A simulation platform to facilitate the design of distributed energy systems for buildings and districts

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Abstract

The *Holistic Urban Energy Simulation (HUES) platform* is a set of open source computational tools to support the design of distributed energy systems from the level of buildings to cities. The platform consists of a growing array of models, datasets and algorithms addressing different aspects of distributed energy systems including building energy demand, renewables potentials, storage and multi-energy networks. The core of the platform is a set of computer models for optimizing the design of energy systems from the scale of buildings to cities. Additional modules deal with certain aspects in more detail, such as renewable energy potentials, building characteristics, technology properties and building occupancy. The current version of the HUES platform is targeted to the research community, and aims to support the integration and dissemination models, data and algorithms in the domain of distributed energy systems. Future development will focus on deployment of the platform's resources for the planning and control of distributed energy systems in practice, and will include the validation of key modules, identification and integration of additional metrics and development of interfaces.

Zusammenfassung

Die *Holistic Urban Energy Simulation (HUES) Plattform* besteht aus einer Reihe von Open-Source-Computertools, deren Ziel es ist, die Gestaltung dezentraler Energieanlagen, von Gebäuden bis hin zu Städten, zu unterstützen. Die Plattform besteht aus einer Anzahl von Modellen, Datensätzen und Algorithmen, zur Behandlung verschiedener Aspekte dezentraler Energieanlagen; darunter zum Beispiel Gebäudeenergiebedarf, Energiespeicherung und Multi-Energie-Netzwerke. Den Kern der Plattform bildet eine Gruppe von Computermodellen, die sich auf die Optimierung der Auslegung von Energieanlagen auf verschiedenen Ebenen konzentrieren. Weitere Module befassen sich näher mit bestimmten Aspekten, wie zum Beispiel dem Potential für erneuerbarer Energien, Gebäudeeigenschaften, technologischen Eigenschaften und Gebäudenutzung. Die aktuelle Version der HUES Plattform ist eher auf die Bedürfnisse der Forschung ausgerichtet, und zielt darauf ab, die Integration und Verbreitung von Modellen, Daten und Algorithmen zum Thema dezentrale Energieanlagen zu unterstützen. In der weiteren Entwicklung der Plattform wird die Nutzung für die Planung und die Regelung von dezentralen Energieanlagen in der Praxis im Vordergrund stehen, zusammen mit der Validierung von Modulen, der Entwicklung von Interfaces und der Definition und Integration von Beurteilungsgrössen.

1. Introduction

By serving as hubs for the production, storage and consumption of energy in multiple forms, distributed energy systems are essential to the realization of sustainable urban systems. However, the effective design of distributed energy systems necessitates consideration of diverse aspects such as time-varying resource availability, multi-energy demand patterns, technical constraints and uncertainties regarding future climatic changes, fuel prices and energy demand. Computer models are essential to effectively navigating the complex interplays amongst these factors, and to developing cost-effective, sustainable and resilient energy system designs.

Numerous tools exist for modeling and optimizing distributed energy systems, each of which is well-suited to supporting certain aspects of distributed energy system design and/or operation. However, each of these tools is also limited in the range of problems it is able to address, and rests on sets of assumptions that restrict its scope of validity. Adequately supporting the development and realization of distributed energy systems requires methods and tools which support *holistic* design and analysis, allowing for the integration of models reflecting different scales and perspectives and the systematic testing of assumptions.

This paper describes the features and ongoing development of the *Holistic Urban Energy Simulation (HUES) platform*. The HUES platform is an extensible simulation environment for the holistic study of distributed energy systems. A distinguishing feature of the HUES platform is its modular composition which enables the integration of models reflecting a diversity of scales, disciplines and perspectives. The core of the platform is a set of computer models for optimizing the design of energy systems from the scale of buildings to cities. Additional modules enable accounting for certain aspects in more detail, such as building characteristics, technology properties, network topology and building occupancy.

This paper continues in the following section with a limited review of existing tools for modeling distributed energy systems, and motivates the need for the HUES platform. After this, we provide an overview of the platform's features and composition, and a description of its component modules. We conclude with an outlook concerning the platform's future development.

2. Models and tools for modeling distributed energy systems

Many tools for modeling and optimizing distributed energy systems exist, including DER-CAM[1], CitySim[2], EnergyPLAN[3], HOMER[4], TIMES[5] and others. Several attempts have been made to categorize the current array of models, tools and approaches in this area. Keirstead et al [1] performed a review of urban energy system models, and identify six distinct categories of urban energy system models, including models focused on (1) technology design, (2) building design, (3) urban climate, (4) system design, (5) policy design and (6) transportation and land use. The authors note a lack of attempts to integrate models spanning multiple sectors or disciplines, and highlight the key challenges of complexity, data availability and uncertainty, and model integration. In summarizing their findings, the authors suggest a need for models which adequately capture the complexity inherent in urban areas and enable analysis that cuts across traditionally independent but inter-related sectors such as transport, electricity and heating [1].

Van Beuzekom et al [2] performed a review of urban energy systems tools and identify three distinct modelling approaches: (1) *scenario models* – used to translate explicit goals (e.g. reduction in greenhouse gas emissions, increase in energy efficiency) into technical scenarios regarding e.g. the required types and quantities of energy demand, supply and or storage; (2) *operational models* – used to fully optimize a future scenario given fluctuating demand patterns and renewables intermittency, and (3) *long-term planning models* – used to account for the long-term evolution of parameters such as fuel prices/availability and technology prices. Based on this review, the authors note that none of the available tools adequately addresses the range of challenges inherent in sustainable urban (energy) development, and suggest the importance of combining

[1] https://building-microgrid.lbl.gov/projects/der-cam
[2] http://citysim.epfl.ch/
[3] http://www.energyplan.eu/
[4] http://www.homerenergy.com/
[5] http://www.iea-etsap.org/web/Times.asp

different tools in order to enable "proper decisions" towards sustainable future energy scenarios [2].

Grosspietsch et al [3] performed a partial review of models of decentralized energy systems, and identify a handful of different approaches, including steady-state flow models, co-simulation platforms, optimization-based approaches using mixed-integer linear programming and heuristic approaches. Based on this review – which also encompassed decentralized energy system projects in practice – the authors identify a discrepancy between the focus of scientific studies of distributed energy systems and priorities in practice. In particular, the authors note a gap between key issues in the realization of distributed energy system projects – including technical, economic and regulatory constraints in system operation and barriers to setting up projects – and the key issues dealt with in scientific literature, which focuses more on the methodological aspects of optimizing economic and environmental performance [3].

Taken together, these reviews highlight the diversity of modeling activities around distributed energy systems. Moreover, they suggest the need: (1) for models and tools that adequately deal with the complexity of distributed energy systems, (2) to integrate models and tools reflecting different disciplines, sectors and approaches, and (3) to bridge the gap between scientific research and key issues with the realization of distributed energy systems in practice. The sections that follow describe the HUES platform and how we are attempting to explicitly address these needs in platform's development.

3. Purpose and structure of the HUES platform

The HUES platform is an extensible simulation environment for the study of distributed energy systems from the scale of buildings to cities. The platform implements a *multi-model ecologies* approach [4], which entails the cultivation of an evolving set of resources that can be integrated in different ways for different purposes. A distinguishing feature of the platform is its modular composition, which enables the integration of models reflecting a diversity of scales, disciplines and perspectives.

The HUES platform has been developed at Empa and ETH Zurich in Switzerland in collaboration with research partners in the *SCCER Future Energy Efficient Buildings & Districts* (FEEB&D) project, including EPFL, HSLU and the University of Geneva. Currently, most of the modules in the platform represent the raw outputs of ongoing computational research in the domain of distributed energy systems. The platform in its current form is targeted largely to the research community, though via further development it is aimed to realize an industry-targeted version of the platform (see "Future development" section below).

The purpose of the HUES platform is two-fold:

1. To support **open science and open source dissemination** of models, algorithms and data on the topic of distributed energy systems.
2. To enhance the ability of researchers to effectively address the **complexity of distributed energy systems** through multi-model investigations.

In line with this dual purpose, the structure of the platform is composed of two layers:

3.1 Layer 1 – Repository of open source modules

Layer 1 is a repository of open source computational modules – including models, algorithms and datasets – addressing different aspects of distributed energy systems. Each module is represented in the form of a web page providing key information about the module, including a brief description of the module, documentation, a download URL, licensing details and links to related publications (see Figure 1). In most cases, the code and/or data constituting these modules is publicly accessible and freely downloadable. In this manner, the platform facilitates the ability of researchers to understand, adapt and readily build on the work of others, promoting transparency and accelerating the process of scientific discovery. Currently, Layer 1 of the platform consists of approximately 30 computational modules, each addressing a different aspect of distributed energy systems. An overview of the current modules in the platform is provided in the following section.

The platform itself and a complete list of modules within it can be accessed at: https://hues.empa.ch.

Energy hub batch run with minute resolution

File names	Run_AIMMS.m (Energy hub batch run with minute resolution), EnergyHub.ams (Energy hub batch run with minute resolution), DHWDemandData_525600.xlsx (Energy hub batch run with minute resolution), HeatingDemandData.xlsx (Energy hub batch run with minute resolution), SolarRadiationData_525600.xlsx (Energy hub batch run with minute resolution)
Description	This model is a modified version of the energy hub model developed by Omu (2015), modified to operate at one minute resolution and to enable testing of energy hubs with varying numbers of buildings. The model takes the results of a building energy model 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 25% of their baseline level. The energy hub model 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 April at one minute time resolution.
Authors	Andrew Bollinger
Download URL	https://bitbucket.org/empa_lbst/energy-hub-batch-run-minute-resolution/get/HEAD.zip
Documentation URLs	https://bitbucket.org/empa_lbst/energy-hub-batch-run-minute-resolution/overview
Related publications	(1) Omu, A., Hsieh, S., and Orehounig, K. (2015) Energy hub modelling for the design of solar thermal district heating networks with short-term and seasonal storage. CISBAT 2015, Lausanne, Switzerland. (2) L.A. Bollinger and R. Evins (2015). HUES: A Holistic Urban Energy Simulation Platform for Effective Model Integration. CISBAT 2015, Lausanne, Switzerland.
License type	CC BY-NC-SA
Tags	energy hub model, aimms
Derivation of	-
Timestamp	2015-05-13 09:19:47

Figure 1 Screenshot of a module information page in the HUES platform

3.2 Layer 2 – Multi-model simulator

Layer 2 consists of a subset of the modules in Layer 1. The key difference between modules in Layers 1 and 2 is that modules in Layer 2 have been augmented to allow for interoperability in the form of automated data exchange, enabled by way of standard data formats. These standard formats are defined in the *HUES data specification*[6], which prescribes precisely how different classes of data – e.g. time series data, network data, technology component data – must be specified such that they may be understood and processed by the modules of Layer 2. This allows the modules of Layer 2 to communicate with one another in an automated fashion, enabling the development of multi-module workflows – (semi-)automated chains of computational modules – and facilitating the execution of comparative studies.

Layer 2 of the platform is still in development[7], and is being built around a modular energy hub modeling framework which enables the development and execution of energy hub models spanning multiple scales, from the level of individual buildings to the level of large urban areas. Additionally, Layer 2, when completed, will contain a pair of databases, a *technology database* and a *case study database*. The technology database comprises detailed descriptions of distributed energy technologies, which can be dynamically queried to generate instances of technologies for inclusion in energy system optimization models. The case study database includes the contextual details of various case studies – building characteristics, existing infrastructure, etc. – with a focus on Swiss cases studies being explored in the context of the SCCER FEEB&D project. The purpose of these databases is to facilitate the development of models based on common technology and case study descriptions, in order to enable comprehensive comparisons across different case studies and technological scenarios.

By enabling the combined simulation of modules in the HUES platform, Layer 2 aims to fulfill the second stated purpose of the platform: to enhance possibilities for addressing the complexity of distributed energy systems through multi-model investigations. In particular, development of Layer 2 is focusing on developing three key capabilities:

[6] https://hues.empa.ch/index.php/HUES_data_specification
[7] The core functionalities of Layer 2 are anticipated to be completed by Fall 2016.

1. **Multi-scale optimization of urban energy systems**. Layer 2 enables the development and solution of energy hub models on different scales, from buildings to cities. Through the integration of energy demand/supply modules and energy system modules, Layer 2 enables energy system optimization in a manner which adequately accounts for building occupancy characteristics and building physics, as well as site-specific renewable energy potential. Moreover, Layer 2 will enable the development of "hierarchically nestable" energy hub models, facilitating the optimization of large city-scale energy systems at a relatively high level of detail.
2. **Comparison of different modeling techniques and approaches.** Layer 2 aims to include different optimization algorithms and a variety of models representing technical systems at different resolutions and levels of fidelity. Using the case study database, it will be possible to carry out controlled analyses comparing the accuracy and efficiency of these different algorithms and model resolutions under different conditions.
3. **Scenario analysis of different technological options.** Drawing from the technology database, Layer 2 aims to enable comprehensive investigation of different technological scenarios for the development of distributed energy systems. For instance, it will be possible to efficiently compare the performance of systems based on different types of energy storage, such as heat tanks, batteries and hydrogen, as well as systems including thermal networks of different topologies and extents.

4. Modules in the HUES platform

Each module in the HUES platform addresses a different aspect of distributed energy systems. Modules are developed in different software languages and packages, are in different stages of development, and may constitute computer models, databases/datasets or algorithms. The majority of modules in the platform fall into one of two categories: (1) energy demand/supply modules and (2) energy system modules.

Energy demand/supply modules are models and databases for calculating the energy demand and/or renewables potential of a building, district or urban area. This includes, amongst others:

- **Building energy performance models** which calculate a time series of building electricity, heat and cooling demand of a building given the building's geometry and physical construction, occupancy estimates and weather data.
- **A GIS-based heat demand database**, which calculates yearly final energy demand for space heating and domestic hot water for buildings in Switzerland.
- **Load generator tools** for calculating realistic artificial time series for building-level domestic hot water and electricity demand.
- **Tools for estimating solar energy potential** of urban areas and buildings, also given complex geometries of the built environment.

Some examples of energy demand/supply modules in the platform are provided in Box 1.

Box 1: Examples of energy demand/supply modules

Geo-dependent energy demand and supply web service

This module includes data concerning aggregated yearly heat demand and solar rooftop PV potential in Switzerland, which may be accessed at either the commune or pixel level (200-by-200 meter). The module consists of a demand/supply database, a web service (implemented in ASP.NET) and a web-service client (implemented in PHP, Java, C# and Python). The module has been developed by the University of Geneva and EPFL.

https://hues.empa.ch/index.php/Data:Geo-dependent_energy_demand_and_supply_Web-Service

GenFC load generator tool

This module produces typical, random time series of domestic hot water and non-HVAC electrical loads for single dwellings (single family house), multiple dwellings (multi-family house) or a cluster of multi-family houses. The module uses a statistical event-based approach, in which stochastic single usages are generated and superposed, and loads are defined as events which are characterized by a start time, a duration, and a power consumption.

https://hues.empa.ch/index.php/Model:GenFC_load_generator_tool

Occupancy profile generator

This module is a modified version of the model developed by Richardson, et al [5] used to generate stochastic data sets representing the number of active occupants in a house, which can be used to estimate dynamic heat and electricity demand patterns. The original model uses data from a UK time use survey to generate the occupancy profiles. This original model has been modified from its original version to enable batch runs and disable external irradiance calculations.

https://hues.empa.ch/index.php/Model:Occupancy_profile_generator

Energy system modules constitute various models for optimizing the design and/or operation of energy systems from the level of buildings to urban areas. This includes, amongst others:

- **Energy hub models** for optimizing the selection and sizing of energy conversion and storage technologies in a distributed energy system, given (possibly uncertain) resource availability and energy demand patterns. An *energy hub* is a conceptual model of multi-carrier energy systems used to represent the interactions of multiple energy conversion and storage technologies [6]. The energy hub concept serves as a basis for developing 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.
- **Detailed simulation models** of distributed energy systems with a predefined technical composition, including for instance detailed dynamic representations of thermal and/or electrical networks and energy flows.

Examples of energy system modules in the platform are provided in Box 2.

Box 2: Examples of energy system modules

District heating network routing and Nonlinear power flow constraints

This pair of modules constitutes a set of energy hub models for identifying the optimal design and operation of distributed energy systems. In addition to optimizing the selection and sizing of energy conversion and storage technologies, the first module enables optimization of routing for a district heating network. The second module includes a representation of a local electricity grid and allows for inclusion of nonlinear power flow constraints.

https://hues.empa.ch/index.php/Model:District_heating_network_routing,
https://hues.empa.ch/index.php/Model:Nonlinear_powerflow_constraints

Uni-directional and bi-directional massflow low-temperature network

This pair of modules, developed by researchers at HSLU, simulates a low-temperature heating network with (1) uni-directional mass flow and (2) bi-directional massflow, and enables monitoring of exergetic flows over the system borders. The models are implemented in the software package IDA-ICE, and include a source, a cooling unit and a heating unit. Required data inputs are annual profiles of the ambient temperature, and cooling and heating demands with a frequency of one hour.

https://hues.empa.ch/index.php/Model:Unidirectional_massflow_LTN_(IDA_ICE),
https://hues.empa.ch/index.php/Model:Bidirectional_massflow_LTN_(IDA_ICE)

Multi-agent reinforcement learning-based energy hub model

This module is an initial multi-agent-based implementation of an energy hub model. The model identifies an optimal dispatch schedule for technologies in a distributed multi-carrier system. The model implements two different reinforcement learning algorithms, a Q-learning algorithm and a Continuous Actor Critic Learning Automaton (CACLA) algorithm. Both the Q-learning and CACLA implementations of the model are able to identify near-optimal dispatch solutions for cases without storage.

https://hues.empa.ch/index.php/Model:Multi-agent_reinforcement_learning-based_energy_hub_model

5. Future development – realization of an industry-ready HUES platform

In addition to expanding the diversity and quality of modules in the HUES platform and facilitating module interoperability, future development will focus on the realization of an industry-targeted version of the HUES platform. Main activities in realizing this will include: (1) validation of key modules, (2) identification and integration of additional metrics/parameters, (3) assembling of problem- and purpose-specific toolsets and (4) development of related user and software interfaces.

With regard to module validation, future efforts will focus on reducing the performance gap – the discrepancy between model results and real-world performance of the energy systems being represented. This will require further investigation into the optimal level of detail at which to represent buildings, technologies and energy systems at different scales, given the specific knowledge needs of industry actors, and the validity of different model assumptions in practice.

Grosspietsch et al [3] note a gap between key issues in the implementation of distributed energy system in practice and those issues dealt with in scientific literature. Via the incorporation additional metrics and parameters into the HUES platform, we aim to better reflect the issues and priorities of distributed energy system development in practice. In particular, metrics such as technology risk, system complexity and resilience to regulatory/policy uncertainty must be considered in addition to metrics for cost and carbon emissions. Additionally, the suitability of different business models for realizing distributed energy systems must be considered in combination with optimization of their technical configuration.

Building on Layer 2, future development will entail the assembling and refinement of problem- and purpose-specific toolsets from the pool of modules in the HUES platform, directed to addressing specific problems/questions of industry actors. Access to these toolsets will be enabled via the development of interfaces. This may include graphical interfaces which enable the manual selection of simulation parameters and the visualization of results, as well as software interfaces (e.g. via an API) to enable interoperability of the HUES platform with tools commonly used by industry actors.

Literature/references

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