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Energy hub optimization framework based on open-source software & data - review of frameworks and a concept for districts & industrial parks

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ABSTRACT:

Multi-model energy systems are gaining importance in a world where different types of energy, such as electricity, natural gas, hydrogen, and hot water, are used to create more complex but also more economic energy systems to support defossilization. While the research community is using open source for a long-time collaborative work on open-source tools is not yet the norm within the research community. To increase the open and sharing efforts between research organizations governments are driving publicly funded projects to share their outcomes. Today no open-source modelling framework exists able to assess different optimization tools. The proposed open-source framework is based on the principle of maximizing the reuse of existing data, software snippets and packages, and add individual code only as necessary. An intensive software package screening identified six suitable open-source tools (and their contributors) to be partly incorporated into the proposed open-source framework. The best tools of individual contributors has been combined and further improved by adding supplementary features such as a scenery model to incorporate shadowing and elevation effects on conventional and renewable power generation technologies are included. Going forward, this approach allows to expand research into urban air assessment in which traffic and energy emissions can be assessed jointly.

Keywords

Open source;
Energy hub;
Energy system modeling;
City multi modal energy systems;

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1. Introduction

The European Green Deal is one of the six priorities of the European Commission between 2019 and 2024 [1]. This Green Deal aims to lead the European Union (EU) into a sustainable and net-zero greenhouse gas emission society by latest 2050. Figure 1 shows how the Green Deal aims to change the European energy system from a linear and non-sustainable into a sustainable and fully integrated circular ecosystem. The most important principles are to electrify all end-use sectors as much as they can and to use clean biofuels for the sectors that cannot be electrified in an economic manner (such as heavy industry and long-distance transportation). The vision of the EU and its Member States could and should be an aspiration for municipalities, districts, and industrial parks.

All energy system design tool assessments known to the author are covering high-level details, such as numbers of regions, types of technology, or types of energy being able to be modeled in their analysis [2]. Their study is another piece of work focusing on abstract details, such as the categorization of conducted studies, as well as on considered features, or energy coverage of the model. It then defines which of the assessed details are seen as mandatory, complementary, or facultative. It does cover a lot of details of modeling, such as spatial resolution, time horizon, path dependencies, energy independence, and social acceptance of individual solutions. However, it does not assess in detail how the

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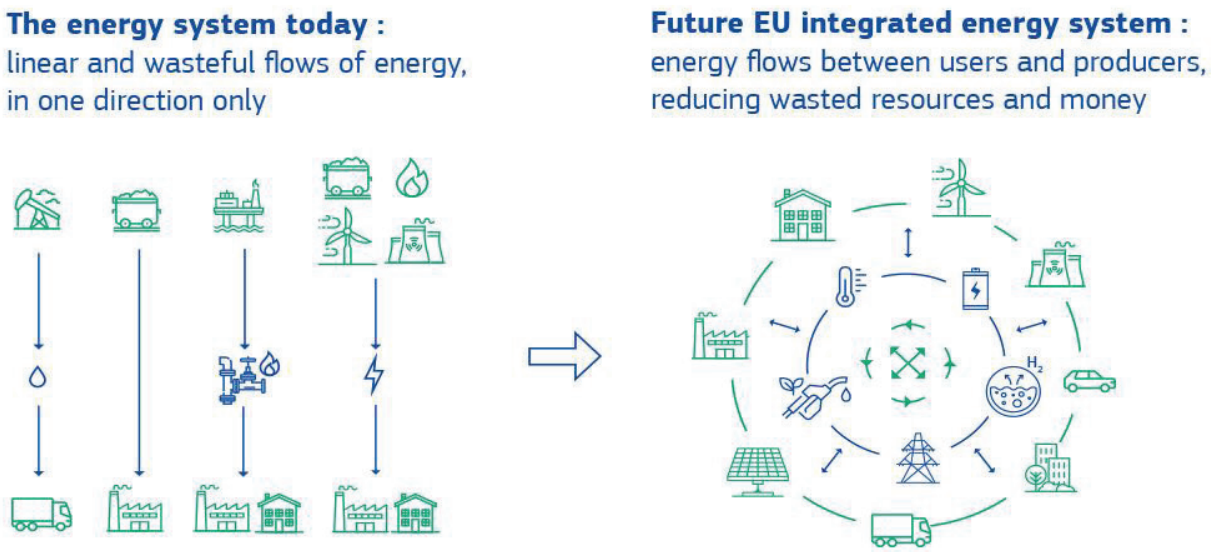

Figure 1: Aim of the European Green Deal [1]

individual aspects are implemented (mathematically formulated) in the optimization model. This kind of model assessment is very common and has been done for over a decade now [3].

To the best knowledge of the author, the first comprehensive attempt analyzing which constraints are incorporated in individual optimization tools was done by the author himself [4]. He analyzed 31 energy models (mainly open-source) and, thereby, assessed 81 modeling details, such as power flow (PF), optimal PF (OPF), security-constrained OPF, or unit commitment (UC) versus security-constrained UC. This level of analysis still does not allow assessing the whole potential of the individual modeling tools. Merely a few months later, a publication from Priesmann et al. was assessing 160 combinations of modeling details to answer the question if complex models are more accurate than simple ones [5]. Therefore, to avoid being bias for one or another reason during the model pre-selection and assessment, this work aims to provide a framework definition to allow a detailed assessment of open-source tools.

With the two exceptions mentioned above, today's energy tool assessment covers only high-level details. The work from Priesmann et al. can be seen as a groundwork complementary to the overall aim of this work. While their focus was on how adding or removing a modeling detail impacts the solution time and accuracy of the solution, they have not assessed the results of several energy modeling tools. The aim of this work is to create an open-source framework that offers the possibility of an unbiased energy system tool comparison.

The structure of the remaining paper is as follows: Chapter II contains an introduction into the concept and idea of energy hubs and a brief overview demonstrating the importance of open source and where it stands today. Chapter III shows the detailed methodology of this project and highlights some of the encountered problems. Chapter IV discusses the preliminary results. Chapter V summarizes the findings, draws a conclusion, and presents proposed next steps within this research work.

2. Literature Review

The first part of the literature review provides an introduction of the *energy hub* concept combined with a brief history around energy system design. The second part of this chapter will show the origins of open-source research in energy system modelling and the status-quo.

2.1. Energy hub

The term *energy hub* was coined by Geidl et al. [6]. In their concept, the exchange of energy between energy hubs was possible within one physical pipe combining electricity, thermal energy, and chemical energy (as shown in Figure 2). Especially for urban areas and industrial parks, this concept was seen as a perfect fit to cover heat and electricity demand through, e.g., combined heat and power applications at the same time.

Figure 3 shows a generalized example of an energy hub containing the typical elements "electrical transformer, gas turbine, heat exchanger, battery storage, hot water storage, and absorption chiller" as well as a wood

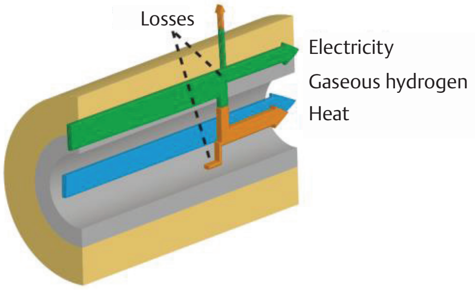

Figure 2: Possible layout of an energy interconnector [6]

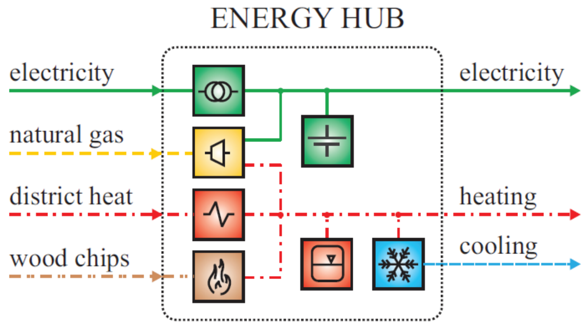

Figure 3: Exemplary energy hub [6]

chip furnace [6]. This energy hub was a key element in the "Vision of Future Energy Networks" project. Energy hubs could be extended through considering additional input streams (e.g., water, hydrogen, and carbon dioxide) as well as additional output streams representing 'power-to-X' options (e.g., green/blue/grey hydrogen, synthetic methane, methanol, ammonia, and carbon dioxide). From a mathematical modeling perspective, energy hubs are units (locations) where multiple forms of energy can be either converted (e.g., wood chips to heat), conditioned (e.g., electricity use in appliances), or stored (e.g., battery storage) for later use. All this transformation and processing comes with conversion and storage losses. It creates a place where all available and possible future energy carriers can have interactions to minimize the overall system cost.

While an energy hub has some inputs (such as electricity, natural gas, and district heating), it has to fulfill the energy demand within the energy hub (such as power demand, heating or cooling loads, or compressed air demand). It can be used to forward any or all of the energy carriers to other energy hubs through transportation (such as power lines, and natural gas or district heating pipelines). Within the energy hub, energy conditioning can happen through, e.g., combined heat and power technologies, compressors, or heat exchangers. Energy hubs can represent industrial facilities, larger buildings, but also rural and urban districts or isolated systems.

In 1997, Bruckner focused on overall energy efficiency improvements through the optimal configuration of available energy technologies [7]. In 2004, Biberacher concentrated on the implementation of geographical information systems (GIS) into the optimization model to optimize the long-term energy fulfillment on a national scale [8]. Both did not include a detailed energy model assessment in their work. In 2007, Geidl focused purely on the modeling aspect of energy hubs as his work was the first of its kind considering multiple forms of energy jointly within one expansion planning and operation application [9].

Connolly et al. listed 68 tools and investigated 37 out of them with the aim to validate if they can be used for renewable energy integration assessments [10]. While there were no typical applications identified a screening for the use of the individual tools was examined. The 'ideal' tool depends on the final use case: e.g., building or energy system analysis, energy-sectors to consider, technologies to consider, and time parameters the tool is able to deal with. Nevertheless, the paper claims to provide 'the information necessary to direct the decision-maker towards a suitable energy tool for an analysis that must be completed'.

In 2011, Mendes et al. focused on energy modeling assessments with a special interest in communities and districts [3]. The analysis was based on a survey of available bottom-up energy models for optimal planning of integrated community energy systems (including HOMER, DER-CAM, EAM, MARKAL/TIMES, RETScreen, and R2RES). After describing and examining these tools, a SWOT (strengths, weaknesses, opportunities, and threats) analysis was conducted. A detailed overview of approaches on how to optimize problems in energy distribution networks (such as simulated annealing, genetic algorithms, tabu search, and particle swarm optimization) was also presented. The overall finding was that DER-CAM is an appropriate energy model for optimized energy provisioning for communities.

In 2014, Mancarella provided a detailed overview of existing concepts and evaluation models within the multi-energy system (MES) community [11]. Based on this work, MES aims to increase the final energy conversion, optimizes the split into centralized and decentralized energy conversion technologies, and increases the energy system flexibility. MES is characterized by its spatial, multi-service, multi-energy, and network perspective and an ideal concept for integrating different energy sectors (nowadays known as ‘sector coupling’ or ‘integrated energy systems’) which traditionally have been treated in isolation. A brief discussion about the features of MES tools also considered the tools RETScreen, EnergyPLAN, DER-CAM, and eTransport. The study aimed to show the state-of-the-art of MES concepts and models but did not conduct a detailed assessment.

In 2017, Dorfner provided a very brief overview of optimization tools based on an assessment conducted Keirstead et al. [12]. The only tools discussed are MARKAL, TIMES, and MESSAGE as the study’s objective was to provide open-source tools (via the source code sharing platform github.com) to support the idea of maintainability of models, reproducibility of case studies, and co-optimization of heat and electricity carriers. Their work reviewed 219 papers and identified five key areas of practice: “technology design, building design, urban climate, systems design, and policy assessment” [13]. A great future for urban energy system modelling is seen if challenges such as model complexity and data uncertainty can be resolved.

In 2017, Thiem looked briefly into existing tools such as Balmorel, DER-CAM, EnergyPLAN, energyPRO, HOMER, MARKAL&TIMES, MGEOS, RETScreen, TOP-Energy, TRNSYS, and urbs [14]. After a brief discussion of these tools, the focus of the remaining literature review focused on six groups of applications (see Table 1). The groups have been created based on existing energy model reviews and the scope of optimization tools (such as spatial dimension, covered model details, and type of optimization problem) but no. The focus of his research lies within group 5 with the aim to design multi-modal energy systems under consideration of part-load efficiencies.

In 2020, Ridha et al. assessed surveys collected during the MODEX (Model Experiments) project in which the research center Projektträger Jülich asked modelers to provide their views on a questionnaire [15]. The survey data was analyzed based on the criteria of mathematical complexity (e.g., LP, MILP, MINLP, stochastic), temporal complexity (e.g., temporal resolution and horizon of planning), spatial complexity (e.g., geographical resolution and horizon), and system complexity (e.g., modeled scope). The focus of their work was to assess how complexity can be reduced through clustering, through use of less techno-economic details such as ramp rates, or through use of less information about the individual sectors to consider. Therefore, the common practice is that energy system modeling tools set their focus on their area of interest and ignore other aspects to decrease the complexity of the overall problem to a level on which available optimization solvers are able to deliver results in a reasonable time.

Also, in 2020, Prina et al. provided a novel classification schemes for bottom-up energy system modelling tools [16]. They identified two main categories and challenges: resolution and transparency. Hereby, resolution is further divided into time resolution, space resolution, techno-economic detail, and details around sector coupling. Their valuation with low, medium, and high shows that there is no tool which has been benchmarked with ‘high’ in all categories. The closest to reach this is the open-source optimization tool PyPSA followed by the commercial tool PLEXOS. The only category where PyPSA has received a rating of ‘medium’ is within the category ‘sector coupling’. It is not transparent why optimization tools such as Oemof, Calliope, and Ficus have been rated with ‘high’ in this category as to the best knowledge of the author the tools have very similar or almost the same capabilities in this regard. Another top ranked tool is the LUT model which unfortunately is not available for the public. EnergyPLAN, a simulation tools, is also mentioned in this paper. It is freeware but not open source. Therefore, only freely available and open-source models such as PyPSA, oemof, Calliope, and Ficus have been considered in this work going forward.

Table 1: Classification of previous research [14]

<table>
<tr><th>Group</th><th>Description</th><th colspan="2">Type of optimization problem</th></tr>
<tr><td>1</td><td>Large-scale grid studies relying on simplified models</td><td rowspan="3">LP</td><td rowspan="2"></td></tr>
<tr><td>2</td><td>Simple tools for quick assessments of small-scale energy systems</td></tr>
<tr><td>3</td><td>Buildings & city district energy system design studies with simplified models</td><td rowspan="4">MILP</td></tr>
<tr><td>4</td><td>On-site energy system studies with additional features</td><td rowspan="3"></td></tr>
<tr><td>5</td><td>Mixed-integer linear programming with part-load efficiencies</td></tr>
<tr><td>6</td><td>Mixed-integer nonlinear programming with complex models</td></tr>
</table>

1.2. Open source

Open source has a long history within information technology where several leading software packages have been made available to the public (e.g., Apache - web server, Netscape - browser, MySQL - database, Linux - operating system) [17]. Unfortunately, in research and development (R&D) as well as in some companies, there are serious ethical, security, and commercial concerns that open source is more threat than an organization can benefit from [18]. The fear relates to unwanted exposure from, e.g., flawed source code, data, or analysis. Another assumption is that time-consuming activities (such as programming, verifying results, or writing documentation) are competitive advantages. Perhaps it is only natural that sometimes the institutional and personal inertia stops organizations and people from following open-source principles.

But what are some of these open-source principles? First, adding transparency to the source code and allowing peer review increases the quality of the software package, which then can also be used by other organizations instead of writing the same piece of functionality again. A peer review process can also lead to increased collaboration. With a focus on R&D, this also means that sharing data, models, and results increases productivity through burden-sharing. As a result, the focus can be set on doing something new and helpful for society instead of repeating necessary, important, but sometimes monotonic tasks.

Of importance within the R&D community is that only results, which are seen and challenged from other parts of the community, are useful to R&D and the overall society. Everything else can be considered self-adulation. An ethical argument is that if R&D is funded by public money, the results should be publicly available as well. Open access to data, source code, energy system models, and results is crucial for a balanced social and political debate. On top of this, R&D needs to support the public and scientific discourse to model for insights and thereby increasing transparency about possible opportunities and risks [19].

Fostering open source to get more transparency and repeatability of analysis was written by DeCarolis et al. [20]. One of the main findings was that a thorough review of results and conclusions is currently impossible. A multi-national research team (Howells et al.), in which DeCarolis was part of, developed the first open-source energy modeling tools: OSeMOSYS (Open Source Energy Modeling System) [21]. One of the key features of OSeMOSYS's implementation is the mathematical formulation in 'plain English' meaning that the mathematical formulation is basically the documentation as well. The formulation has less than five pages of documentation and an easily accessible code. This slim formulation of course comes with the downside of having a simple optimization tool covering only the most necessary techno-economic details.

DeCarolis et al. started the development of another open-source energy modeling tool: Temoa (Tools for Energy Model Optimization and Analysis) [22]. The design of this tool aims for more tractable uncertainty analysis and utilization of multi-core high-performance computing to perform rigorous uncertainty investigation. Pfenninger et al. highlighted that energy models and data are an important part of energy policy assessments [23]. They also found that open up R&D, including models and data, would show immense benefits for all participating parties inside and outside of R&D.

Hülk et al. represent one of the latest open-source energy modeling approaches: oemof (Open Energy Modeling Framework - A modular open-source framework to model energy supply systems) [24]. This initiative aims to provide flexible and generic components to model cross-sectoral (e.g., heat, power, mobility) and multi-regional open, modular, and transparent models allowing everyone to contribute (community-driven). Publications stemming from this imitative became the steppingstone for an overall open R&D community, in which raw data, model formulation, energy model choice, raw results, interpretation, and dissemination is shared transparently with interested people. Its recommended to read papers such as Prina et al. for more detailed discussions about strengths and weaknesses of different energy system models [16].

Figure 4 shows how an overall open-source energy system modeling project might be divided into several distinct process steps in which individual R&D communities and projects contribute to one or several of these process steps. An often-ignored step is the numerical solver, as the R&D community assumes access to commercial solvers; some of them are free or very affordable for academics.

Table 2 shows some of the exemplary open-source related initiatives, which have been launched several years ago and in which process steps they are active in. The table shows five of numerous evolving initiatives and platforms and compares them with the overall aim of this work. The grey cells indicate an area in which the

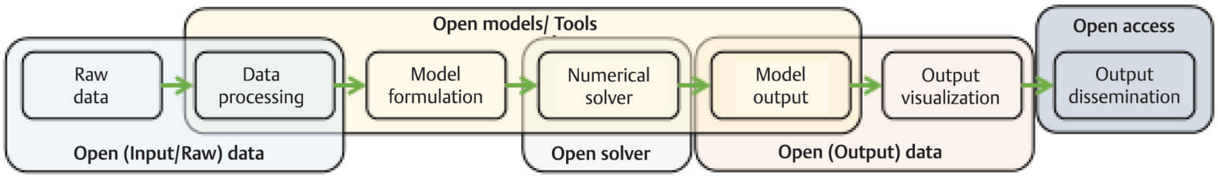

Figure 4: Distinct steps within the open-source discussion (based on [25])

Table 2: Examples of open-source initiatives

Examples	**Raw Data**	**Data Processing**	**Model Formulation**	**Numerical Solver**	**Model Output**	**Output Visualization**	**Output Dissemination**
Open Energy Modeling Initiative [25]							
Energy Modeling Platform Europe [26]							
Open Power System Data [27]							
Computational Infrastructure for Operations Research [28]							
Open Street Map [29]							
This work – link to existing work	API	Python	Pyomo	NEOS			OA journals, arXiv, …

individual initiative and platform is active. While some of them cover a wide range of the process, others are focused on one of the required process steps. The suggested framework aims to support the entire process with limited efforts by developers using existing software and data.

Of course, open and transparent R&D has to be incentivized. Closer cooperation between national and international R&D bodies is necessary to reduce parallel efforts and duplication of work. Therefore, a very important step for implementation of open R&D has been initiated in July 2019: The Open Data Directive (EU) 2019/1024 of the European Parliament and of the Council of 20 June 2019 on open data and the re-use of public sector information [30]. This directive has to be implemented in all Member States until July 2021.

A final remark related to open source is that licensing plays a part that must not be underestimated as it defines what the user can do with the shared source code, data, or models. Morrison provides a very detailed overview of available licenses used in the space of open source and open data [31]. Using one of the licenses from the GPL family results in the highest copyleft while ISC, MIT, BSD, and Apache-based licenses are very permissive granting the user a wide range of activities, including the use of the code and/or data in their commercial products.

3. Methodology

The initial step of this research was to assess existing open-source software tools and to better understand their strengths and weaknesses [4]. A thorough screening of 31 energy modeling tools was based on characterizing them into 12 applications and 81 functions. The applications cover the geographical scope (or use) of the tool (house, industry, district, city, region or country), types of covered energy (electricity, heat, natural gas), being an open-source tool, and is it an optimization or a simulation tool. The functions screening cover aspects such as hourly or variable time steps, altermatic or direct current modeling of power transmission, (security-constrained) unit commitment details and (security-constrained) economic dispatch. The conclusion from this initial work was that open-source energy system modeling tools are ready for serious use compared to commercially available tools. Possible enhancements could be considering the impact of ambient air conditions, part-load behavior, and redundancy aspects. The top scoring tools (Switch Model 2.0 [32], Temoa [20], OSeMOSYS [21], and PyPSA [33]) and about 50% of the assessed tools were based on the programming language Python. As a result, further assessments represented in this work focuses on Python-based tools solely.

The second step of the research involved the assessment of additional tools, software packages, and software snippets to identify what the open-source community has done already and what can be used as a basis for this work. A summary of the assessed Python packages and snipes is available online at Zenodo [34]. As usually for engineering tasks, the difficulty lies in the details: the number of Python-based packages are almost countless. By the end of September 2020, more than 260,000 packages have been registered at pypi.org [35], neglecting thousands of additional software snippets and tools shared via github.com [36], gitlab.com [37], or other code sharing platforms with millions of registered repositories and active developers. This shows one of the biggest downsides of open-source package writing: there is no or very limited coordination between the countless number of packages. Duplicate work also happens in the open-source community. It's very hard to keep track with all the frequent changes as well as new developments. Also, relying on some of these packages means that if there is a (major) redesign of the package once has to adjust accordingly.

The here proposed open-source framework divides the required process steps between having no data at the top of the process (see the left box in Figure 5) and having all data, results, and visualization in eleven steps (indicated by small numbers within the workflow). The right box in Figure 5 shows a selection of assessed tools and data, which have been found useful in the proposed framework. The text in bold marked with a times sign (*) shows where enhancement by the author is considered or have been incorporated already.

The author's sophisticated research revealed that there was no tool considering the z-coordinate within a detailed GIS representation shared within the open-source community. This means that none of the assessed tools considers a proper scenery model in which elevation details are included. Another insufficiently addressed aspect within the tools is profile clustering. Most of them are not able to adequately deal with multiple time-series at once (e.g., multiple energy demands and price time-series).

4. Preliminary Results

The preliminary assessment highlights six open-source oriented R&D contributors where parts of their tools might be incorporated into the here suggested framework (see Table 3). The identified contributors developed several individual tools such as GIS-related data collection, building stock-related load curves, or optimization tool. All of this individual tools usually have been made available by the framework contributors with the

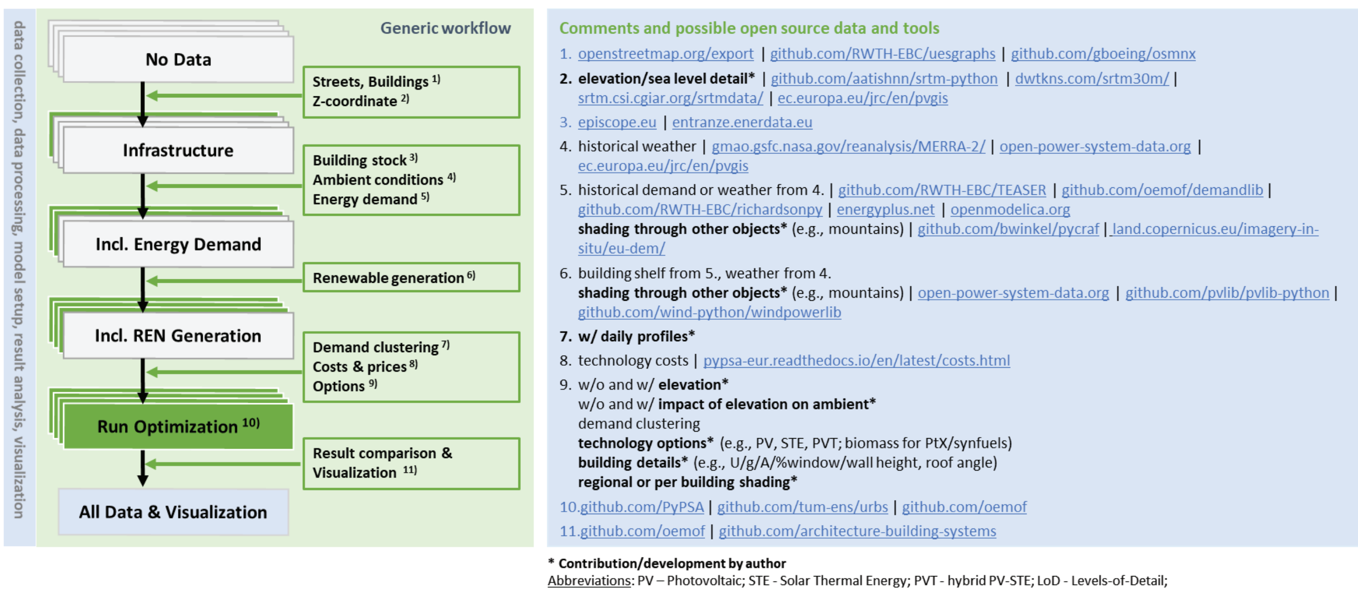

Figure 5: Proposed methodology & selection of considered open-source data and tools

aim to support city or national energy system design. The cells shown in dark blue indicate areas where the individual tools have no or very little contribution to the predefined eleven process steps. Light blue cells indicate a partial contribution. Typical for such assessments, it always depends on the conducted analysis by the author and, therefore, might not reflect the opinion of the open-source framework owners and maintainers.

Regarding the previously mentioned disregard of the GIS z-coordinate, the City Energy Analyst (CEA) tool shown in the last column on the right considers this detail for line and pipeline calculations but not for elevation adjustments of, e.g., efficiency of conventional power generation technologies. As known, individual tools set different focuses. For example, PyPSA's focus is spatial nature, therefore spatial clustering is considered accordingly. Other frameworks, such as the one from FZJ-IEK3-VSA, are focused on time-series aggregation and clustering. Within the proposed framework, both options shall be available to assess the importance of the individual clustering option.

Obviously only European R&D organizations are listed iBased on the conducted analysis, the proposed framework aims to incorporate particular features from

Table 3: Selective contributors and their tools

	* Spatial focus:	≥ State	≤ City	≥ State	≥ State	≤ City	≤ City
	Link to contributor page on github:	FZJ-IEK3-VSA	RWTH-EBC	oemof	PyPSA	tum-ens	architecture-building-systems
1	Streets, buildings,	n/a	n/a	n/a	n/a	n/a	CEA
	land use,	n/a	n/a	n/a	n/a	pyGRETA	CEA
	district heating,	n/a	n/a	n/a	n/a	n/a	CEA
	power,	n/a	n/a	n/a	bdw/GridKit	n/a	CEA
	gas, oil, biomass	n/a	n/a	n/a	n/a	n/a	n/a
2	Z-coordinate	n/a	n/a	n/a	n/a	n/a	CEA
3	Building stock	tsib (for EU)	TEASER (for EU)	tabular (for EU)	n/a	n/a	CEA (for CH)
4	Historical ambient conditions	tsib (TRY, TMY, ISO 12831)	pyCity (TRY, TMY)	feedinlib.era5	n/a	n/a	E+ weather files (epw)
5	Energy demand	tsib, tsorb:occupation	pyCity:occupancy, TEASER, AixLib, IBPSA	demandlib	n/a	n/a	CEA
6	Renewable profile	RESKit, windtools	pyCity	feedinlib	Atlite	pyGRETA	CEA
7	Demand Clustering	tsam	pyCity	solph	PyPSA	pyCLARA	n/a
8	Cost & prices, …	n/a	n/a	n/a	Collection (e.g., DEA, DIW, IEA)	n/a	CEA
10	Optimization	FINE	pyCity	solph	PyPSA	pyPRIMA	CEA
	Solvers abstraction	any local (pyomo)	tbd	any local (pyomo)	any local (pyomo)	any local (pyomo)	Gurobi, GA
11	Visualization	n/a	n/a	OEDB	n/a	n/a	n/a
	Design for addition	n/a	n/a	yes	yes	n/a	n/a
	Additional features	n/a	n/a	visio oemof.db	nomopyomo (cbc, gurobi)	n/a	GUI
	Contributors:	FZJ	EBC	RLI, FHF	KIT, FIAS	TUM	ETHZ

* *Spatial focus*: Household, District, City, State, Region, Country, Continent, World
Abbreviations: FZJ: Forschungszentrum Jülich, EBC: RWTH Aachen, E.ON EBC, RLI: Reiner Lemoine Institute, FHF: FH-Flensburg, KIT: Karlsruhe Institute of Technology, FIAS: Frankfurt Institute for Advanced Studies, TUM: Technical University of Munich, ETHZ: Eidgenössische Technische Hochschule Zürich

Table 4: Examples of open-source initiatives

Framework / Process step	FZJ-IEK3-VSA	RWTH-EBC	oemof	PyPSA	tum-ens	architecture-building-systems	new features
1 – Streets, buildings, land use	-	-	-	-	-	-	osmnx
2 – Z-coordinate	-	-	-	-	-	-	pycraf, tkrajina/srtm.py
3 – Building stock	tsib	TEASER	tabular	-	-	-	-
4 – Ambient conditions	-	-	-	-	-	-	OPSD/ weather_data
5 – Energy demand	-	pyCity:occupancy, TEASER	-	-	-	CEA	-
6 – Renewable profile	-	-	feedinlib	-	-	-	pvlib, windlib, Solar3DCity
7 – Demand clustering	tsam	-	-	-	-	-	-
8 – Cost & prices, technologies, …	-	-	-	technology-data	-	-	economy of scale
9 – Options	-	-	-	-	-	-	sensitivity analysis
10 – Optimization	-	-	-	-	pyPRIMA	-	solver: NEOS*
11 – Visualization	-	-	OEDB	-	-	-	-
Additional features	-	-	-	-	-	-	PyPSA: market, reserve margin

* NEOS: free internet-based service for solving numerical optimization problems (http://www.neos-server.org/neos/)

the assessed contributors into a new open-source framework (see Table 4). The table specifies which process step has been taken from which contributor and the according tool to use. For example, step1, the street and building data can be initialized by using the osmnx package. Step 3, as another example, will use the packages tsib, TEASER, and tabular. While a lot of it has been already implemented, severe actions are still required to finish the framework in a first shareable and stable release. Once available in a shareable and stable release, it will be made available via Zenodo [34]. As indicated during the introduction, the ultimate goal is to have a single framework in which several energy optimization tools can be assessed against each other to verify the resulting quality of the individual tools as well as support the decision-making on which one to use for which purpose.

5. Conclusion & Future Work

As a result of increasing interactions between historically isolated energy systems (e.g., electricity, natural gas, hydrogen, and hot water) multi-model energy systems are gaining importance to create more economic and decarbonized energy systems. The term energy hub can be seen as a synonym for a multi-model energy system. Open-source software has a long history. Also, the research community is using open source for a long time. Public companies have realized that cooperation saves costs and increases the speed for go-to-market with new offerings and solutions. Unfortunately, the research community has not fully accepted that collaborative work on open-source tools is more beneficial than working isolated. More and more governments are convinced that publicly funded projects should end in publicly available data and tools.

Hundred thousand of repositories are available on code sharing platforms, and the number is growing daily. The proposed open-source framework in this work is based on the principle of maximizing the reuse of existing data, software snippets, and packages and adding individual code only as much as ultimately necessary. After careful screening of additional software packages, six favorite open-source frameworks have been identified were the best parts of each of these frameworks are combined into a single open-source framework (see Table 3).

Table 3 might give the impression that there exist already six complete frameworks. This is not the case. The listed 6 contributors do have some individual tools which they use in their daily work, but a comprehensive framework does not exist yet. At least non which does fulfil the proposed eleven steps (from having no data towards having all data, results, and visualization, see Figure 5).

To further improve the energy system framework for the purpose of this research, some more features were added (see Table 4). Those features include a scenery model to incorporate shadowing and elevation effects on conventional power generation technologies. By doing so the utilization of limited resources such as human resources could be improved significantly. Going forward, this approach allows for further research, for example, with a focus on city air assessment in which traffic and energy emissions can be assessed jointly with urban climate effects (e.g., heat islands or cold stream through rivers) [38].

The framework test and verification process are still ongoing and will be applied in a demonstration village to ensure proper quality and stability. The aim of the framework test is to ensure the quality of the new framework. Afterward, the framework will be made accessible on Zenodo [37]. Other framework enhancements and evaluations are still ongoing. Within the next weeks, additional energy system models, such as FlexiGIS [39], might be analyzed whether it provides a useful option for consideration. Another aspect to consider is a standardized database schema for saving GIS-related information. Therefore, the current 3D City DB schema might be assessed for its potential fit. A completely different topic for future work could be to assess why open-source R&D is string in Europe but not outside of Europe.

It is good to see that more and more tools within the energy system modelling area are shared and made available for interested R&D community. Unfortunately, cooperation between different R&D organization still is limited to some exceptions. It would be appreciated to see more multi-national R&D efforts working on open-source energy system modelling tools such as the Spine project does [40]. In this project organizations from Finland, Ireland, Belgium, and Sweden cooperate with one from the US.

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