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Expert survey and classification of tools for modeling and simulating hybrid energy networks

Edmund Widl [a,*], Dennis Cronbach [b], Peter Sorknæs [c], Jaume Fitó [d], Daniel Muschick [e], Maurizio Repetto [f], Julien Ramousse [g], Anton Ianakiev [h]

[a] AIT Austrian Institute of Technology, Center for Energy, Vienna, Austria
[b] Fraunhofer Institute for Energy Economics and Energy System Technology (IEE), Kassel, Germany
[c] Aalborg University, Department of Planning, Aalborg, Denmark
[d] Univ. Grenoble Alpes, CEA, Liten, Campus Ines, 73375, Le Bourget-du-Lac, France
[e] BEST – Bioenergy and Sustainable Technologies GmbH, Graz, Austria
[f] Politecnico di Torino, Department of Energy, Torino, Italy
[g] LOCIE UMR5271, CNRS – Université Savoie Mont Blanc, Chambéry, France
[h] Nottingham Trent University, School of Architecture Design and the Built Environment, Nottingham, United Kingdom

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A B S T R A C T

Sector coupling is expected to play a key role in the decarbonization of the energy system by enabling the integration of decentralized renewable energy sources and unlocking hitherto unused synergies between generation, storage and consumption. Within this context, a transition towards hybrid energy networks (HENs), which couple power, heating/cooling and gas grids, is a necessary requirement to implement sector coupling on a large scale. However, this transition poses practical challenges, because the traditional domain-specific approaches struggle to cover all aspects of HENs. Methods and tools for conceptualization, system planning and design as well as system operation support exist for all involved domains, but their adaption or extension beyond the domain they were originally intended for is still a matter of research and development. Therefore, this work presents innovative tools for modeling and simulating HENs. A categorization of these tools is performed based on a clustering of their most relevant features. It is shown that this categorization has a strong correlation with the results of an independently carried out expert review of potential application areas. This good agreement is a strong indicator that the proposed classification categories can successfully capture and characterize the most important features of tools for HENs. Furthermore, it allows to provide a guideline for early adopters to understand which tools and methods best fit the requirements of their specific applications.

1. Introduction

Sector coupling of power, heat and gas has been identified as an important enabler for a transition towards a more sustainable energy system [1]. However, even though the enabling technologies are well understood on the component level, their effects on the system level are still subject of investigations. This is true for the integration of coupling points in multi-energy systems (MESs), and even more so for hybrid energy networks (HENs). From an energetic and a technical point of view, a MES is a means to cover the energy demand by combining thermal, electrical and/or chemical energy carriers. A HEN can be defined as a combination of physically separated electricity, heating and/or gas networks, which in combination supply a single demand such as heating or cooling. Whereas MESs can be considered as a general approach for sector coupling, HENs focus specifically on the network, which is a necessary requirement for implementing sector coupling on a large scale.

Unfortunately, there is still a lack of tools for the assessment of HENs. On the one hand, established tools for system design, optimization and operation exist for all relevant domains (heat, power, gas, etc.). However, tools for energy networks are typically concerned with a single domain only. On the other hand, established tools for modeling of MESs have no focus on energy networks. Hence, they are not able to capture important features of energy networks such as network capacity or congestion. For this reason, in recent years a lot of effort has been put into developing new tools and methods for the assessment of HENs. These new methods and tools are very diverse in terms of modeling the HEN subsystems (power, heat, gas, etc.) as well

* Corresponding author.
E-mail address: edmund.widl@ait.ac.at (E. Widl).

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as the targeted applications (technical assessment, operational optimization, planning, etc.). This gives researchers and engineers more and more possibilities to study and analyze HENs. At the same time, the growing number of available tools and methods makes it more challenging for users to keep track and select the best possible tool for their specific application. This is all the more true in light of the fact that – to the best knowledge of the authors – there exists no categorization of these new tools and methods that would guide users to make an informed decision as to which to select.

1.1. Scope and main contributions

The present work addresses the following research questions (RQ):

- RQ1: What types of tools are available for the assessment of HENs? How do they model the HEN subsystems and what insights can they provide?
- RQ2: For what types of applications are the available tools applicable?

For answering these questions, the present work starts with a survey of available approaches for the assessment of HENs. To put a strong focus on applicability for potential users, care was taken to select only tools that are publicly available (commercially, open-source or otherwise) and whose use for assessing HENs is documented (see Section 3.1). Based on this, RQ1 is addressed by categorizing the corresponding tools, based on dedicated classification categories that focus on their spatial and temporal resolutions, the applied modeling approaches and other related properties (see Section 3.2). This enables a systematic analysis and detailed comparison of the selected tools (see Section 4), revealing different types of tools and methods for the assessment of HENs (see Section 5).

RQ2 is addressed by mapping the resulting types on specific application classes, from which a guideline of recommended methods is derived. Given a certain application (e.g., system design, generation portfolio optimization, controller design), this guideline provides a concrete recommendation on which tools to use based on the proposed classification (see Section 6).

2. Background

Tools and methods for the simulation-based analysis of energy networks typically target just one specific engineering domain, e.g., heat networks [2] or power grids [3–5]. At best, only coupling points to other domains can be modeled, but not HENs in their full complexity. The reason is that these tools are either the result of long-term academic research efforts of specific fields of engineering or have been developed by industry with a specific aim and audience in mind. With the advent of smart grids, this focus has been broadened to include communication networks [6,7], but not HENs.

Research on MESs has focused primarily on matching supply and demand through the optimization of either the planning or the operation of a diverse set of generation, storage and conversion units [8,9]. This is also reflected by the tools and methods used for the assessment of MESs, see for instance recent reviews on tools and methods for modeling energy systems on the urban scale [10–14], for standalone and grid-connected hybrid energy systems [15,16], or the energy transition in general [17].

The consideration of effects of multi-energy applications on the related network infrastructures started basically with studies on coupled power and gas grids. In this traditional type of HEN, the subsystems are primarily coupled through gas-fired generators on a large scale. Research focused therefore on long-term expansion planning [18], long-term optimal planning [19], and short-term optimal operation [20] of coupled power and gas networks. However, it turns out that the vast majority of publications on this subject introduces methods (i.e., typically a mathematical optimization model combined with an optimization method), but no readily available tools for users.

Work on HENs that couple power and heat, in comparison, is a rather new topic [21,22]. Especially the simulation-based technical assessment of this type of HENs – where the focus lies on issues related to the operation and closed-loop control of the networks themselves – has remained a challenge. The development of tools and methods for overcoming this challenge is basically still ongoing [23–28].

To the best knowledge of the authors, there exists no survey and no categorization of available tools with an explicit focus on HENs. For the specific case of HENs that couple power and gas grids, surveys focus mostly on methods, but not on available tools [18–20]. For the general case of HENs that couple power, heat and gas, the importance of understanding the impact on the network infrastructure is frequently highlighted in literature. Previously conducted reviews [8–17] provide an overview of tools and methods for the modeling and simulation of closely related topics such as urban energy, building systems, and multi-energy applications. But none has so far considered the specific requirements for analyzing HENs, which exhibit phenomena (such as congestion, distribution losses, flow reversal and others) not encountered in other energy domains and which therefore require customized tools and methods. This paper aims to fill this gap by providing such an overview and goes even further by providing a guideline for early adopters.

3. Methodology

The overall process that has been applied for selecting and assessing tools is shown in Fig. 1. It consisted of the following steps:

1. *Screening*: A preliminary list of tools was compiled with the help of an online survey, which was targeted at tool developers from academia and industry.[1] The results from the online survey were augmented with a survey of tools reported in literature. This was based on the most recent reviews on tools for MESs, especially Refs. [13,14,16,17] (compare to Section 2).
2. *Selection*: A predefined set of selection criteria (see Section 3.1) was applied to the preliminary list to arrive at a final selection. Only tools from this final selection have been used for the results and conclusions reported in Sections 5 and 6, respectively.
3. *Assessment*: The assessment of the selected tools was based on a classification of their features according to a predefined set of categories (see Section 3.2). The results reported in the present work are the outcome of a consensual synthesis of the individual assessments of at least two expert reviewers.

The intention behind the screening and selection process was to find a compromise between inclusiveness and a narrow scope. The online survey was successful in reaching a rather large audience from different communities (district heating and cooling, Smart Grids, buildings, etc.) working towards the subjects of MES and HEN from different angles. The resulting feedback was

[1] The survey was promoted through the international network of the IEA DHC Annex TS3, with the aim of reaching as many potential contributors with a relevant background in energy modeling as possible. For more information on the IEA DHC Annex TS3 please refer to the acknowledgment section below.

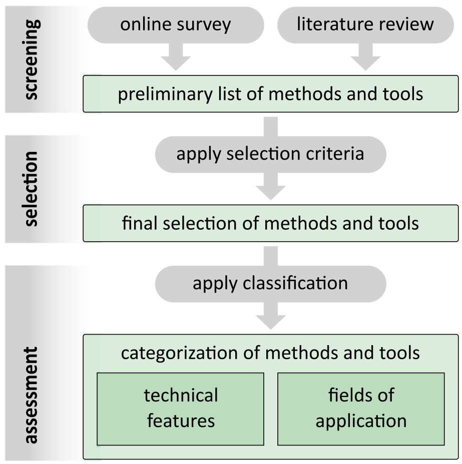

Fig. 1. Schematic view of the methodology applied for selecting and reviewing tools.

correspondingly broad and diverse. Hence, applying the selection criteria described in Section 3.1 was a necessary prerequisite for focusing specifically on readily available tools and methods intended for the analysis of HENs.

Basing the assessment for each tool on the consensual synthesis of at least two reviews had several reasons. First, this allowed to have a pool of experts (i.e., the authors) with complementing areas of expertise for performing the reviews. Second, applying the same set of classification categories to different types of tools is challenging, even if the categories are well defined. In case of ambiguity or uncertainty, a discussion among experts – together with input from contacting the developers directly – can best clear up possible inconsistencies, leading to an improvement in the accuracy and reliability of the results.

In the following, the selection criteria and classification categories are presented and discussed.

3.1. Selection criteria for tools

For the final selection of tools presented in this work, the following selection criteria (SC) have been applied to the preliminary candidate list:

- SC1 – Focus on multi-energy networks: At least two types of energy networks must be considered. Each energy network must be considered at least on the level of energy balances (implicit network model).
- SC2 – Documentation: An application in the context of hybrid energy networks must be publicly documented (manual, journal article, etc.).
- SC3 – Availability: An implementation of the tool must be publicly available, either commercially or otherwise (open source, freeware, etc.).

These 3 selection criteria were chosen to have a reproducible selection process based on relevant and quantifiable facts. Only tools that verifiably meet all 3 criteria have been selected. Sections 4 and 5 report the resulting outcomes for the selected tools.

The requirements formulated by SC1 and SC2 aim at distinguishing tools for MES from tools with the narrower focus on HEN. SC2 restricts multi-purpose tools that could be theoretically used for analyzing a HEN to those where a specific demonstration of this use-case was found. This follows the spirit of this work, which explicitly puts the attention on tools for the assessment of HENs.

The constraint of SC3 on the final selection is unusual for surveys of tools and methods. However, SC3 assures that the approaches presented in this work are accessible for users and easily applicable to their problems. This is important in view of the discussion in Section 6, which aims at providing a guideline for early adopters for understanding which tools and methods best fit the requirements of their specific applications.

3.2. Classification categories for tools and methods

In the following, the classification categories applied to the final selection of tools are presented. All categories have been defined in such a way that a classification can be made using fixed, predefined attributes. Attributes either map to

- a range of items (possibly a continuum), which exhibit a strict, hierarchical order (e.g., sub-range out of seconds, minutes, hours, days, weeks, etc.) or to
- exactly one item out of a discrete, finite set (e.g., yes or no) or to
- one or more items out of a discrete, finite set (e.g., A and B, but not C).

Although it is a challenge to formulate categories and attributes that are meaningful for classifying different types of tools (even within the already quite narrow scope of HEN), it has the advantage of making the results directly comparable. Also, the resulting space spanned by all possible classification results is discrete and compact.

Furthermore, all except the most simple energy systems are systems of systems, i.e., their components are complex enough to be considered as systems themselves. Hence, in the following it is assumed that all methods and tools use, to a certain extent, a modular approach in which *component models* are used as sub-models to form the overall *system model* to be simulated or optimized.

The preliminary results from the online survey showed that even seemingly simple categories are sometimes difficult to apply. For instance, experience showed that the distinction between black/white/gray-box models or simulation/optimization models is often ambiguous and subject to interpretation. Based on this feedback, the following classification categories have been defined.

Spatial resolution of component models

This category provides a measure for the spatial resolution of the component models used by a tool. The spatial resolution has a strong impact on which phenomena a tool can address, depending on whether component models correspond to individual network assets and devices or aggregated structures like buildings or districts. For instance, economic models require less spatial details than technical models for the assessment of energy-related aspects. The classification result must be a sub-range of the following attributes: network assets/devices, buildings, districts/settlements, cities, regions, nations, and continents.

Temporal resolution of component models

This category provides a measure for the intrinsic temporal resolution of the component models used by a tool. The temporal resolution has strong implications for the potential applications a tool can be applied to. For instance, models for control applications need to address time scales in the order of the dynamics of the underlying process. Other models may require only aggregated or averaged information. The classification result must be a sub-range of the following attributes: seconds, minutes, hours, days, weeks, months, and years.

Targeted scale of system model

This category provides a measure for the targeted scale of the system model, which can range from very large (e.g., intercontinental transmission networks) to comparatively small structures (e.g., local distribution grids). The targeted scale has strong implications for the potential applications a tool can be applied to, ranging from technical performance validations of HENs at local level to the assessment of economical or environmental aspects in a broader scope. Therefore, this category does not focus on a feature of a tool itself, but rather its intended use. The classification result must be a sub-range of the following attributes: network assets/devices, buildings, districts/settlements, cities, regions, nations, and continents.

Targeted time horizon of system model

This category provides a measure for the targeted time horizon of the system model, denoting the period for which the system model will be simulated or optimized. This might only be a couple of hours or days for very detailed models with high temporal component model resolutions of a second or less, but for hourly or yearly models the time horizon can range from years to decades. As with the previous category, the focus is not on the features of a tool itself, but rather its intended use. The classification result must be a sub-range of the following attributes: seconds, minutes, hours, days, weeks, months, and years.

Application class

This category specifies the class of application (technical, economical, and/or environmental) a tool addresses. Different types of models and methods are required for different classes of applications. Examples are the validation of network performance and control (technical), assessments of capital expenditures and operating expenses (economical) or the impact of renewable-based versus fossil-based energy sources (environmental). The classification result must be one or more of the following attributes: technical, economical, and environmental.

Types of network models

This category specifies the approach used by a tool for representing energy networks. Considered are power networks, heating and cooling networks as well as gas networks (including hydrogen). The classification result indicates whether a network is modeled explicitly (e.g., line model with cables and loads for power networks) or if a generalized energy balance approach is used (implicit model). If modeled explicitly, the modeling approach must be specified. The choice of modeling approach is highly relevant as it determines which physical phenomena can be considered and analyzed. For instance, an assessment of the gas or heat storage capacity within a network requires an explicit grid model that represents the physical properties of the individual pipes. The classification result must be exactly one of the following attributes for each type of network:

- power networks: not modeled, energy balance (implicit: no lines, cables, etc.), quasi-static (power flow), electro-mechanical, and electro-magnetic transients
- thermal networks: not modeled, energy balance (implicit: no pipes, etc.), quasi-static (pressure equilibrium), and hydraulic transients
- gas networks: not modeled, energy balance (implicit: no pipes, etc.), quasi-static (pressure equilibrium), and hydraulic transients.

Table 1
Selected tools for HENs.

Tool name	Modeling tool	Simulation tool	Optimization tool
COMANDO	✓		✓
co-simulation		✓	
EHDO	✓		✓
EnergyPLAN	✓	✓	
energyPRO	✓	✓	✓
ESSIM	✓	✓	
GasPowerModels.jl	✓		✓
Integrate	✓		✓
Modelica	✓	✓	
Pandaplan	✓	✓	
PLEXOS	✓		✓
PyPSA-Eur-Sec	✓		✓
rivus	✓		✓
SAInt	✓	✓	

Energy storage

This category specifies if the tool is capable of modeling peripheral energy storage devices (such as batteries or hot water tanks). Energy storages are important for the operation of networks and conversion technologies, because they provide significant flexibility for accommodating renewable energy sources and exploit synergies between generation and demand. The classification result must be exactly one of the following attributes: yes or no.

4. Selected tools

This section introduces the tools that have been selected according to the procedure outlined in Section 3. Table 1 lists all selected tools in alphabetical order and presents their purpose in terms of modeling, simulation and optimization according to the developers. In the following, a brief introduction to each tool is provided, outlining their different approaches for modeling, simulating and/or optimizing HENs (satisfying SC1). This also includes a reference that demonstrates their application to HENs (satisfying SC2) as well as a reference that provides details about their public availability (satisfying SC3). More details on how the tools satisfy SC1 are provided in Section 5.

After the initial online survey and literature review, a preliminary list of 60 tools had been compiled. After applying the selection criteria discussed in Section 3.1, the 14 tools listed in Table 1 remained. It should be noted that this low selection rate does not reflect the quality of the considered tools. The reason for exclusion was in most cases the narrow scope of HEN rather than MES (see selection criteria SC1 and SC2), which shows that considering the effects of multi-energy applications on the related network infrastructure is in general still a comparably new subject. In many cases – especially for approaches related to coupled power and gas grids – a published method is not available as a dedicated tool (or at least a modeling library for an available tool). Furthermore, all approaches based on Modelica or co-simulation have been subsumed as one method, respectively (see Sections 4.2 and 4.9). In one case, a tool has been described in literature but is not available for the public [29]. In another case, a tool has been announced publicly but was not available at the time of writing [30].

It should also be noted that the high ratio of open source tools among the final selection is not due to the selection procedure. Proprietary tools were neither excluded from the process nor ignored. Rather, the high ratio of non-commercial open-source tools reflects the fact that work on HEN is still mainly carried out by research organizations and that there has been little commercial exploitation in this area to date.

4.1. COMANDO

The open-source framework COMANDO [31] provides component-oriented modeling and optimization for the nonlinear design and operation of energy systems. COMANDO is developed at the Institute of Energy and Climate Research at Forschungszentrum Jülich (Germany). The behavior of individual components is represented with detailed models, considering dynamic and nonlinear effects with the help of physics-based, data-driven or hybrid modeling approaches. These component models are used for building energy system models, based on which optimization problems related to the design and/or operation of the energy system can be formulated. In addition, COMANDO includes capacitive models[2] for peripheral storage units (electrical, heat, cold). COMANDO allows to consider multiple operating scenarios via stochastic programming formulations, allowing to find system designs that are suitable for operation under uncertainty. To solve these optimization problems, COMANDO translates its models to representations that are suitable for external solvers (Gurobi, BARON, SCIP, etc.). Alternatively, it can be integrated into other algebraic modeling languages (Pyomo, GAMS). The implementation in Python makes it possible to extend COMANDO by including additional Python modules. Examples of applying COMANDO to heat and power networks are given in [32,33], respectively.

4.2. Co-simulation of network simulators

Modeling an entire system of systems in one universal language, with one tool, may lead to simplifications that neglect important properties and dynamic dependencies [34]. In contrast, domain-specific tools provide validated libraries, optimal solvers, and a language that perfectly fits the problem domain. Therefore, combining specialized simulators for different types of energy networks in a so-called co-simulation is a viable approach for assessing HENs. In general, co-simulation refers to a generic approach where simulators are coupled at runtime for jointly simulating a system. The simulators exchange data at specific synchronization points, in between they calculate the state of their respective subsystems independently. Dedicated co-simulation environments exist which help with the coupling of simulators and their synchronization. The modeling of the individual subsystems is done separately with the help of the corresponding network simulators. The features of the resulting overall model depends on the features implemented by the selected simulators. A detailed example of using a co-simulation approach for the assessment of coupled power and heat networks is given in [23], which uses the co-simulation framework FUMOLA [35] for interfacing the Modelica library DisHeatLib [36] and pandapower [37]. Similar examples are provided in [24] which uses the co-simulation framework mosaik [38] and in [25] which uses the co-simulation framework ZerOBNL [39].

4.3. EHDO

EHDO [40] is an open-source webtool for the optimal design of complex MESs. It is developed by the Institute for Energy Efficient Buildings and Indoor Climate at RWTH Aachen University (Germany) for academic teaching. EHDO is conceived as a support tool for the early planning phase of future smart energy systems, optimizing the choice and the sizing of energy conversion units. A user-friendly graphical user interface enables the creation of energy hubs of different sizes (from building complexes to large districts) from a variety of component models (PV, wind turbines, fuel cells, electrolyzers, biomass and waste-to-energy technologies, etc.). In addition, it provides capacitive models of peripheral storage units (electricity, gas, hydrogen, heat, cold). EHDO uses mixed-integer linear programming (MILP) to define a set of mathematical constraints for each component model and asserts energy balances, conversion efficiency ratios, maximal load limitations, and storage constraints at hourly time steps. It relies on an external solver (Gurobi) for solving optimization problems. The implementation in Python makes it possible to extend EHDO by including additional Python modules. An example for using EHDO for HENs is given in [28], where the developers present the full range of supported systems and carriers, and provide two illustrative case studies.

4.4. EnergyPLAN

EnergyPLAN [41] is a freeware simulation tool for holistic energy system analyses including all energy sectors. EnergyPLAN is programmed in Delphi Pascal and is developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University (Denmark). EnergyPLAN is based on a series of endogenous priorities within, e.g., power and heat production and predefined procedures for simulating the operation of units that are freely dispatchable. In addition, it provides capacitive models for peripheral storage units (electricity, gas, hydrogen, heat, hydro). The inputs to EnergyPLAN are energy demands, energy conversion units and resources, costs, and choices related to simulation methods incl. operational constraints in relation to electricity grid stability. EnergyPLAN chronologically simulates the operation of an energy systems for a leap year on an hourly basis, including the electricity, heating, cooling, industry, and transport sectors and the interconnections between these. EnergyPLAN provides a graphical user interface (GUI) but can also be used from the command line or via dedicated toolboxes from MATLAB [42] and Python [43]. An example for using EnergyPLAN for HENs is given in [22], which analyzes the benefits of a combined, cross-sectoral use of all types of grids (power, heat and gas) for renewable heating strategies.

4.5. energyPRO

energyPRO [44] is a tool for combined techno-economic analysis and optimization of energy flows with a focus on combined energy supply of e.g. electricity and thermal energy (process heat, hot water, and cooling). energyPRO is a commercial tool that is developed and maintained by EMD International A/S (Denmark). The focus of energyPRO is on the operation of energy conversion technologies and energy storage technologies (electrical, fuel, heat, cold, pumped hydro). However, capacity constraints in energy grids can be included in the modeling, as they relate to the operation of energy conversion and storage technologies. energyPRO optimizes the operation of the modeled components based on the technical and economic parameters defined in the model, which can include local energy demands, fuel costs, tariffs, electricity markets, part-load efficiencies, etc. This optimization is either performed via an internal analytical method or via a MILP approach (using CBC or Gurobi as solver). energyPRO provides a GUI but can also be used in batch mode from the command line. An example for using energyPRO for HENs is given in [21], which analyzes how small-scale district heating plants can improve their economic feasibility by providing balancing services to the electricity system.

[2] Capacitive models describe all kinds of energy storage systems (batteries, hot water tanks, etc.) by means of their maximum energy storage capacity and state of charge, analogous to a capacitance in an electrical circuit.

4.6. ESSIM

The Energy System Simulator (ESSIM) [45] is an open-source tool for calculating energy flows in interconnected HENs developed by TNO (The Netherlands). ESSIM calculates energy flows between network components – referred to as assets – and between different types of networks over a period of time with hourly intervals. Assets representing peripheral storage devices (electricity, gas, hydrogen, heat) are included as capacitive models. For each time interval, the scheduling of controllable, "flexible" assets and the energy balance for all involved networks is determined based on marginal costs. ESSIM is implemented using the modeling language Energy System Description Language (ESDL). A GUI is provided for defining assets and their geographical locations. ESSIM computes and visualizes key performance indicators and gives insights into how well the assets in a network are dimensioned, e.g., if there is overloading in any given transport asset (pipe, cables, etc.). ESSIM provides a REST API [46] that allows users to interact with it and enables the combination with more detailed power flow models (e.g., pandapower). An example for using ESSIM for HENs is given in [47], which demonstrates how excess electricity production from local energy sources is converted to hydrogen and used in a hydrogen gas network.

4.7. GasPowerModels.jl

GasPowerModels.jl is a package for the joint optimization of power transmission networks and natural gas networks. Its development is a joint effort of the Los Alamos National Laboratory, the University of Michigan and the Pennsylvania State University. The package combines elements and steady state models from two preceding packages, i.e., GasModels.jl for gas flows and PowerModels.jl for power flows [48]. The model used by GasPowerModels.jl decouples network formulations (e.g., mixed-integer convex) from problem specifications (e.g., network expansion planning). Thanks to this decoupling, it is possible to define a variety of optimization formulations and compare them on common problem specifications. The resulting models are in general mixed-integer nonlinear programs. GasPowerModels.jl is implemented in JuMP which makes it possible to extend it by including additional Julia or Python modules. JuMP depends on external solvers for solving optimization problems and supports a number of open-source (SCIP, Ipopt, etc.) and commercial solvers (Gurobi, CPLEX, etc.) for a variety of problem classes. The application of GasPowerModels.jl to HENs is documented and illustrated in [49], analyzing the natural gas and electric power systems in the Northeastern United States, and [50], which combines the IEEE 14 bus test system with the Belgian natural gas network.

4.8. Integrate

Integrate [51] is a tool for investment planning of multi-carrier energy grids [52]. Formerly called eTransport, it is being developed by SINTEF Energy Research (Norway). Integrate takes into account projections in energy demands as well as mature and emergent technologies for energy supply, conversion and distribution of different energy carriers. It provides capacity models for different types of peripheral storage units (hot water tanks, hydrogen storage, etc.) and also considers carbon dioxide capture and storage (CCS), in order to comply with end-use measures and CO_2 emission restrictions. Integrate performs an operational optimization by formulating a MILP problem, solved with the COIN-OR solver [53]. It minimizes investment, operation and emissions costs while meeting predefined demands of electricity, space heating, tap water heating and gas over a given time horizon, including alternative supply infrastructures [54]. The tool comes with a graphical user interface for modeling energy systems. At the time of writing, Integrate provides no API but a connection with the SPINE toolbox [55] is planned. The application of Integrate to HENs is documented in [56], which analyzes the potential of seasonal thermal storage for local energy systems.

4.9. Modelica

Modelica [57] is an object-oriented language for modeling cyber–physical systems, developed by the Modelica Association. A system modeled in Modelica may combine electrical, mechanical, thermal or hydraulic components. It is also possible to add controllers in order to simulate different control strategies. A comprehensive standard library is available open-source, additional relevant libraries are available either free of charge (e.g.,TransiEnt [58] for HENs, OpenIPSL [59] for power systems, or the DisHeatLib [36] for heat networks) or commercially (e.g., the multi-domain Modelon Library Suite [60]). Modelica relies on differential, algebraic and discrete equations for modeling, enabling the analysis of both static and dynamic system behavior. Modelica itself is a text-based modeling language but there are several Modelica-based modeling and simulation environments available (both open-source and proprietary). They typically provide graphical user interfaces for modeling, advanced numerical solvers for simulation, and various interfaces to other simulation environments (e.g. via the Functional Mock-up Interface [61] standard). An example for using Modelica for HENs is given in [27], where the effects of cascading failures are analyzed for a coupled heat and power network. Another example is given in [62], where networks for gas, heat and power are coupled through a combined-cycle power plant with heat extraction and an electrolyzer.

4.10. Pandaplan

Pandaplan [63] consists of the two open-source tools pandapower [37] and pandapipes [26]. It is developed at the Fraunhofer Institute for Energy Economics and Energy System Technology (Kassel, Germany). Both pandapipes and pandapower are based on the programming language Python. While pandapower can be used to model and simulate power grids, pandapipes can be utilized to evaluate the pressure, flow velocity and temperature distribution in gas and district heating grids. pandapower and pandapipes use the same data structure to describe networks and can thus be combined easily in order to simulate coupled infrastructures. Coupling points, like heat pumps or power-to-gas plants may be modeled using controller components, which can also be used to implement a specific operational strategy. In addition, pandapower provides capacitive models for electrical storages. Components are described by algebraic and/or differential equations, and the resulting system of equations is solved with the Newton–Raphson method. While it is possible to simulate time-dependent systems, it is not possible to study the dynamic system behavior, as inertial effects are neglected. The implementation in Python makes it possible to extend the simulation by including additional Python modules. The application of Pandaplan to HENs is illustrated in [26], which studies the flexibility potential of power-to-gas in a coupled power and gas grid.

4.11. PLEXOS Integrated Energy Model

The PLEXOS Integrated Energy Model [64] is an energy modeling and forecasting platform. PLEXOS is a commercial tool that is developed and maintained by Energy Exemplar Pty Ltd (Australia). Previously developed as an electricity market simulator, its functionality has been extended to integrate electric power, gas and hydro. PLEXOS supports primarily assessments such as price forecasting, portfolio optimization (unit commitment and economic dispatch problems) or long-term capacity expansion planning. However, it also supports network modeling at different levels of detail (regional, zonal, nodal) which allows to capture technical aspects relevant for HENs such as congestion and network losses. In addition, it provides capacitive models for batteries, pumped hydro storage and gas storage. Modeling is generally carried out using deterministic linear programming techniques that aim to minimize a single objective function subject to the expected dispatch costs, taking into account a number of constraints including availability and operational characteristics of generating plants, fuel costs, operator and transmission constraints, and others. PLEXOS is primarily used through a graphical user interface but also has an API that can be used from any .NET environment. PLEXOS allows to use different commercial optimization engines (e.g., CPLEX, Gurobi). The application of PLEXOS to HENs is illustrated in [65], which shows a multi-vector energy analysis for interconnected power and gas systems in Britain and Ireland.

4.12. PyPSA-Eur-Sec

PyPSA-Eur-Sec [66] is an open model of the sector-coupled European energy system. At the time of writing, the tool is maintained by the Department of Digital Transformation in Energy Systems at the Technical University of Berlin (Germany), developed in collaboration with the KIT Karlsruhe Institute of Technology (Germany) and Aarhus University (Denmark). PyPSA-Eur-Sec is designed as a module of the PyPSA toolbox [67], enabling the modeling of the transmission networks of the ENTSO-E area. It can model electricity, hydrogen and gas grids, with numerous sources (e.g., renewables, biomass or fossil fuels) and generation technologies (e.g., heat pumps, fuel cells or CHP). In addition, it provides capacity models for energy storage at different time scales, including batteries, pumped hydro storage, hydrogen storage and hot water storage. Moreover, PyPSA-Eur-Sec considers transformations in industry, aviation and shipping, and the use of CCS. PyPSA-Eur-Sec uses a myopic approach with 5-year time steps from 2020 to 2050, minimizing for every time step the total system cost (incl. CO_2 constraints). For every time step, the overall model is optimized with the help of an external solver (Gurobi, CPLEX, etc.), assuming a long-term market equilibrium with perfect competition and perfect foresight. The implementation in Python makes it possible to extend the simulation by including additional Python modules. An example for using PyPSA-Eur-Sec for HENs is given in [68], which identifies economy-optimal energy transition paths at the European level under different carbon budgets.

4.13. rivus

rivus is an optimization model for capacity planning for multi-commodity energy infrastructure networks, developed at the Technical University of Munich (Germany). Its name – Latin for stream or canal – stems from its origin as a companion model for urbs [69], an optimization model for urban energy systems. rivus implements a single-objective MILP model that finds the minimum cost energy infrastructure network to satisfy a given energy distribution for multiple commodities (e.g., electricity, heating, cooling). Time is represented by a (small) set of weighted time steps that represent peak or typical loads. Spatial data can be provided in form of shapefiles, while technical parameters can be edited in a spreadsheet. rivus relies on Pyomo for modeling equations and as the interface to optimization solvers (CPLEX, Gurobi, CBC, etc.). The implementation in Python makes it possible to extend the simulation by including additional Python modules. An example of using rivus for the assessment of HENs is reported in [70], where different network topologies for coupled power, heat and gas networks are analyzed for a city district.

4.14. SAInt

SAInt [71] is a simulation tool for assessing security of supply in interconnected gas and electrical transmission networks. SAInt is a commercial tool that is developed and maintained by encoord GmbH (Germany). It comprises a transient hydraulic model for the gas system to reflect the changes in pressure and the quantity of gas stored in pipelines, enabling for instance the assessment of imbalances between gas supply and gas demand and the resulting fluctuations in linepack. For the electrical power system an augmented AC optimal power flow model is used, which includes dispatchable loads and considers ramp rates and the start-up times of generation units. The bidirectional interconnection between both systems is considered through equations describing the fuel gas offtake for power generation in gas fired power plants, and the electric power supply to liquefied natural gas terminals (LNG) terminals and electric driven compressors in gas compressor stations. The resulting system of equations is solved iteratively by a sequential linearization method which updates the boundary conditions expressed by the coupling equations at each iteration step. SAInt is able to assess the gas storage capacity in pipeline systems and also provides models for gas storage in peripheral facilities (LNG terminals, underground caverns, etc.). SAInt is mainly programmed with Visual Basic and uses IronPython as a scripting language for interacting with the user. It provides a graphical user interface and an API that can be used from any .NET environment for accessing solvers and classes representing the different assets in gas and power systems. The application of SAInt to HENs is illustrated in [72], which shows how disruptions in a coupled gas and power system can affect the operation of both systems and how counter measures to mitigate their impact can be assessed.

5. Classification of tools

A main goal of the present work is to identify what types of tools and methods are available for the assessment of HENs, how they model the HEN subsystems and what insights can they provide (cf. research question RQ1 in Section 1.1). For this purpose, the categories from Section 3.2 have been applied to the tools presented in Section 4 to provide a classification that reflects their typical use. An attempt was made not to include edge cases, where tools and methods are applied to HENs in ways not intended by the developers. As discussed in Section 3, the assessments are based on a consensual synthesis of at least two expert reviews. Where required, also input from contacting the developers directly was included into the assessments.

Fig. 2 shows the comparison of the temporal resolution and the spatial resolution of the component models for the selected tools. It is interesting to note that the spatial resolution of the component models is quite similar in most cases, with the exception of PyPSA-Eur-Sec and PLEXOS which are intended for larger spatial scales. However, it is mostly the temporal resolution of the component models that differs quite substantially.

Things look a bit different when comparing the temporal resolution of the component models with the targeted scale of the system model in Fig. 3. There is a correlation showing that tools with a higher temporal resolution for the component models also

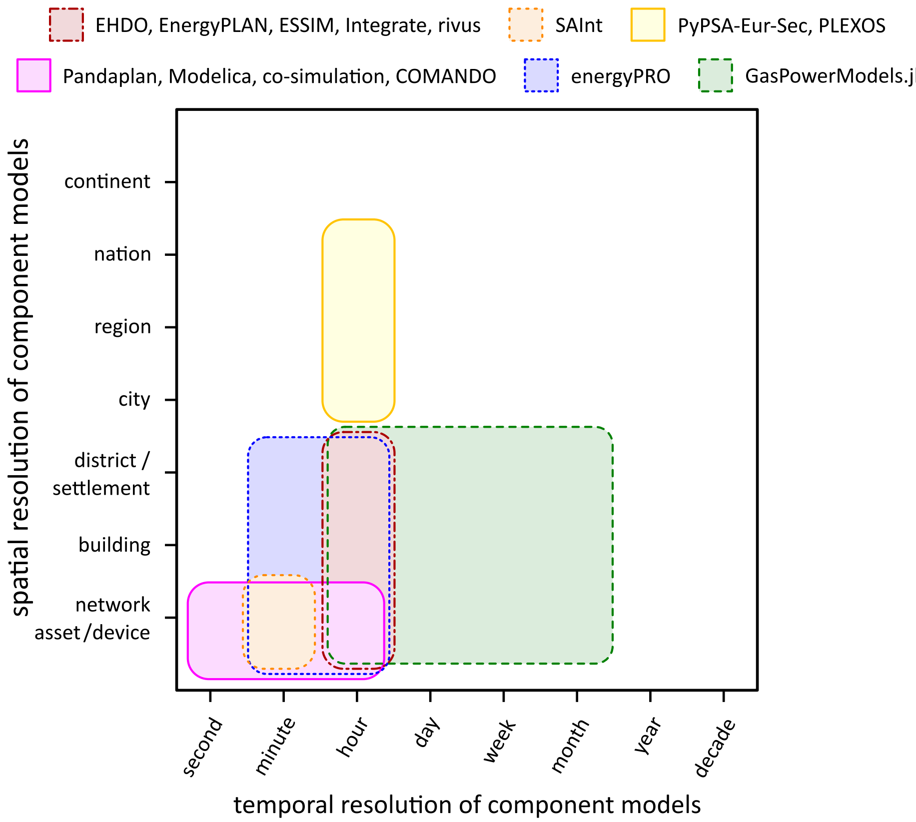

Fig. 2. Comparison of temporal resolution versus spatial resolution of component models.

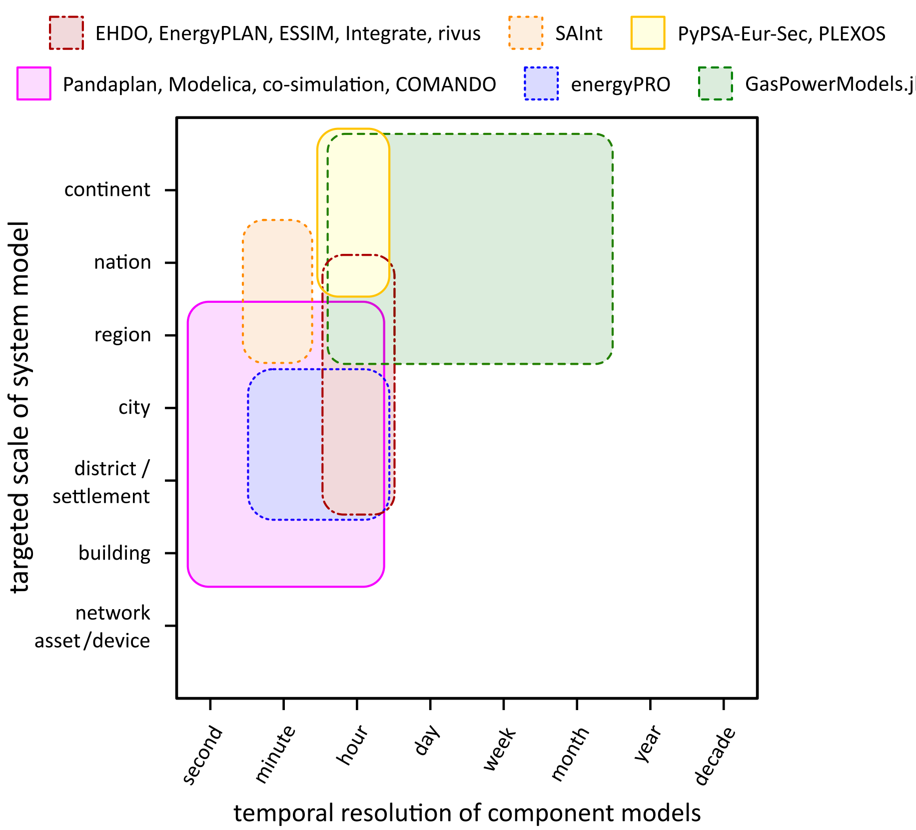

Fig. 3. Comparison of temporal resolution of component models versus targeted scale of system model.

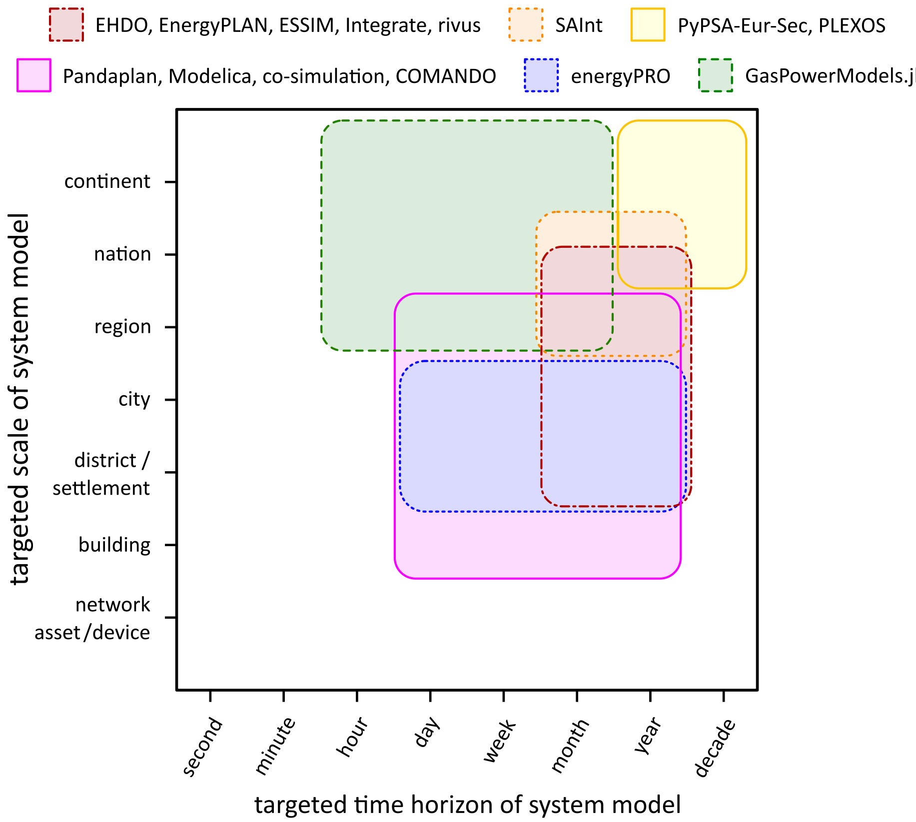

Fig. 4. Comparison of targeted time horizon versus targeted scale of system model.

have a higher resolution for the targeted scale of the system models. This observation is important for selecting the appropriate tool or method as a function of the targeted application.

Fig. 4 compares the targeted time horizon (i.e., the temporal resolution of the system model) with the target scale (i.e., the spatial resolution of the system model). This reveals that the selected tools differ substantially with respect to the targeted scale of the system model, even though the cover in most cases quite similar time horizons (months and years in most cases).

An important feature of Figs. 2–4 is the fact that several tools have very similar resolutions. For the sake of a more readable visualization, these tools have been grouped together. However, it turns out that these groups of tools and methods do not only have similar resolutions, but that they also have similar approaches for modeling HENs, as can be seen from Table 2. Furthermore, the tools and methods in these groups have a similar focus in terms of technical, ecological and environmental aspects, as can be seen in Table 3.

These groups are basically the result of a clustering of the selected tools in the entire space of possible combinations spanned by the classification categories. Hence, these groups can be interpreted as "distinct types" of tools and methods for the assessment of HENs in the sense of research question RQ1. Even though the significance of this result is limited due to the rather small sample size (i.e., 14 selected tools), this suggests that the categories from Section 3.2 provide a meaningful classification for tools with this specific focus.

The implications of this interpretation are further analyzed in the following discussion in the next section.

6. Discussion

The classification results – and the resulting grouping – shown in Section 5 can be used for an evaluation beyond a simple listing of resolutions and the types of models used. It turns out that they are also an indicator of the type of application a tool or method is useful for (cf. research question RQ2 in Section 1.1). To this end, four areas of application specific to HENs have been defined: *characterization/state determination*, *optimization of planned grids*, *operational optimization (technical)*, and *operational optimization (economical)*. See Table 4 for details. Each area of application is characterized by an objective, i.e., the rationale and intended purpose of using a specific tool.

In addition to the classification from Section 5, an expert review was performed to assess the selected tools in terms of their usefulness for these areas of application. Table 5 shows the corresponding result. It turns out that the grouping of tools based on the (objective) classification categories (see Figs. 2 to 4) correlates well with the (subjective) expert judgment of their usefulness for specific areas of application. In other words, tools that are similar in terms of the classification categories also have a similar scope of application.

This is remarkable in view of the fact that any attempt of categorizing the tools in a different way (e.g., based only on either resolutions, modeling approaches or application classes) is very likely to produce a very different result. Hence, this good agreement is a strong indicator that the proposed classification categories can successfully capture and characterize the most important features of tools and methods for assessing HENs. On the one hand, this result gives confidence that Table 4 can serve as a guideline for early adopters to understand which tools best fit the requirements of their specific applications. Taking into account the information from Section 5, Table 4 can be interpreted by classifying the tools in the following application categories:

- Tools for *technical assessments*: Pandaplan, Modelica, co-simulation, COMANDO, SAInt
- Tools for *operational optimization* (technical & economical): energyPRO

Table 2
Modeling approaches for energy networks applied by selected tools.

Tool	Power network model	Thermal network model	Gas network model	Energy storage
Pandaplan	quasi-static (power flow)	quasi-static (pressure equilibrium)	quasi-static (pressure equilibrium)	✓
Modelica [a]	electro-mechanical[a]	hydraulic transients[a]	hydraulic transients[a]	✓
co-simulation[b]	quasi-static[b] (power flow)	hydraulic transients[b]	not modeled[b]	✓
COMANDO	quasi-static (power flow)	quasi-static (pressure equilibrium)	quasi-static (pressure equilibrium)	✓
energyPRO	energy balance (implicit: no lines, etc.)	quasi-static (pressure equilibrium)	energy balance (implicit: no pipes, etc.)	✓
EHDO	energy balance (implicit: no lines, etc.)	energy balance (implicit: no pipes, etc.)	energy balance (implicit: no pipes, etc.)	✓
EnergyPLAN	energy balance (implicit: no lines, etc.)	energy balance (implicit: no pipes, etc.)	energy balance (implicit: no pipes, etc.)	✓
ESSIM	energy balance (implicit: no lines, etc.)	energy balance (implicit: no pipes, etc.)	energy balance (implicit: no pipes, etc.)	✓
Integrate	quasi-static (power flow)	quasi-static (pressure equilibrium)	quasi-static (pressure equilibrium)	✓
rivus	energy balance (implicit: no lines, etc.)	energy balance (implicit: no pipes, etc.)	energy balance (implicit: no pipes, etc.)	×
GasPowerModels.jl	quasi-static (power flow)	not modeled	quasi-static (pressure equilibrium)	×
PyPSA-Eur-Sec	quasi-static (power flow)	not modeled	quasi-static (pressure equilibrium)	✓
PLEXOS	quasi-static (power flow)	not modeled	quasi-static (pressure equilibrium)	✓
SAInt	quasi-static (power flow)	not modeled	hydraulic transients	✓

[a]For approaches described in [27,62].
[b]For approaches described in [23–25].

Table 3
Application classes of selected tools.

Tool	Technical	Economical	Environmental
Pandaplan	✓		
Modelica [a]	✓[a]		
co-simulation[b]	✓[b]		
COMANDO	✓		
energyPRO	✓	✓	✓
EHDO	✓	✓	✓
EnergyPLAN	✓	✓	✓
ESSIM	✓	✓	✓
Integrate	✓	✓	✓
rivus	✓	✓	✓
GasPowerModels.jl	✓	✓	
PyPSA-Eur-Sec		✓	✓
PLEXOS		✓	✓
SAInt	✓	✓	

[a]For approaches described in [27,62].
[b]For approaches described in [23–25].

- Tools for *planning on the scale of cities/regions*: EHDO, EnergyPLAN, ESSIM, Integrate, rivus
- Tools for *planning on the scale of nations/continents*: GasPowerModels.jl, PLEXOS, PyPSA-Eur-Sec

On the other hand, it is reasonable to assume that the reverse conclusion is also permissible, i.e., tools and methods useful for a certain area of application should ideally have the features of the corresponding group from Section 5. This can be used as a hint for future development efforts in the areas of HENs.

7. Conclusions

In recent years, several new tools and methods have been developed for the assessment of HENs. They are not simply extensions of established domain-specific or multi-energy tools, but rather provide new features specifically for analyzing HENs, e.g., the assessment of the combined state of the networks or the mutual impact of the networks on each other. They cover a wide range of modeling and simulation approaches, and thus enable different insights regarding HENs. As such, they help to provide as results the real technical, economic and environmental advantages of the hybrid paradigm.

The present work provides an expert survey of available approaches for the assessment of HENs. To put a strong focus on applicability for potential users, care was taken to select only tools that are publicly available (commercially, open-source or otherwise) and whose use for assessing HENs is documented. Based on this, a systematic categorization of the corresponding methods has been carried out, based on a set of classification categories specifically devised for this particular type of tools. The results reveal different types of tools for analyzing HENs, inferred from clusters within the entire space of possible combinations spanned by the classification categories.

The applicability of the classification categories and the significance of the resulting types is substantiated by a mapping to potential areas of application. It turns out that tools that are similar in terms of the classification are also useful for similar applications. This good agreement is a strong indicator that the proposed classification categories can successfully capture and characterize the most important features of tools and methods for assessing HENs.

Furthermore, the selected tools can be grouped in four application categories: tools for technical assessments, operational optimization (technical and economical), planning on the scale of cities/regions, and planning on the scale of nations/continents. The good agreement between the classification results and application areas suggest that each tool can be assigned to one of the above application categories. This basically provides a concrete recommendation of which tools to use for certain applications (e.g., system design, generation portfolio optimization, controller design).

Table 4
Applications areas for selected tools for HENs.

Application area	Description	Examples
Characterization/state determination	Evaluation of the state of a HEN without interpreting or changing its properties	Calculation of gas/heat storage potential of pipelines; load flow analysis for calculating the voltages, currents, pressures or temperatures at the network nodes
Optimization of planned grids	Useful for the planning of HENs, where the overall network design is optimized	Improvement of grid topology for optimizing the efficiency of coupling points; positioning of plants and devices for reducing network losses
Operational optimization (Technical)	Improvement of the HEN system performance with a main focus on technical aspects	Model-predictive control for storages to improve local self-consumption; control algorithm for power-to-gas plants to maintain a given gas composition in the grid
Operational optimization (Economical)	Improvement of the HEN system performance with a main focus on economical aspects	Model-predictive control for cost-optimal unit commitment of plants; algorithm deciding how to use PV excess power (grid feed-in or self consumption) based on market price predictions

Table 5
Intended purpose of selected tools for HENs.

Tool	Characterization/ State determination	Optimization of planned networks	Operational optimization (Technical)	Operational optimization (Economical)
Pandaplan	✓		✓	
Modelica [a]	✓[a]		✓[a]	
co-simulation[b]	✓[b]		✓[b]	
COMANDO	✓		✓	
energyPRO			✓	✓
EHDO		✓		
EnergyPLAN		✓		
ESSIM	✓	✓		
Integrate		✓		✓
rivus		✓		
GasPowerModels.jl		✓	✓	✓
PyPSA-Eur-Sec		✓		✓
PLEXOS		✓		✓
SAInt	✓	✓	✓	

[a]For approaches described in [27,62].
[b]For approaches described in [23–25].

8. Outlook

This work intends to show the added value the selected tools for the analysis of HENs can contribute to the planning and operation of future integrated energy systems. It is to be hoped that not only these existing tools will continue to be used and improved in the future. Rather, it would be an important step forward if traditional, domain-specific tools for energy networks were also extended for the analysis of HENs in the future.

New developments must also continue to address the challenges for the implementation of HENs. In most cases, the tools and methods consider a HEN from a primarily scientific perspective, neglecting certain practical constraints. For instance, a critical challenge for the planning and operation of a HEN lies in the fact that the individual subsystems are often owned and operated by different utility companies [20]. For a modeling or simulation tool with a "centralized" approach, this can create administrative barriers due to data protection. Even though the tools for modeling and simulating HENs will not be able to solve this and other real-world challenges by themselves, their further development must contribute to the solution (e.g., through the distribution of models by means of co-simulation and co-optimization).

Abbreviations

The following abbreviations are used in this manuscript:

API	Application programming interface
CCS	Carbon capture and storage
CHP	Combined heat and power (plant)
ENTSO-E	European Network of Transmission System Operators
EHDO	Energy Hub Design Optimization
ESDL	Energy System Description Language
ESSIM	Energy System Simulator
GUI	Graphical user interface
HEN	Hybrid energy network
LNG	Liquefied natural gas
MES	Multi-energy system
MILP	Mixed-integer linear programming
PV	Photo-voltaic (system)
RQ	Research question
SC	Selection criterion
SINTEF	Stiftelsen for industriell og teknisk forskning
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek

CRediT authorship contribution statement

Edmund Widl: Conceptualization, Methodology, Investigation, Writing – original draft, Visualization, Project administration. **Dennis Cronbach:** Methodology, Investigation, Writing – original draft, Writing – review & editing. **Peter Sorknæs:** Methodology, Investigation, Writing – original draft, Writing – review & editing.

Jaume Fitó: Investigation, Writing – original draft, Writing – review & editing. **Daniel Muschick:** Methodology, Investigation. **Maurizio Repetto:** Investigation, Writing – original draft, Writing – review & editing. **Julien Ramousse:** Investigation, Writing – review & editing. **Anton Ianakiev:** Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] H. Lund, P.A. Østergaard, D. Connolly, B.V. Mathiesen, Smart energy and smart energy systems, Energy 137 (2017) 556–565, http://dx.doi.org/10.1016/j.energy.2017.05.123.
[2] B. Talebi, P.A. Mirzaei, A. Bastani, F. Haghighat, A review of district heating systems: Modeling and optimization, Front Built Environ 2 (2016) http://dx.doi.org/10.3389/fbuil.2016.00022.
[3] L. Bam, W. Jewell, Review: power system analysis software tools, in: IEEE Power Engineering Society General Meeting, Vol. 1, 2005, pp. 139–144, http://dx.doi.org/10.1109/PES.2005.1489097.
[4] A. Foley, B. Ó Gallachóir, J. Hur, R. Baldick, E. McKeogh, A strategic review of electricity systems models, Energy 35 (12) (2010) 4522–4530, http://dx.doi.org/10.1016/j.energy.2010.03.057.
[5] M. Pöchacker, A. Sobe, W. Elmenreich, Simulating the smart grid, in: 2013 IEEE Grenoble Conference, 2013, pp. 1–6, http://dx.doi.org/10.1109/PTC.2013.6652259.
[6] S.C. Müller, H. Georg, J.J. Nutaro, et al., Interfacing power system and ICT simulators: Challenges, state-of-the-art, and case studies, IEEE Trans. Smart Grid 9 (1) (2018) 14–24, http://dx.doi.org/10.1109/TSG.2016.2542824.
[7] T. Duy Le, A. Anwar, R. Beuran, S.W. Loke, Smart grid co-simulation tools: Review and cybersecurity case study, in: 2019 7th International Conference on Smart Grid, IcSmartGrid, 2019, pp. 39–45, http://dx.doi.org/10.1109/icSmartGrid48354.2019.8990712.
[8] P. Mancarella, MES (multi-energy systems): An overview of concepts and evaluation models, Energy 65 (2014) 1–17, http://dx.doi.org/10.1016/j.energy.2013.10.041.
[9] E. Guelpa, A. Bischi, V. Verda, M. Chertkov, H. Lund, Towards future infrastructures for sustainable multi-energy systems: A review, Energy 184 (2019) 2–21, http://dx.doi.org/10.1016/j.energy.2019.05.057.
[10] D. Markovic, D. Cvetkovic, B. Masic, Survey of software tools for energy efficiency in a community, Renew. Sustain. Energy Rev. 15 (9) (2011) 4897–4903, http://dx.doi.org/10.1016/j.rser.2011.06.014.
[11] J. Allegrini, K. Orehounig, G. Mavromatidis, et al., A review of modelling approaches and tools for the simulation of district-scale energy systems, Renew. Sustain. Energy Rev. 52 (2015) 1391–1404, http://dx.doi.org/10.1016/j.rser.2015.07.123.
[12] I. van Beuzekom, M. Gibescu, J. Slootweg, A review of multi-energy system planning and optimization tools for sustainable Urban development, in: 2015 IEEE Eindhoven PowerTech, 2015, pp. 1–7, http://dx.doi.org/10.1109/PTC.2015.7232360.
[13] S. Ferrari, F. Zagarella, P. Caputo, M. Bonomolo, Assessment of tools for Urban energy planning, Energy 176 (2019) 544–551, http://dx.doi.org/10.1016/j.energy.2019.04.054.
[14] F. Scheller, T. Bruckner, Energy system optimization at the municipal level: An analysis of modeling approaches and challenges, Renew. Sustain. Energy Rev. 105 (2019) 444–461, http://dx.doi.org/10.1016/j.rser.2019.02.005.
[15] S. Sinha, S. Chandel, Review of recent trends in optimization techniques for solar photovoltaic–wind based hybrid energy systems, Renew. Sustain. Energy Rev. 50 (2015) 755–769, http://dx.doi.org/10.1016/j.rser.2015.05.040.
[16] J.M. Weinand, F. Scheller, R. McKenna, Reviewing energy system modelling of decentralized energy autonomy, Energy 203 (2020) 117817, http://dx.doi.org/10.1016/j.energy.2020.117817.
[17] M. Chang, J.Z. Thellufsen, B. Zakeri, B. Pickering, S. Pfenninger, H. Lund, P.A. Østergaard, Trends in tools and approaches for modelling the energy transition, Appl. Energy 290 (2021) 116731, http://dx.doi.org/10.1016/j.apenergy.2021.116731.
[18] C. He, X. Zhang, T. Liu, L. Wu, M. Shahidehpour, Coordination of interdependent electricity grid and natural gas network – a review, Curr Sustain/Renew Energy Rep 5 (2018) 23–36, http://dx.doi.org/10.1007/s40518-018-0093-9.
[19] M. Farrokhifar, Y. Nie, D. Pozo, Energy systems planning: A survey on models for integrated power and natural gas networks coordination, Appl. Energy 262 (2020) 114567, http://dx.doi.org/10.1016/j.apenergy.2020.114567.
[20] E. Raheli, Q. Wu, M. Zhang, C. Wen, Optimal coordinated operation of integrated natural gas and electric power systems: A review of modeling and solution methods, Renew. Sustain. Energy Rev. 145 (2021) 111134, http://dx.doi.org/10.1016/j.rser.2021.111134.
[21] P. Sorknæs, H. Lund, A.N. Andersen, Future power market and sustainable energy solutions – the treatment of uncertainties in the daily operation of combined heat and power plants, Appl. Energy 144 (2015) 129–138, http://dx.doi.org/10.1016/j.apenergy.2015.02.041.
[22] H. Lund, Renewable heating strategies and their consequences for storage and grid infrastructures comparing a smart grid to a smart energy systems approach, Energy 151 (2018) 94–102, http://dx.doi.org/10.1016/j.energy.2018.03.010.
[23] B. Leitner, E. Widl, W. Gawlik, R. Hofmann, A method for technical assessment of power-to-heat use cases to couple local district heating and electrical distribution grids, Energy 182 (2019) 729–738, http://dx.doi.org/10.1016/j.energy.2019.06.016.
[24] T.P. Richert, T.V. Jensen, Simulating services from power-to-heat components in integrated energy systems, Electr. Power Syst. Res. 189 (2020) 106778, http://dx.doi.org/10.1016/j.epsr.2020.106778.
[25] P. Puerto, E. Widl, J. Page, ZerOBNL: A framework for distributed and reproducible co-simulation, in: 2019 7th Workshop on Modeling and Simulation of Cyber-Physical Energy Systems, MSCPES, 2019, pp. 1–6, http://dx.doi.org/10.1109/MSCPES.2019.8738787.
[26] D. Lohmeier, D. Cronbach, S.R. Drauz, et al., Pandapipes: An open-source piping grid calculation package for multi-energy grid simulations, Sustainability 12 (23) (2020) http://dx.doi.org/10.3390/su12239899.
[27] R. Song, T. Hamacher, V.S. Perić, Impact of hydraulic faults on the electric system in an integrated multi-energy microgrid, in: Proc. of the 9th Workshop on Modeling and Simulation of Cyber-Physical Energy Systems, 2021, pp. 1–6, http://dx.doi.org/10.1145/3470481.3472709.
[28] M. Wirtz, P. Remmen, D. Müller, EHDO: A free and open-source webtool for designing and optimizing multi-energy systems based on MILP, Comput Appl Eng Educ 29 (5) (2021) 983–993, http://dx.doi.org/10.1002/cae.22352.
[29] C. Hauk, A. Ulbig, A. Moser, Integrated planning of grids and energy conversion units in municipal multi-energy carrier systems, Energy Inf 4 (3) (2021) http://dx.doi.org/10.1186/s42162-021-00178-0.
[30] PlaMES project, 2022, https://plames.eu/. (Accessed 09 May 2022).
[31] COMANDO – component-oriented modeling and optimization for nonlinear design and operation of integrated energy systems, 2022, https://jugit.fz-juelich.de/iek-10/public/optimization/comando. (Accessed 09 May 2022).
[32] M. Langiu, D.Y. Shu, F.J. Baader, D. Hering, U. Bau, A. Xhonneux, D. Müller, A. Bardow, A. Mitsos, M. Dahmen, COMANDO: A next-generation open-source framework for energy systems optimization, Comput. Chem. Eng. 152 (2021) 107366, http://dx.doi.org/10.1016/j.compchemeng.2021.107366.
[33] P. Glücker, M. Langiu, T. Pesch, M. Dahmen, A. Benigni, Incorporating AC power flow into the multi-energy system optimization framework COMANDO, in: 2022 Open Source Modelling and Simulation of Energy System, OSMSES, 2022, pp. 1–6, http://dx.doi.org/10.1109/OSMSES54027.2022.9769138.
[34] P. Palensky, E. Widl, A. Elsheikh, Simulating cyber-physical energy systems: Challenges, tools and methods, IEEE Trans. Syst. Man Cybern. Syst. 44 (3) (2014) 318–326, http://dx.doi.org/10.1109/TSMCC.2013.2265739.
[35] FUMOLA – functional mock-up laboratory, 2022, https://fumola.sourceforge.io. (Accessed 09 May 2022).

[36] Modelica DisHeatLib library, 2022, https://github.com/AIT-IES/DisHeatLib. (Accessed 09 May 2022).

[37] L. Thurner, A. Scheidler, et al., Pandapower–an open-source python tool for convenient modeling, analysis, and optimization of electric power systems, IEEE Trans. Power Syst. 33 (6) (2018) 6510–6521, http://dx.doi.org/10.1109/TPWRS.2018.2829021.

[38] Mosaik — A flexible smart grid co-simulation framework, 2022, https://mosaik.offis.de. (Accessed 09 May 2022).

[39] ZerOBNL, 2022, https://integrcity.github.io/zerobnl. (Accessed 09 May 2022).

[40] EHDO – energy system optimization webtool, 2022, https://ehdo.eonerc.rwth-aachen.de. (Accessed 09 May 2022).

[41] EnergyPLAN – advanced energy systems analysis computer model, 2022, https://www.energyplan.eu. (Accessed 09 May 2022).

[42] P. Cabrera, H. Lund, J.Z. Thellufsen, P. Sorknæs, The MATLAB toolbox for EnergyPLAN: A tool to extend energy planning studies, Sci. Comput. Program. 191 (2020) 102405, http://dx.doi.org/10.1016/j.scico.2020.102405.

[43] M.G. Prina, M. Cozzini, G. Garegnani, G. Manzolini, D. Moser, U. Filippi Oberegger, R. Pernetti, R. Vaccaro, W. Sparber, Multi-objective optimization algorithm coupled to EnergyPLAN software: The EPLANopt model, Energy 149 (2018) 213–221, http://dx.doi.org/10.1016/j.energy.2018.02.050.

[44] EnergyPRO – tutorials & guides, 2022, https://www.emd.dk/energypro/support/tutorials-guides. (Accessed 09 May 2022).

[45] ESSIM documentation, 2022, https://essim-documentation.readthedocs.io. (Accessed 09 May 2022).

[46] ESSIM API, 2022, https://essim-documentation.readthedocs.io/en/latest/essim_api/index.html. (Accessed 19 July 2022).

[47] ESDL MapEditor ESSIM tutorials, 2022, https://essim-documentation.readthedocs.io/en/latest/tutorials. (Accessed 09 May 2022).

[48] The GasPowerModels mathematical model, 2021, https://lanl-ansi.github.io/GasPowerModels.jl/stable/math-model/. (Accessed 20 July 2021).

[49] R. Bent, S. Blumsack, P. Van Hentenryck, et al., Joint electricity and natural gas transmission planning with endogenous market feedbacks, IEEE Trans. Power Syst. 33 (6) (2018) 6397–6409, http://dx.doi.org/10.1109/TPWRS.2018.2849958.

[50] C. Borraz-Sánchez, R. Bent, S. Backhaus, et al., Convex optimization for joint expansion planning of natural gas and power systems, in: Proc. of the 49th Annual Hawaii International Conference on System Sciences, HICSS 2016, 2016, pp. 2536–2545, http://dx.doi.org/10.1109/HICSS.2016.317.

[51] Integrate, 2022, https://www.sintef.no/en/software/integrate/. (Accessed 09 May 2022).

[52] B.H. Bakken, I. von Streng Velken, Linear models for optimization of infrastructure for CO_2 capture and storage, IEEE Trans. Energy Convers. 23 (3) (2008) 824–833, http://dx.doi.org/10.1109/TEC.2008.921474.

[53] R. Lougee-Heimer, The common optimization interface for operations research: Promoting open-source software in the operations research community, IBM J. Res. Dev. 47 (1) (2003) 57–66, http://dx.doi.org/10.1147/rd.471.0057.

[54] B.H. Bakken, H.I. Skjelbred, O. Wolfgang, eTransport: Investment planning in energy supply systems with multiple energy carriers, Energy 32 (9) (2007) 1676–1689, http://dx.doi.org/10.1016/j.energy.2007.01.003.

[55] Project spine, 2022, http://www.spine-model.org. (Accessed 19 July 2022).

[56] H. Kauko, D. Pinel, I. Graabak, O. Wolfgang, Assessing the potential of seasonal thermal storage for local energy systems: Case study for a neighborhood in Norway, Smart Energy 6 (2022) 100075, http://dx.doi.org/10.1016/j.segy.2022.100075.

[57] The Modelica Association, 2022, https://modelica.org. (Accessed 09 May 2022).

[58] TransiEnt library, 2022, https://www.tuhh.de/transient-ee/en/index.html. (Accessed 09 May 2022).

[59] OpenIPSL: Open-instance power system library, 2022, https://github.com/OpenIPSL/OpenIPSL. (Accessed 09 May 2022).

[60] Modelon Library Suite, 2022, https://www.modelon.com/products-services/modelon-library-suite-modelica-libraries. (Accessed 09 May 2022).

[61] T. Blochwitz, et al., The functional mockup interface for tool independent exchange of simulation models, in: Proc. of the 8th Internat. Modelica Conference, 2011, pp. 105–114.

[62] A. Senkel, C. Bode, J.-P. Heckel, O. Schülting, G. Schmitz, C. Becker, A. Kather, Status of the TransiEnt library: Transient simulation of complex integrated energy systems, in: Proc. of the 14th International Modelica Conference, 2021, pp. 187–196, http://dx.doi.org/10.3384/ecp21181187.

[63] Pandaplan, 2022, https://www.iee.fraunhofer.de/de/geschaeftsbereiche/energiesystemtechnik/netzplanung-und-netzbetrieb/netzstudien/pandaplan.html. (Accessed 09 May 2022).

[64] Energy Exemplar – PLEXOS, 2022, https://www.energyexemplar.com/plexos. (Accessed 18 July 2022).

[65] J. Devlin, K. Li, P. Higgins, A. Foley, A multi vector energy analysis for interconnected power and gas systems, Appl. Energy 192 (2017) 315–328, http://dx.doi.org/10.1016/j.apenergy.2016.08.040.

[66] PyPSA-Eur-Sec: A sector-coupled open optimisation model of the European energy system, 2022, https://pypsa-eur-sec.readthedocs.io. (Accessed 09 May 2022).

[67] PyPSA: Python for power system analysis, 2022, https://pypsa.org/. (Accessed 25 February 2022).

[68] M. Victoria, E. Zeyen, T. Brown, Speed of technological transformations required in Europe to achieve different climate goals, 2022, arXiv:2109.09563.

[69] J. Dorfner, Open Source Modelling and Optimisation of Energy Infrastructure at Urban Scale (Ph.D. thesis), Technical University of Munich, 2016.

[70] A. Alhamwi, H. Bents, W. Medjroubi, Open source tool for the analysis and simulation of Urban energy infrastructures, in: 2022 Open Source Modelling and Simulation of Energy System, OSMSES, 2022, pp. 1–6, http://dx.doi.org/10.1109/OSMSES54027.2022.9769155.

[71] Encoord – Scenario Analysis Interface for Energy Systems (SAInt), 2022, https://www.encoord.com/SAInt.html. (Accessed 18 July 2022).

[72] K.A. Pambour, B. Cakir Erdener, R. Bolado-Lavin, G.P. Dijkema, SAInt — A novel quasi-dynamic model for assessing security of supply in coupled gas and electricity transmission networks, Appl. Energy 203 (2017) 829–857, http://dx.doi.org/10.1016/j.apenergy.2017.05.142.

[73] Annex TS3: Hybrid energy networks , 2022, https://www.iea-dhc.org/the-research/annexes/2017-2021-annex-ts3. (Accessed 09 May 2022).