Optimization-based planning of local energy systems - bridging the research-practice gap

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Abstract. Optimization-based planning of local energy systems – though increasingly mature from a methodological perspective – is not commonly applied in practice. This paper synthesizes learnings from 4 case studies – focused on 4 different sites – in which optimization-based methodologies have been applied to the planning of local energy systems. The aim is to generate insights to facilitate the more effective application of optimization-based methodologies to local energy systems planning in practice. The results indicate that an intensively iterative methodology is critical not only as a basis for adapting the analysis based on stakeholder input, but also to facilitate learning on the part of stakeholders with regard to the value and limitations of the approach and the results. With regard to optimization methodologies, in particular temporal decomposition methodologies are identified as critical to preserving computational tractability in the optimization of complex technical systems, especially those featuring networks and those with many energy carriers or technology options. It is suggested that the methodological tailoring of an optimization model to a specific case and the calculation/visualization of key indicators can be largely automated, which could significantly accelerate future studies and reduce the knowledge required for their execution.

1. Introduction

Optimization-based planning of local energy systems refers to the use of computational optimization methodologies to facilitate the planning of decentralized energy systems for neighborhoods, campuses, urban quarters/districts and municipalities. In particular over the past decade, significant research has been dedicated to the development of optimization-based methodologies to facilitate local energy system planning. The added value of these methodologies is their ability to enable a more comprehensive and holistic perspective in the design of local energy systems. This research domain is generally characterized by the application of linear or mixed-integer linear programming approaches, sometimes in combination of genetic algorithms or other meta-heuristic approaches, and a focus on energy systems featuring multiple energy carriers and multiple conversion/storage technologies.

Optimization-based planning of local energy systems – though increasingly mature from a methodological perspective – is not commonly applied in practice. While numerous examples of the application of this approach to practical cases can be found in literature [1-7], the focus is generally on methodological demonstration/validation. Systematic integration of this approach into local energy systems planning processes is lacking. If the potential of optimization-based local energy systems planning is to be realized, it is critical to understand the reasons for this lacking, and how the research-practice gap can be more effectively bridged.

This paper synthesizes learnings from 4 case studies – focused on 4 different sites – in which optimization-based methodologies have been applied to the planning of local energy systems. Each of the case studies was carried out in close collaboration with one or more industry partners with a strong interest in using the results of the study for the planning of the respective site's energy system. The aim of this paper is to generate insights to facilitate the more effective application of optimization-based methodologies to local energy systems planning in practice.

In the next section, the approach of optimization-based local energy systems planning is clarified, and important methodological developments explained. Each of the 4 case studies is then briefly described, after which key learnings are extracted and elaborated.

2. Optimization-based planning of local energy systems

Optimization-based planning of local energy systems encompasses a range of methodologies, which may be combined or adapted depending on nature of the problem. Most commonly, the problem is formulated as one of cost minimization [2,4,8-10], with costs most often (though not always) expressed as the system's life-cycle costs (investment costs + maintenance costs + energy/fuel costs + decommissioning costs). Most often, the problem is formulated as a linear or mixed-integer linear programme. Variables commonly include the input and output energies of conversion and storage technologies per timestep and the capacities of these technologies. Mixed-integer formulations are necessary for cases in which binary variables are required to represent the installation of the specific components or their operation within a given timeframe. Less commonly programming approaches are combined with meta-heuristic approaches – in particular genetic algorithms – in the context of a bi-level approach as a basis for enabling the solution of more complex problems [11,12]. Multi-objective optimization – the simultaneous optimization with respect to multiple objectives – is most often enabled through the use of an epsilon (ϵ)-constraint method [13], in which a pareto front of optimal solutions is built up by optimizing with respect to costs and constraining a second variable to sequentially higher or lower values.

This basic optimization problem may be augmented or adapted in different ways depending on the requirements of the study and the complexity of the problem to be solved. Research in recent years has led to the development of various methodologies which may be applied in combination with the basic approach described above. This includes, for instance:

- **Thermal and electrical network optimization methodologies**, which extend the basic approach from a single-node to a linked multi-node problem. This enables the identification, e.g. of optimal structures and capacities of thermal networks between buildings [9, 14,15]
- **Spatial clustering methodologies**, which reduce the complexity of multi-node problem formulations by clustering nodes so as to decrease the number of problem variables. Different algorithmic clustering methodologies have been developed, including density-based clustering (most common), load-based clustering and combined clustering [16,17]
- **Temporal decomposition methodologies**, which reduce the complexity of the basic optimization problem by reducing the number of timesteps and thus the number of problem variables. Whereas the basic optimization problem is characterized by a set of sequential timesteps – most commonly hourly over the time horizon of one year – temporal decomposition methodologies either select a subset of "representative" timesteps for capturing the most critical features over the entire year (e.g. typical days methodology), or divide the optimization problem into smaller chunks (e.g. rolling horizon methodology) [18,19]
- **Multi-stage optimization methodologies**, which entail optimizing not just a "snapshot" system design, but rather the sequence of technology investments to be made over a defined period of time. This is essential for cases in which multiple planning phases are foreseen, or in which the composition (e.g. number/type of buildings) of a site is expected to change over time [20,21].
- **Stochastic and robust optimization methodologies**, which enable the explicit representation of parameter uncertainties into the optimization problem, either with associated probabilities (stochastic optimization) or windows of feasible values (robust optimization) [22-24].

Each of these methodologies may essentially be viewed as modular add-ons to the basic optimization problem outlined above. It is possible, and sometimes even necessary, to apply multiple of these methodologies in combination in order to arrive at a formulation of the optimization problem which both sufficiently accurately represents the real-world problem and is capable of being solved within a reasonable amount of time. A particular challenge, however, is that each methodology requires a (to some degree) fundamentally different formulation of the optimization problem (i.e. different sets, parameters, variables and constraints). Insofar as the application of optimization-based approaches to local energy systems planning in practice requires identifying solutions on a short timeframe, the manual development of a tailored problem formulation based on the specific needs of a given case is prohibitive. Within this context, an important motivation for the research team behind the case studies described below was to understand which specific methodologies are necessary for addressing different types of real-world cases and if/how the associated formulation of the optimization problem could be automated to enable rapid but tailored assessment of each case.

3. Case studies

In this section, the 4 case studies are introduced and briefly described. Each case study was carried out in close collaboration with an industry partner, and focused on a specific physical site (see Table 1). However, to a greater or lesser degree, each case study was a broader collaborative initiative involving multiple stakeholders including for instance the building-/land-owners, general planners, local utilities and municipalities. The case studies addressed sites of different sizes. The first two dealt with building agglomerations of 10-15 buildings. The second two case studies dealt with building agglomerations on the scale of hundreds of buildings. All case studies dealt with sites located in Switzerland. The second case study dealt with a greenfield site, whereas the others were focused on sites with an existing and, importantly, evolving building stock. The different scales and characteristics of each case study, as well as the different categories of stakeholders involved, meant that each case came with a specific set of questions and methodological requirements. The case study descriptions below are presented in anonymized form at the request of the involved partners.

Case study	Main industry partner	Size of site (buildings)	Type of site
1	Municipal authority	10-20	Existing
2	Local utility	10-20	Greenfield
3	Local utility	600	Existing
4	Engineering consultancy	1000+	Existing

Table 1: Key features of the case studies.

The analysis for each case study was carried out using a common software tool – the *Ehub Tool* – developed by the researchers prior to the start of the case studies. In the course of carrying out the case studies, the tool was further developed to accommodate the specific requirements of each case and the specific knowledge needs of the respective industry partners. In addition to contributing to the development of an energy plan for each site, a goal of the researchers was to adapt and extend the software base of the Ehub Tool to meet the requirements of real-world problems such that the Tool could be more efficiently applied to similar cases in the future. A third goal of the researchers was to develop a replicable methodology for applying the Tool to local energy systems planning in practice. Prior to the start of the case studies, the research team defined a preliminary version of such a methodology. This methodology provided a common overarching sequence of steps to be carried out – or at least considered – in each of the projects, although it was understood that this methodology would inevitably vary to some degree across the case studies. Indeed, better understanding the necessary deviations from this methodology was a central goal of the research team. The following basic steps defined the methodology:

1. **Requirements definition & problem specification**: Define the scope and objectives of the study, the assumptions to be made and the key performance criteria.
2. **Data collection & processing:** Compile and prepare the necessary input data for the study, including e.g.: estimated building energy demands (hourly profiles for heat, electricity, cooling, steam, etc.), technical & cost specifications of supply technologies (e.g. efficiencies, lifetimes, installation costs, operation costs), on-site renewable energy potentials (e.g. solar, groundwater)
3. **Adaptation Ehub Tool:** As necessary, adapt or extend the Ehub Tool based on the specifications of the problem, by adding custom constraints, objectives or evaluation criteria.
4. **Case implementation & execution:** Implement the problem specification in the input files of the Ehub Tool. Run the tool.
5. **Results analysis & interpretation:** Assess the results to identify the optimal technical configurations under different conditions and the performance of each in terms of the specified evaluation criteria. Key outputs of the tool include the optimal sizing and locations of conversion, storage and thermal network components to be installed, the respective optimal operational schedules of each, and the resulting life-cycle costs and CO_2 emissions of the system.
6. **Iteration:** Iterate to evaluate alternative scenarios or test sensitivities to boundary conditions.

3.1. Case study 1 - Strategic energy planning for a mixed-use urban neighborhood
The first case study focused on the development of a strategic energy plan for an existing mixed-use urban neighborhood. The primary energy users on the site are currently industrial operations with large demand for high-temperature process heat (85-170 degrees C). Significant uncertainty exists regarding the long-term development of the site and thus the future quantity and type of energy demands, in particular after 2030. After 2030, it is possible that industrial operations may cease at the site, being replaced for instance by greater intensity of residential or commercial use. A set of 15 scenarios for the future development of the site in terms of floor area and building tenants were defined. The site is furthermore characterized by the existence of several historically protected buildings, which limits possibilities for energy-focused building retrofitting. It is also characterized by an existing groundwater well which may serve as a low-temperature thermal source for heating and cooling. In the short-term, it will be necessary to replace or renovate parts of the site's current energy system. The industry partner would prefer to make these short-term decisions in line with a longer-term strategy for the future development of the site's energy system. The task of the research partner was – given the inherent uncertainties in the future development of the site – to facilitate the identification of an energy strategy in line with the stakeholders' priorities.

3.2. Case study 2 - Early-stage energy planning for a greenfield commercial campus
The second case study focused on the development of an early-stage energy plan for a greenfield commercial campus. The future tenants of the site and precise configuration of buildings was uncertain, though it was possible to bound this uncertainty in the form of a handful of scenarios for the future tenants and energy demands of the site. Unlike the first case study in which a high-level, long-term energy plan was sought, here the stakeholders sought to identify a specific technological energy system configuration for the site. Key criteria for evaluating potential configurations were life-cycle costs, carbon dioxide emissions and energy autonomy. Of particular interest were technology configurations based around a thermal network. The optimal topology and temperature levels for this network, as well as the optimal set of buildings to be connected to the network, was an open question to be addressed by the analysis. Additionally to be addressed by the analysis was the optimal mix of production and storage technologies to install at each parcel within the site, and the optimal location of an energy center. Next to more conventional technologies, the potential roles of rooftop and facade PV technologies and seasonal ground heat storage were of particular interest.

3.3. Case study 3 - Strategic energy planning for an urban district

The third case study dealt with the development of a strategic energy plan for an urban district of ca. 600 buildings. The site in question is a mixed-use site with significant industry presence. Already now and even more so in the future, the site is undergoing a transition towards greater intensity of commercial and residential use. This shift is expected to result not only in changing energy demand patterns – in particular, increased future cooling demand by commercial buildings is foreseen – but also greater demand for sustainably produced energy. The goal of the industry partner was to determine which technological energy supply options may be best suited to meet these demands, and to what degree it is technically and economically feasible to achieve an energy supply based largely on renewable resources. The site already features a thermal network which provides heating to a fraction of the buildings in the district. An important question was the degree to which, and in which areas, it might be desirable to extend this network, and potentially complement it with a groundwater-fed cooling network.

3.4. Case study 4 - Energy master planning for an Alpine municipality

In 2008, the first energy master plan for the municipality in question was developed. Ten years later, the municipality requested an update of its energy master plan, which was to review the last 10 years while also giving an updated outlook for 2035 and 2050. The 2018 master plan sets new targets for the municipality based on the Swiss Energy Strategy 2050. The goal of the study was to understand how different combinations of energy technologies could best contribute to meeting the new targets. Of particular interest in this case was the potential of an energy system based around the provision of groundwater-based heating and cooling distributed via an anergy (low-temperature, <20°C) thermal network. In addition to groundwater, the potential contributions of various hourly-/seasonally-varying renewable energy resources such as local hydroelectricity and solar energy were a particular focus of the study. A critical question was how to bridge the winter shortfall in renewable energy availability.

4. Synthesized learnings

In this section, key learnings from the four case studies are synthesized. The actual results of the case studies are not presented – rather we focus here on methodological learnings which may inform future studies applying optimization-based approaches to the planning of local energy systems in practice. Three categories of learnings are presented here:

1. Learnings with regard to *project methodology*, i.e. the overarching procedure followed to achieve the stated goals of the study.
2. Learnings with regard to *optimization methodologies*, i.e. which optimization methodologies were of relevance.
3. Learnings with regard to *key indicators and results presentation*, i.e. which indicators were relevant to the involved stakeholders and to which forms of presentation did they best respond.

4.1. Project methodology

In section 3 above, the basic sequence of steps foreseen to be used in each of the case studies was presented. This basic methodology proved to be relatively robust across the case studies, with the major differences across cases seen in the duration and manner of execution of the individual steps rather than the structure of the methodology itself. Two specific patterns are worth noting.

Firstly, the data collection and processing phase was generally found to take considerably longer than foreseen, and was itself subject to multiple iterations. Two categories of data were most effort intensive: building energy demand data and technology cost data. For each of the case studies, building- or parcel-scale energy demands at hourly resolution were required. In all cases a combination of building simulation, standards-based assumptions, public building databases and monitored data was used to obtain suitable demand profiles. A particular challenge – the scale of which was not foreseen in advance – was the presence of missing and erroneous values in building databases and monitored data. This challenge was particularly onerous in case studies 3 and 4 due to the large number of buildings and the inconsistency of the databases used. In both cases, considerable manual effort was required to identify

anomalous data points and replace them with justifiable estimates. A second challenge was the estimation of time resolved demands for industrial buildings. The energy intensity and temporal distribution of industrial energy demands are very specific to the processes involved, which are often not precisely known in such studies. Monitored data was therefore especially critical to estimating the energy demands of industrial buildings – sometimes workarounds using available data were necessary. For instance, in case study 1, highly resolved electricity demand data could be used as a basis for estimating the refrigeration demand of the industrial buildings. A specific challenge with regard to technology data was to estimate the capital costs of technologies in a comparable manner. These costs may be highly local, and reliable databases covering the full range of possible technologies do not exist. Moreover, different data sources may rely on different assumptions, meaning that the costs of two technologies may not be comparable if the data is drawn from two different sources. Most of the case studies here included several dozen different conversion and storage technologies, more than was anticipated. For each technology, multiple data sources had to be compared and necessary assumptions had to be verified with the involved stakeholders.

Secondly, for most case studies, the overarching methodology was more iterative than anticipated. Each iteration turned up unexpected results which had to be verified, and adjustments made. For instance, in case study 2, it was observed after one iteration that an external district heating network connection – the costs of which had been roughly approximated – was being used exclusively to cover heat demand peaks rather than provide for the heat base load. This was deemed an unrealistic modelling artifact and adjustments were made to the technology definitions in the subsequent iteration. It was also observed that multiple iterations are necessary not only as a basis for refining the results, but also as a basis for helping stakeholders to grasp the approach, the inherent assumptions underlying it, and the value and limitations of the results. These iterations therefore served the secondary purpose of a learning process for the stakeholders. In most of the case studies, 4 to 6 iterations were eventually necessary to arrive at a set of results acceptable and understandable to the stakeholders. In most of the cases, the possibility and benefit for further iterations beyond the conclusion of the original project was foreseen, in particular focused on the development of detailed concepts for specific subsystems, such as district heating networks or seasonal storage, which could be addressed at only a relatively high level in the holistic analysis.

4.2. Optimization methodologies

As evident in the descriptions above, the requirements of each case study differed, due to the varying knowledge needs of the involved stakeholders. This resulted in different sets of demands on the optimization methodologies used. As illustrated in Table 2, two of the case studies required multi-node problem formulations due to the need for optimizing the topology and dimensioning of a thermal network. In both cases, a temporal decomposition approach was required to preserve computational tractability of the optimization problem. Due to the large size of the site, case study 3 also required clustering in the spatial dimension to reduce the problem size. In case study 2, temporal decomposition was complicated by the need to represent seasonal storage technologies, requiring a solution tailored specifically to that case. Case study 1 – uniquely amongst the case studies – required a multi-stage problem formulation in order to accommodate phased changes in the spatial development of the site. Although a single node problem, the need for a multi-stage formulation in case study 1 and the large number of technologies being represented (due to many different energy carriers), significantly increased the complexity of the optimization problem, again requiring the use of temporal decomposition. None of the case studies used stochastic or robust optimization methodologies. Rather it was generally preferred by the stakeholders to address uncertainties through the use of scenarios and sensitivity analyses, as this provided a transparent basis for assessing the effects of different sources of uncertainty.

Methodology	Case study			
	1	2	3	4
Network optimization		thermal	thermal	
Spatial clustering			density-based	
Temporal decomposition	typical days	typical days	typical days	
Multi-stage optimization	3-stage			
Uncertainty handling	scenarios	scenarios		scenarios

Table 2: Overview of the methodological extensions used in each of the case studies.

Although the different case studies were subject to different methodological requirements, it was possible to carry them out using a common code base. In particular, it was possible to implement each of the methodologies into the Ehub Tool such that they could be active or inactive depending on the requirements of the problem at hand. This allowed for the formulation of the optimization problem to be automatically structured based on the problem definition as expressed in the Tool's input files, which are prepared individually for each case. However, it was noticed that each case came with certain characteristics that required the implementation of a limited set of parameters and constraints tailored specifically to that case. Based on the authors' experiences in these case studies, this is unavoidable, and suggests that there are limits to the development of a standardized "one-size-fits-all" software code base for optimization-based local energy systems planning.

4.3. Key indicators and results presentation
Based on the preferences and feedback of the stakeholders, a specific set of key performance indicators was calculated based on the results of each case. Five categories of indicators were relevant in one or more of the case studies: economic, sustainability, resource use, system design, system operation and energy autonomy. As indicated in Table 3, certain indicators were requested by the stakeholders in all case studies, including life-cycle costs, CO_2 emissions and the optimal supply system configuration. Groundwater energy use and electricity grid interaction patterns were also required in 3 of the 4 case studies. In 2 of the 4 case studies, the stakeholders requested that all indicator values be compared with those of a "reference" scenario – a scenario based around the use of a conventional (in both cases natural gas-based) system configuration for the site. Comparison to the reference scenario served as an indication to the stakeholders of the potential benefits of developing a "non-conventional" energy supply system for the site. This was critical to enabling the industry partners to justify the results to other stakeholders and decision makers not directly involved in the project.

A challenge for the research team, especially in case studies 1 and 2, was the large number scenarios calculated. In all cases, multiple pareto fronts composed of 4-8 "optimal" solutions – a cost-minimizing solution, as CO_2-minimizing solution and several in-between solutions – were calculated. In case study 2, such a pareto front was calculated for each of 45 different scenarios. This produced 180 "optimal" solutions for which each indicator was calculated. Identifying and communicating key patterns within this large body of results data were key challenges in this case. This was accomplished through the use of color-coded comparison matrices, which condensed a large amount of information into a single visualization, facilitating the identification and communication of important patterns. Detailed results for selected solutions were additionally provided to enable greater depth of understanding.

Category	Indicator	Case study			
		1	**2**	**3**	**4**
Economic	Life-cycle costs (per kWh or per m2)	■	■	■	■
	Cost breakdown (CAPEX, OPEX)		■	■	■
	Overnight costs (per technology)		■		
Sustainability	CO2 emissions (per m2)	■	■	■	■
	CO2 avoidance costs	■			
Resource use	Primary energy use		■	■	
	Groundwater use patterns	■		■	■
System design	Optimal supply system configuration (optimal set & dimensioning of technologies)	■	■	■	■
	Optimal thermal network structure		■	■	
System operation	Storage utilization patterns		■	■	
	Renewables-based production			■	■
	Electricity grid interaction pattterns		■	■	■
Energy autonomy	Hours of autonomous operation		■		

Table 3: Overview of the key indicators calculated for each case study.

5. Conclusions

The aim of this paper has been to generate insights to facilitate the effective application of optimization-based methodologies to local energy systems planning in practice. Key learnings from 4 different case studies were presented, each carried out in close collaboration with industry partners and focused on a specific physical site. The following learnings have been emphasized:

- It is possible to apply a *common overarching methodology* to case studies with different requirements and in the presence of different knowledge needs.
- An *intensively iterative methodology* for optimization-based local energy systems planning projects is critical not only as a basis for adapting the analysis based on stakeholder input and developing detailed concepts for specific subsystems, but also to facilitate learning on the part of stakeholders with regard to the value and limitations of the approach and the results.
- The presence of *anomalous, inconsistent and incomplete data resources* – especially with regard to building energy demands and technology costs – requires significant manual effort.
- *Temporal decomposition methodologies* are a critical enabler to preserving computational tractability in the optimization of complex technical systems, especially those featuring networks and those with many energy carriers or technology options.
- Both the methodological tailoring of a model to a specific case – i.e. the selection and adaptation of methodological extensions suited to solving the problem at hand – and the calculation of key indicators (see Table 3) can be *largely automated* using basic object-oriented software approaches.

In general, it was observed that at least 4 categories of knowledge are necessary for carrying out case studies similar to those presented in this paper: (1) on-the-ground knowledge and data concerning the site in question, (2) engineering knowledge regarding feasible technological solutions, (3) knowledge of optimization methodologies, and (4) software development knowledge. In the experience of the authors based on the case studies described in this paper, the 3rd and 4th categories of knowledge can be effectively solidified in a generally applicable – within certain limitations – software tool. To a certain degree, the 2nd category of knowledge can be solidified within a consistent and complete technology database linked with such a tool.

Taken together, the findings of this paper suggest that a combination of software tools and consistent/complete technology and building databases could significantly accelerate future studies and reduce the knowledge required for their execution. Effectively implemented, such a resource has the potential to facilitate the uptake of optimization-based local energy systems planning approaches in practice.

Acknowledgements

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