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Distributed Urban Energy Systems (Urban Form, Energy and Technology, Urban Hub)

The Ehub Modeling Tool: A flexible software package for district energy system optimization

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Abstract

Effective planning and control of district energy systems must account for numerous complexities and uncertainties, requiring advanced computational tools. This paper introduces the Ehub Modeling Tool, an open source software package for preliminary design optimization of district energy systems. Using automated code generation techniques that directly translate raw data descriptions of a given district into executable optimization code, the tool simplifies and accelerates the process of developing and executing district energy system optimizations, and visualizing/interpreting results. Example applications of the tool in research and education are described.

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Keywords: District energy systems; Energy hubs; Modeling; Optimization; Software tool

1. Introduction

District energy systems can be an efficient means of enabling the integration of renewable and low-carbon energy sources into the built environment. However, effective planning and control of such systems must account for numerous complexities and uncertainties, including the intermittent availability of renewable energy sources, electricity market dynamics, multiple energy carriers, technical constraints, policy/price uncertainty and other factors. Advanced computational tools are necessary to account for the complex interactions of these diverse factors and dynamics.

This paper introduces the *Ehub Modeling Tool*, an open source software tool for preliminary design optimization of district energy systems. Based on the energy hub concept [1], the tool optimizes the selection, sizing and operation of energy conversion and storage technologies in a manner tailored to the characteristics of a given district and project. Key advantages are its ability to capture important complexities in district energy system design/operation and the ease with which the tool can be adapted to different cases and different types of problems. Using automated code generation techniques that directly translate raw data descriptions of a given district into executable optimization

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code, the tool simplifies and accelerates the process of developing and executing district energy system optimizations, and visualizing/interpreting the results.

This paper describes the structure and capabilities of the Ehub Modeling Tool, and provides examples and sample results from application of the tool in research and education. The following section introduces the theoretical basis for the tool and the research/knowledge gap being addressed. Motivation, features and limitations of the tool are introduced, and a set of application examples is provided. Finally, plans for the further development, validation and adaptation of the tool to meet industry needs are described.

2. Energy hub modeling

The mathematical formulations underlying the Ehub Modeling Tool are based on the *energy hub* concept – a conceptual model of multi-carrier energy systems used to represent the interactions of multiple energy conversion and storage technologies [1]. The energy hub concept serves as a basis for developing mathematical models to optimize the operation and design of multi-carrier energy systems at different scales, often with the objective of minimizing total costs or carbon emissions. Energy hub models have been used extensively to identify optimal designs and control regimes for building, district and urban energy systems [2–4]. Most state-of-the-art energy hub models are formulated as mixed-integer linear programmes (MILPs), which offer an advantageous balance of solution efficiency and accuracy. Other formulations have also been implemented, including bi-level formulations, which link a MILP with a genetic algorithm [5], machine learning formulations [6] and nonlinear formulations [7].

Typical objectives of energy hub models are to minimize (operational and/or capital) costs or carbon emissions. Optimized variables include the dispatch schedules, installation and sizing of various energy conversion technologies (e.g. heat pumps, CHP units, solar photovoltaics) as well as the charging/discharging schedules, installation and sizing of various energy storage technologies (e.g. boreholes, batteries). Key constraints in energy hub model formulations include: *load balance constraints* which ensure that energy supply matches energy demand at each timestep (Equation 1); *capacity constraints* which ensure that energy conversion and storage technologies do not exceed their defined capacities in operation (Equation 2); *storage continuity constraints* which ensure that energy stocks and flows from storages balance across time steps (Equation 3); and *carbon or cost constraints*, which cap the total allowable costs or carbon emissions over the specified time horizon. Numerous additional constraints are included in different energy hub formulations, depending on the characteristics of the case, the purpose of the study and the assumptions underlying the analysis. For a more comprehensive overview of energy hub model formulations, the reader is referred to [8].

$$L_k(t) + X_k(t) = P_{k,g}(t) + Q_{k,out}(t) - Q_{k,in}(t) \tag{1}$$

where $L_k(t)$ refers to the demand for energy type k at time t, X_k refers to the energy k exported from the system, P_g refers to the output of generator g, and $Q_{k,dis}$ and $Q_{k,ch}$ refer to the quantity of energy charged/discharged from storages.

$$P_{k,g}(t) <= P_{max,k,g} \tag{2}$$

$$E_k(t) = E_k(t-1) - D_k(t-1) + \eta_{k,ch} \cdot Q_{k,in}(t) - (\frac{1}{\eta_{k,dis}}) \cdot Q_{k,out}(t) \tag{3}$$

where $E_k(t)$ refers to the state of charge of storage k at time t, $D_k(t-1)$ refers to the standing losses from the storage in the previous timestep, and $\eta_{k,ch}$ and $\eta_{k,dis}$ refer to the efficiency of storage charge and discharge, respectively.

An important hindrance to the application of energy hub models in practice is the required time, effort and expertise necessary to develop model formulations which effectively balance accuracy of system representation and solution efficiency. Aggravating this, different cases/projects and different types of problems may demand very different model formulations, limiting the degree to which existing models can be reused. This points to the need for a flexible modeling tool that may be adapted to the demands of different cases and problems, and which reduces the resources needed to implement, execute and analyze the results of energy hub models.

3. The Ehub Modeling Tool

The *Ehub Modeling Tool* is a software tool for creating, executing and visualizing the results of an energy hub model for a given case study (district or urban area) and set of technologies. The purpose of the tool is: (1) to facilitate computational experiments for optimizing the design and operation of district/urban multi-energy systems under different conditions, and (2) to simplify and accelerate the process of developing, executing and analyzing energy hub models. The software workflow of the Ehub Modeling Tool is illustrated in Figure 1. The tool takes as input case data and technology data in defined formats as CSV files. The inputted case data constitutes a quantitative description of the urban area or district being studied, including energy influxes (e.g. solar radiation), energy demands (e.g. electricity, space heating, cooling) and installed infrastructure (devices/components already installed at the site). The inputted technology data includes a quantification of the economic and technical properties of the energy conversion and storage technologies being considered for installation at the site. The case and technology data input files are complemented by a Matlab file where pertinent parameter values may be specified. Parameter values to be specified include the objective of the optimization, fuel and grid electricity prices, properties of the electricity grid, renewable energy support schemes and others.

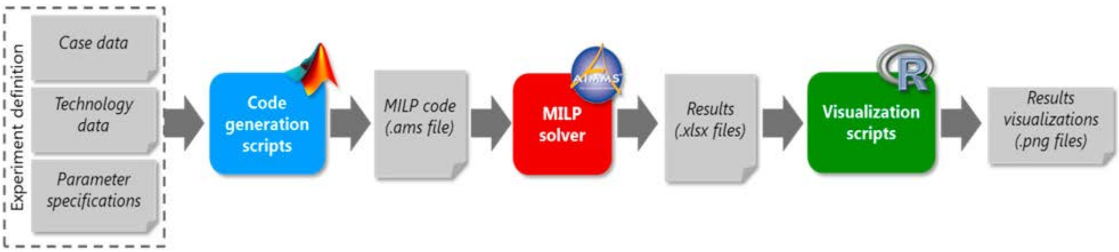

Fig. 1. Software workflow of the Ehub Modeling Tool.

A set of Matlab scripts (*Code generation scripts* in Figure 1) draw from these input files and automatically formulate a MILP model (expressed in the Aimms language). This model is subsequently passed to a MILP solver, and the results are outputted as a set of XLSX files. These files are then accessed by a set of R scripts, which generate a set of visualization based on the results. These visualizations illustrate the characteristics of the optimal system, including e.g. the optimal set of technologies to be installed, the sizing and dispatch schedule of these technologies and the breakdown of costs and emissions over time and by technology. A sample of generated visualizations is illustrated in Figure 2. The generation and execution of an energy hub model, and visualization of its results occur automatically, based on the case and technology data inputted by the user. The automation of these processes significantly reduces the knowledge, effort and time necessary for carrying out advanced analyses.

The Ehub Modeling Tool is capable of optimizing systems with multiple energy carriers, multiple energy demands, and pre-installed infrastructure. It is capable of optimizing single-node systems (all buildings and associated energy demands are aggregated into a single node/hub) or multi-node systems (demands/technologies are disaggregated amongst multiple nodes/hubs) with associated thermal and electrical network structures. The tool is open source and may be easily adapted to the demands of different cases and problems. Current limitations of the tool include a limited library of technical properties/constraints – e.g. part-load efficiencies and on/off constraints are not yet included – and limited possibilities for network optimization. The Ehub Modeling Tool may be downloaded, used and extended upon freely[1]. The tool is part of the HUES Platform, an open source ecology of computational resources to support distributed energy system design and control[2]. Documentation and several application examples are available via the HUES Platform.

[1] https://github.com/hues-platform/ehub-modeling-tool
[2] https://hues-platform.github.io

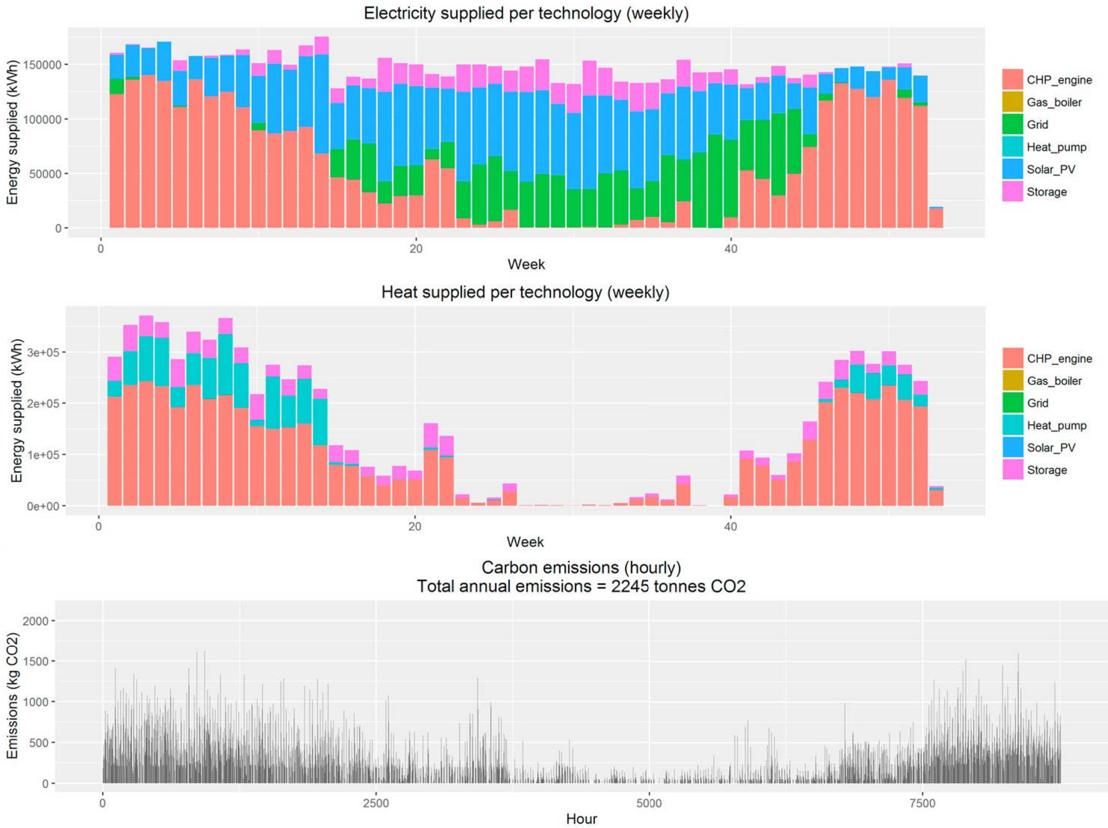

Fig. 2. A sample of results from a single run of the Ehub Modeling Tool, showing the energy production per technology (aggregated weekly) and CO_2 emissions resulting from a cost-optimal system operation. The results pertain to a hypothetical 50-building district in Zurich, Switzerland.

4. Application examples

4.1. Research application: Influence of electricity price policies on district energy systems

A variety of electricity price policies are currently implemented or under consideration in different places around the world, including feed-in tariffs, net metering, time-of-use pricing and real-time pricing. Different electricity price policies may influence the economic feasibility and sustainability performance of district energy systems in different ways. This study applied the Ehub Modeling Tool to investigate the influence of different electricity price policies on the optimal technical configuration, costs and carbon emissions of a hypothetical district energy system. The results highlight the potential benefits of a net metering policy to incentivize technical configurations with low carbon emissions, and of a time-of-use pricing policy to incentivize technical configurations with relatively low carbon emissions and low costs. Additionally, the results suggest that the precise timing of price variations under dynamic electricity pricing schemes may significantly influence system design incentives and system performance. Further details of the investigation can found in Figure 3 and in [9].

4.2. Research application: Evaluation of possibilities for district energy system participation in ancillary services markets

Ancillary services play an important role in ensuring the secure operation of the electricity system by ensuring the real-time balancing of production and demand. This study explored the possible operation outcomes for energy hubs that participate in the ancillary services markets in Switzerland, specifically the tertiary control market. Using the Ehub Modeling Tool, a two-stage stochastic optimization model was created, including participation in the tertiary capacity and energy markets. In the first stage of the model, the decision for the bidding capacities is made, considering a fixed bid price. In the second stage, the information regarding the energy market prices is revealed and the decision on participation in the market and actual delivery of energy is taken. The operation and dispatch schedule of the system is calculated as well as all associated costs. Various technical configurations were examined in order to determine under what conditions participation in the ancillary services markets can prove profitable for district energy systems. Further details of the investigation can be found in Figure 3 and in [10].

4.3. Education application: Optimizing the design of a hypothetical district energy system

The Ehub Modeling Tool was used in a Sustainable Energy Systems course at the Luzern University of Applied Sciences. Students were provided with synthetic data concerning renewable energy fluxes and energy demands for a given district, and were taken through a set of ten exercises during which they systematically explored the influence of different sets of technologies, different optimization objectives, and different technology properties and boundary conditions (electricity prices, feed-in-tariffs, grid carbon intensity)[3]. This exercise was made possible due to the ability of the Ehub Modeling Tool to accelerate and ease the setup and execution of computational experiments for studying district energy systems.

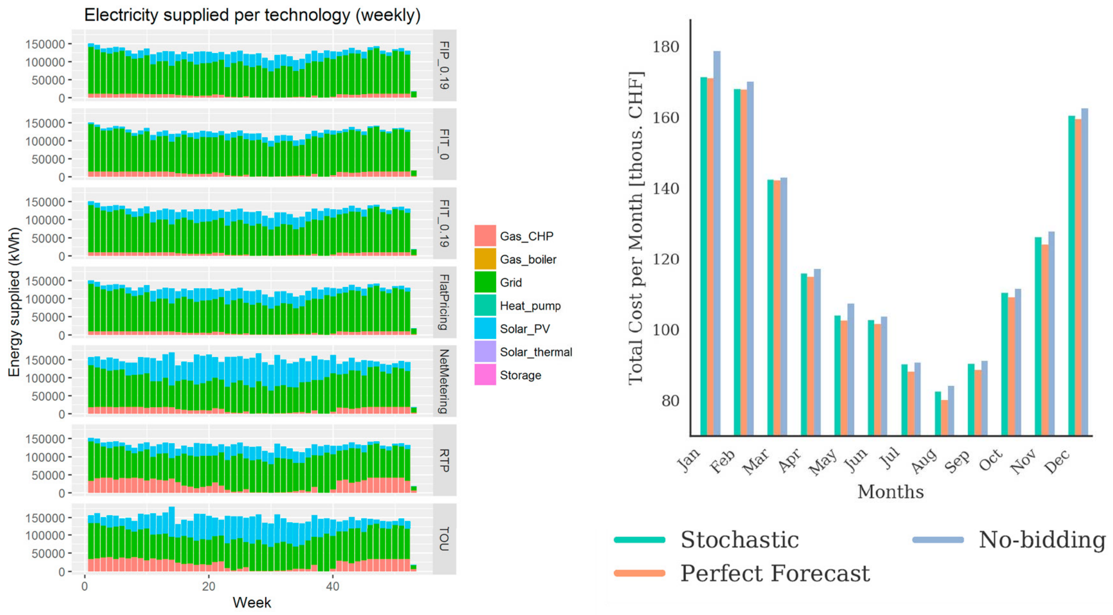

Fig. 3. Results from two different research applications of the Ehub Modeling Tool. The left pane illustrates the optimal operation of a district energy system under different electricity price policies. The right pane illustrates the influence of participation in ancillary services (tertiary control) markets on the total monthly costs of a district energy system.

5. Future work

Future work will focus on expanding the usefulness of the Ehub Modeling Tool for research and education purposes, as well adapting the tool to address the requirements and knowledge needs of industry partners. Specifically, future development efforts will focus on:

[3] Code for carrying out these experiments is open source and available at the aforementioned website for use in other educational contexts.

- *Validation:* Results from the Ehub Modeling Tool have not yet been validated against real-world data. In collaboration with research and industry partners in the context of the SCCER FEEB&D project[4], the tool will be applied to a number of district- and urban-scale cases with different characteristics and different priorities. These studies will serve as a basis for refining the tool (e.g. modifying constraints or objectives) and comparing results from the tool to monitored on-site data and results from detailed simulations.
- *Development of visual interfaces:* To improve ease of use and enhance possibilities for applications in industry and education, we are in the process of developing visual interfaces for inputting data and visualizing/exploring results.
- *Integration of advanced modeling & optimization methods*, including improved representation/optimization of thermal and electrical networks, stochastic and robust optimization techniques, clustering methods to enable optimization of larger districts or urban areas, alternative solution approaches based on meta- or hyper-heuristics, and more realistic representation of control.

6. Conclusions

This paper has introduced the *Ehub Modeling Tool*, an open source software tool for preliminary design optimization of district energy systems. The tool incorporates important innovations in energy hub modeling, such as multi-hub and multi-carrier energy systems. Key advantages of the tool are its flexibility and the ease with which it can be adapted to different cases and different types of problems. Several applications in research and education have been described. Future research will focus on expanding the tool's capabilities and ease-of-use, and adapting it to meet specific knowledge needs and specifications of industry.

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