirectly be included through co-simulation, e.g., with TESP. To this end, GridLAB-D can serve as a testbed for novel market frameworks, where the DER dispatch and market clearing are implemented via TESP, and the GridLAB-D simulation acts as a digital twin for the electric grid and DER systems.
- MESMO is a software tool that caters primarily to the optimization-based analysis of operational problems. The tool focuses on supporting the formulation of convex optimization problems for the operation of district-scale electric grids and DERs. With this focus on the convex domain, the tool is well suited for the analysis of market-clearing problems based on decomposition techniques arising from numerical optimization. For example, MESMO directly outputs the DLMP values for operational problems. However, due to the focus on convex modeling, DER models in MESMO are limited to simple state-space expressions. To this end, simulation-based analysis with MESMO is less powerful than in GridLAB-D. Compared with MATPOWER, the scripting interface of MESMO through Python is less mature and less stable. As presented

in Section 5.3, MESMO is suitable for the analysis of flexibility potentials in DERs of the electric grid, which is enabled through the highly customizable range of DER models without requiring external model coupling. Note that MESMO also supports the analysis of multi-energy systems, e.g., in terms of thermal grids.

- URBS is a toolbox that is heavily focused on the optimization-based analysis of both planning and operation problems. Hence, it is the only one of the presented tools which directly addresses planning problems. Similar to MESMO, URBS focuses on convex modeling of the electric grid and DERs, although the models are significantly more simplified with a focus on capturing capacity constraints. As presented in Section 5.4, URBS can be employed for determining the optimal deployment of renewable generation, where emission reduction and other objectives can be considered in addition to conventional cost minimization.

Although there is an overlap in the capabilities of the presented tools, there is currently no comprehensive solution that covers the complete feature set for electric grid analysis. Particularly, there is a trade-off between optimization-based tools, which are typically restricted in modeling detail, and simulation-based tools, which favor modeling detail over convex mathematical formulations. This highlights the importance of clarifying the focus of electric grid studies with stakeholders in advance to identify a specific set of features expected for the chosen software platform.

7. Conclusion

This chapter discussed the role of open-source software frameworks in the transition towards affordable electricity. To this end, the chapter introduced the different problem types and requirements for electric grid analysis in the context of studies for the integration of novel DERs, such as renewable generators, EV chargers, flexible loads, and energy storage systems. Along with this, a representative set of open-source tools and their feature sets were introduced and compared. This served to identify and differentiate the key use cases for different software frameworks. The main functionalities of each tool were demonstrated for a synthetic electric grid test case based in Singapore. To conclude, this chapter, and Section 6 in particular, is intended as a guideline to open-source tools for various electric grid simulation and optimization applications.

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visualization, S.T., S.H., T.M.; All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The test case definitions for GridLAB-D, MESMO and urbs (see Section 4) are available open-source, online at: https://github.com/mesmo-dev/testcase_transition_towards_affordable_electricity_2022 (accessed on 4 April 2022).

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Conflicts of Interest: The authors declare no conflict of interest.

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