HUES: A HOLISTIC URBAN ENERGY SIMULATION PLATFORM FOR EFFECTIVE MODEL INTEGRATION

L.A. Bollinger[1,2]; R. Evins[1,2]

[1] *Urban Energy Systems Laboratory, Empa, Überlandstrasse 129, 8600 Dübendorf, Switzerland*
[2] *Chair of Building Physics, ETH Zürich, Stefano-Franscini-Platz 5, 8093 Zürich, Switzerland*

ABSTRACT

Effective design and operation of district multi-energy systems is a complex task necessitating novel modeling and simulation approaches. In this paper, we introduce and describe the *Holistic Urban Energy Simulation (HUES)* platform, an extendable simulation environment for the study of urban multi-energy systems. The platform consists of a growing array of modules and datasets which may be linked in different ways to address different problems in the domain of urban energy systems. Via its combined role as model repository and information management system, the HUES platform facilitates the integration and reuse of constituent modules, opening up possibilities to address the complexity of urban energy systems.

We demonstrate the use of the HUES platform via a case study exploring the relationship between district size and the sizing of the necessary infrastructure, considering realistic variability in heat demand between buildings. We hypothesize that larger districts may more effectively leverage the temporal variation of demand between buildings, reducing infrastructure investment needs. This relationship is explored by linking three modules of the HUES platform – a stochastic demand module, a building energy module and an energy system module – each originally developed for different purposes and adapted for this investigation. The results of the case study indicate that the limited coincidence of demand peaks between buildings means that larger districts require less generation capacity.

The combination of computational modules employed in this case study allows us to extract insights unattainable with any of the modules in isolation – precisely the capability we seek to enable with the HUES platform. Key challenges in the further development of the HUES platform include facilitating model validity, ensuring the development of truly reusable modules and dealing with intellectual property issues.

Keywords: Urban energy systems, Energy hub, Complexity, Modeling platform, Demand variability

INTRODUCTION

The realization of sustainable urban systems requires optimal use of distributed and renewable sources of energy. By serving as loci for the production, storage and consumption of energy in multiple forms, district-scale multi-energy systems (energy hubs) can play an important role in this. Recent work has solidified a set of methodologies for optimizing the design and operation of these systems, considering renewables availability, building energy demands, properties of energy storage and other system characteristics [1, 2, 3].

A significant challenge in this body of work is *complexity*, manifest in the variety and diversity of system elements and their interactions with the environment. District multi-energy systems may contain a variety of technical components – multiple generation and storage technologies and multiple sources of demand – with numerous interdependences. Furthermore, these systems are inextricably linked with their (dynamic) environment – fluctuating meteorological conditions, changing occupant behavior and a developing urban and institutional landscape. This complexity challenges our ability to sufficiently represent district multi-energy systems for the purpose of optimizing their design and operation. Novel modeling and simulation approaches are essential.

This paper describes the *Holistic Urban Energy Simulation (HUES)* platform [4], an extensible simulation environment for the study of district multi-energy systems. The HUES platform consists of a growing array of computational modules representing different aspects of district multi-energy systems and related domains. In the remainder of this paper, we introduce the core concepts and composition of the platform, and describe a case study employing the platform.

COMPOSITION OF THE HUES PLATFORM

The HUES platform facilitates the linkage of models representing different aspects of energy hub design and control. In designing the HUES platform, we adopt a *multi-model ecologies* approach [5], which entails the cultivation of an evolving set of resources that – with some additional effort – can be recombined and reconfigured for different purposes. Possibilities for model integration are not predefined, but emerge over time from ongoing development efforts.

Our implementation of the multi-model ecologies approach is characterized by the software architecture illustrated in Figure 1. The architecture of the HUES platform is composed of three layers. The first layer consists of the computational elements (models and datasets) that constitute the modules of the HUES platform. These modules are distributed across the computers of different developers working on different projects, and are written in a variety of different computer languages. Each module is developed for a specific purpose, but is designed and packaged such that it may be adapted for other purposes.

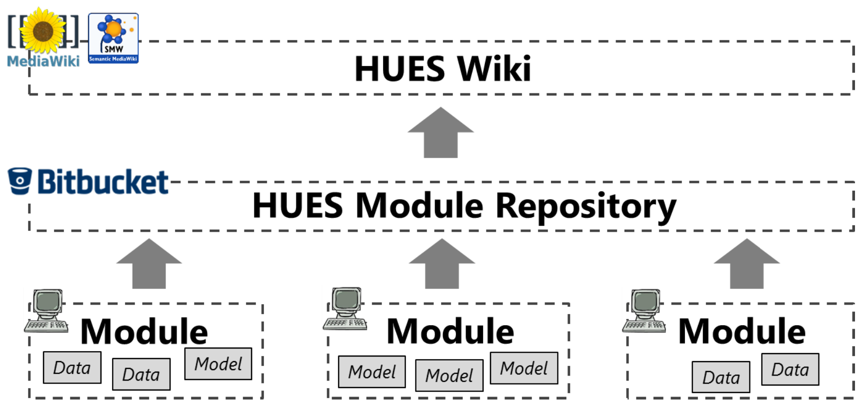

Figure 1: The architecture of the HUES platform consists of three layers.

The second layer is a *module repository*, a cloud-based repository of computational modules. The purpose of this layer is to enable the sharing of modules across diverse platform users. Synchronization of code between the module repository and the files on the computers of individual developers is managed using a Git-based version control system.

The third layer is the HUES wiki[1], a semantic-enabled wiki that acts as an information sharing system for modules in the platform. Each module in the platform is represented by a single wiki page containing key information about the module[2]. Each of the files constituting a module is represented by a separate wiki entry with additional information about that file, allowing platform users to drill down into the precise composition of each module. The wiki also includes *collections*, describing groups of modules that may be used in combination with one another, which enables platform users to understand how modules may be productively combined for different purposes.

The HUES platform has grown around three main types of modules, currently the core elements of the platform. These include: (1) *building energy models* using dynamic thermal simulation to determine the energy demands of individual buildings, (2) *energy system models* which optimize the operation of a district-level system that meets demands by managing supplies through energy conversion and storage, and (3) an *optimization suite* consisting of a range of optimization algorithms that can be applied to any variable or objective present in the platform. In addition, the platform contains many smaller modules that perform specific functions, including stochastic demand models, a longwave radiation model, solar gains calculations, an electricity network model and others.

DEMONSTRATION OF THE PLATFORM

Energy demand may vary significantly between buildings in terms of the magnitude and timing of loads. In the residential sector, this variation is driven by the differing schedules, appliance portfolios, preferences and habits of individuals, as well as the differing physical characteristics of buildings and other factors [6, 7, 8]. When the energy demand of multiple buildings is combined in the context of a district multi-energy system, the energy use patterns of different buildings are aggregated, affecting the sizing and cost of necessary infrastructure. The precise relationship, however, is unclear. Via the set of models described here, we seek to address the following question: *How does the size of a district energy system – in terms of the number of buildings included – influence the optimal sizing of the infrastructure?* To address this question, we link three modules of the HUES platform: (1) a stochastic demand module, (2) a building energy module and (3) an energy system module.

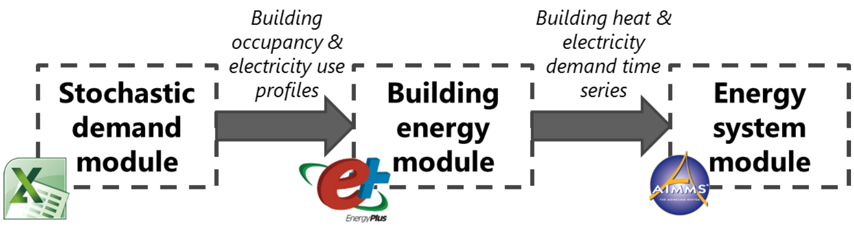

Figure 2: The demonstration model consists of three loosely connected modules.

As illustrated in Figure 2, these three modules are applied in sequence to address the research question above. Each of these modules is represented in the HUES wiki, giving key information about the module and access to the model repository. Likewise, the

[1]The HUES wiki can be accessed at https://hues.empa.ch.

[2]This information includes a description of the module, links to information about the authors of the module, a download link and links to documentation and related publications, the type of license under which the module is released, etc.

combination of modules used in this investigation (and the computer scripts linking the modules) are jointly represented in the wiki as a collection. This information sharing structure is intended to facilitate the future reuse and repurposing of these modules. The computational implementation of the three modules is described below.

Stochastic demand module

This module is based on a model developed by [7][3] that draws from an extensive UK time use survey to stochastically generate residential occupancy and electricity use profiles for households. The model is implemented as a set of Visual Basic scripts run in Microsoft Excel. For a detailed overview of the setup of this model, we refer the reader to [7][4]. A batch run of the stochastic demand module is carried out to generate different occupancy and electricity demand data for 50 identical buildings (with different appliance sets) over a period of one year.

Building energy module

The building energy module takes the results of the stochastic demand module as input, and uses these to generate heat and electricity demand time series for each of building. The physical properties of the buildings are based on those of a hypothetical three-person residence in the Rheinfelden municipality of Switzerland, which is assumed to be connected with a (not yet existing) district heating network. The building energy module uses EnergyPlus. The model is run 50 times to calculate the energy use of a set of 50 hypothetical buildings with identical physical properties. For each run, the model is given a different occupancy and electricity demand profile as input in order to represent the schedule, appliance portfolio, preferences and habits of a different set of occupants. Results for each building are calculated for a period of one year at one minute time resolution.

Energy system module

The energy system module, derived from [9], takes the results of the building energy module as input and calculates an optimal operation schedule for energy hubs of different sizes. It is assumed that each building can be outfitted with solar thermal panels, which (via a district heating network) connect to a centralized heat storage. The aim is to identify a system configuration that minimizes total costs (investment + maintenance + energy) given the goal of cutting carbon emissions to 50% of their baseline level[5].

The energy system module is implemented in the optimization package Aimms as a mixed integer linear program. The outputs of the model include the operation schedule of the energy hub and optimal sizing of the heat storage and solar thermal installations. The calculations account for the investment, maintenance and operational costs of the solar thermal and storage installations, as well as of the grid-connected electric heaters that are assumed to supplement these. A single run of the model represents a timeframe of one week in February at one minute time resolution.

Case study results

Selected results from the energy system module are summarized in Figure 3. As these results illustrate, the maximum heat demand decreases nonlinearly with increasing district

[3] https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/3112

[4] A slightly modified version of the model is used, as described in [8], which enables batch model runs.

[5] The baseline level is defined as the emissions level with no solar thermal or storage installation.

size (left pane) – attributable to the limited coincidence of demand peaks between buildings. On the supply side, the optimal electric heating capacity demonstrates a similar pattern (right pane), as lower peak demand levels translate into lower capacity requirements for heat generation in larger districts. Interestingly, the optimal solar thermal capacity per building exhibits a different pattern (middle-right pane), remaining relatively stable with increasing district size. This may be attributed to the storage, which mitigates the need for higher solar thermal capacity in small districts by covering these demand peaks with stored energy.

While these results are based on a number of assumptions underlying the developed model, they provide an indication of the relationship between district size and infrastructure requirements. Namely, the temporal variation of demand maxima between buildings means that larger districts require less generation capacity to cover these peaks – potentially offering a cost advantage to larger districts. By transferring available energy from times of low demand to high demand, however, energy storage effectively provides the same benefits to smaller districts.

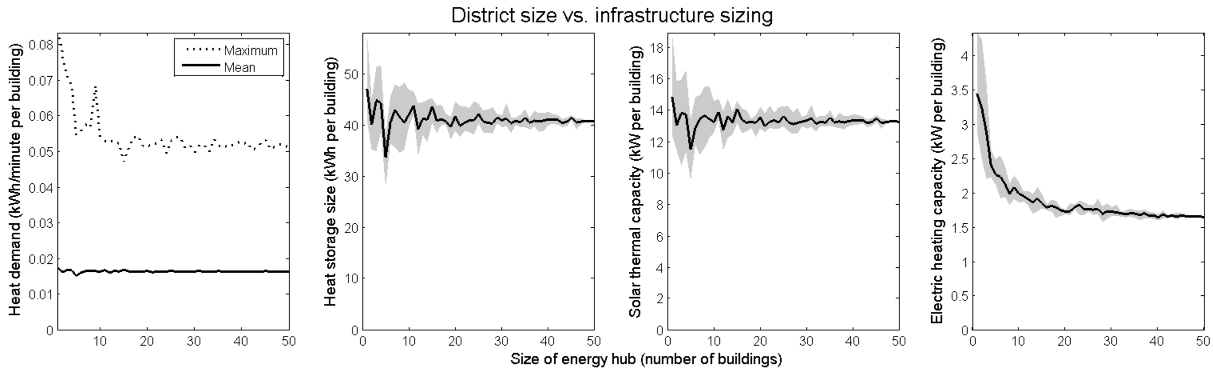

Figure 3: Results of the analysis. Black lines indicate the mean values; shaded areas encompass the range of observed values.

DISCUSSION

Via the combination of modules described in the previous section, we have extracted insights unattainable with any of the modules in isolation. While it would be feasible to construct a single, comprehensive model from scratch to address the same research question, the effort to achieve this would have been considerably larger. By facilitating the sharing, identification and reuse of models, the HUES platform reduces the effort necessary to address research questions such as that above and enhances the complexity of problems that it is feasible to address.

It is important to point out that the modules used in the above investigation were not direct implementations of existing modules. Rather, they were modified – in some cases extensively – to fit the specific needs of our investigation. This process of module adaptation is fundamental to the development of the HUES platform, in which possibilities for module integration are gradually realized through ongoing development efforts.

A key issue moving forward with the HUES platform is *model validity*. The reuse of models beyond the context of their original development risks overstepping their scopes of validity. In general, we leave it to the developers seeking to adapt and integrate modules for specific purposes to understand and accommodate the limitations on module validity. A prerequisite to this, however, is ensuring that scopes of validity are effectively communicated by the original developers. As cultivators of the HUES platform, we are seeking ways to facilitate this through module development guidelines and via the wiki.

CONCLUSIONS

This paper has introduced the HUES platform, an extensible simulation environment for the study of urban energy systems. We have described the composition of the platform and demonstrated its use via an example case. The platform implements a unique approach to dealing with the complexity of district multi-energy systems, based on the development and cultivation of a set of computational modules that can be combined and recombined in different ways. Many challenges remain, such as facilitating model validity, ensuring the development of truly *reusable* modules and dealing with intellectual property issues. Future work on the platform will address these and other issues, and holds significant promise for advancing the study of district multi-energy systems.

ACKNOWLEDGEMENTS

This research has been financially supported by CTI within SCCER FEEB&D (CTI.2014.0119).

REFERENCES

1. Geidl, M. and Andersson, G.: Optimal power flow of multiple energy carriers. *IEEE Transactions on Power Systems*, 22:145–155, 2007.
2. Evins, R., Orehounig, K., Dorer, V., and Carmeliet, J.: New formulations of the 'energy hub' model to address operational constraints. *Energy*, 73:387–398, 2014.
3. Evins, R.: Multi-level optimization of building design, energy system sizing and operation. *Energy*, In review.
4. Bollinger, L. A. and Evins, R.: Facilitating model reuse and integration in and urban energy simulation platform. In *International Conference on Computational Science*, Reykjavik, Iceland, 2015.
5. Bollinger, L. A., Nikolic, I., Davis, C. B., and Dijkema, G. P.: Multi-model ecologies: cultivating model ecosystems in industrial ecology. *Journal of Industrial Ecology*, 2015.
6. Wilson, C. and Dowlatabadi, H.: Models of decision making and residential energy use. *Annual Review of Environment and Resources*, 32:169–203, 2007.
7. Richardson, I., Thomson, M., Infield, D., and Clifford, C.: Domestic electricity use: A high-resolution energy demand model. *Energy and Buildings*, 42(10):1878–1887, 2010.
8. Evins, R., Orehounig, K., and Dorer, V.: Variability between domestic buildings: the impact on energy use. *Journal of Building Performance Simulation*, 2015.
9. Akomeno, O., Hsieh, S., and Orehounig, K.: Energy hub modelling for the design of solar thermal district heating networks with short-term and seasonal storage. In *CISBAT*, Lausanne, Switzerland, 2015.