Title
Platform-based design for energy systems

Authors
Sulzer, Matthias
Wetter, Michael
Mutschler, Robin
et al.

Publication Date
2023-12-01

DOI
10.1016/j.apenergy.2023.121955

Applied Energy 352 (2023) 121955

Contents lists available at ScienceDirect

Applied Energy

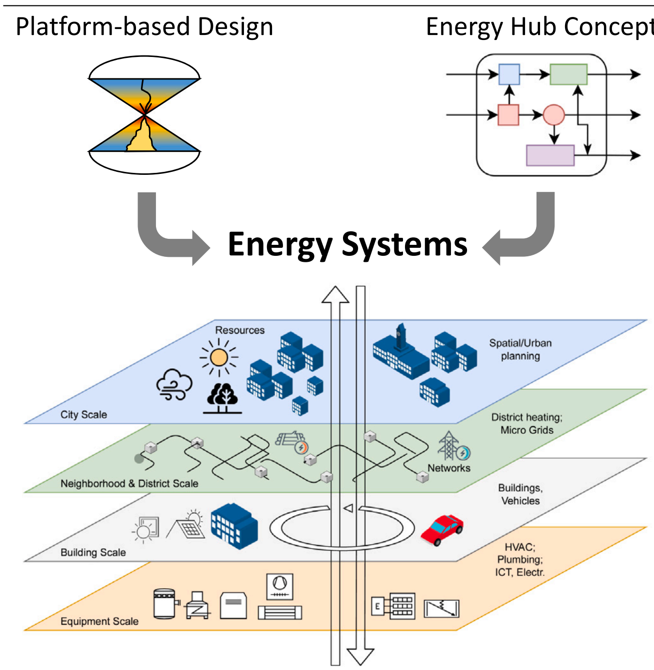
journal homepage: www.elsevier.com/locate/apenergy

Platform-based design for energy systems ☆

Matthias Sulzer [a,b,*], Michael Wetter [a], Robin Mutschler [b], Alberto Sangiovanni-Vincentelli [c]

[a] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, CA 94720, Berkeley, USA
[b] Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, 8600, Dübendorf, Switzerland
[c] University of California at Berkeley, CA 94720, Berkeley, USA

GRAPHICAL ABSTRACT



ARTICLE INFO

Dataset link: https://www.github.com/lbl-srg/modelica-sympheny-district-pub

Keywords:
Energy system design
Decarbonization

ABSTRACT

Defossilization of the current energy system is a major requirement to decelerate anthropogenic climate change. However, a defossilized energy system is vastly more complex than current fossil-based energy systems: The integration of distributed energy resources and sector-coupling increases connectivity, demands interdisciplinary workflows, and creates a need for more sophisticated design processes. Inspired by the semiconductor and automotive industries, digitalization of the design process using platform-based design

☆ This research was funded in part by the Swiss Federal Office of Energy under the project Horizon2020, ERA-Net Geothermica - Geothermal-based Optimized Energy Systems and the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technologies of the U.S. Department of Energy, under contract no. DE-AC02-05CH11231.

* Corresponding author at: Lawrence Berkeley National Laboratory, 1 Cyclotron Road, CA 94720, Berkeley, USA.
E-mail addresses: msulzer@lbl.gov (M. Sulzer), mwetter@lbl.gov (M. Wetter), robin.mutschler@empa.ch (R. Mutschler), alberto@berkeley.edu (A. Sangiovanni-Vincentelli).

https://doi.org/10.1016/j.apenergy.2023.121955
Received 16 August 2023; Accepted 10 September 2023
Available online 25 September 2023

Transformation
Platform-based design
Automated design
Renewables
Distributed energy resources

(PBD), coupled with the energy hub concept, can improve cost-effective energy systems design and accelerate the industry's contributions to achieving net-zero emissions.

PBD is an efficient and effective methodology to manage and de-risk the complexity of integrated energy system design, leading to affordable and reliable solutions due to the inherent techno-economic analysis underlying the decision-making process. Combining the PBD framework with the energy hub concepts establishes a powerful design workflow for developing holistic energy systems from a single building up to the district and city scales. The fundamental tenets of this workflow, as discussed in this paper, are (1) the separation of functions from architectures, (2) the identification of abstraction levels at which systems can be analyzed and optimized, and (3) the ability to repurpose components at all levels of abstraction to aid design reuse and allow performance feedback at every stage of the process.

We argue that PBD can become the next frontier in energy system design. PBD, as presented in this paper, is not limited to the energy sector, and it can also be a sub-process of an even more holistic infrastructure design. Spatial planning, architecture, and civil engineering can all be further integrated with the PBD concept, allowing societies to reach ambitious sustainability goals faster, at lower cost, and with greater resilience.

1. Introduction

1.1. Motivation

The built environment, particularly urban areas with dense building stocks, is facing the challenge of defossilization.[1] Energy systems in urban areas need to transform from centralized fossil fuel based systems into decentralized renewable-based systems. Integrating renewables economically and efficiently forces a system design that locates energy technologies close to the point of use. Buildings are no longer just designed to use energy efficiently but also to harvest, store, and share renewable energy. Buildings will be transformed into *prosumers* and operate as active agents in decentralized energy systems. Such neighborhood and district energy systems can be seen as energy hubs [1,2], incorporating various energy carriers and technologies.[2] Moreover, cities and urban areas will act as multiple energy hubs interacting with one another to guarantee a resilient, sustainable, and affordable energy supply [4,5].

But despite the radical changes needed in urban energy systems, design and decision-making persist in their traditional processes. The industry not only needs innovation for new products, services, and business models, but also needs new design processes to enhance its value chain. The discipline-specific and sequential processes developed over the last four decades still dominate energy system design today. Why are new, renewable concepts not rapidly disseminating, scaling, reducing cost, and increasing reliability? As Einstein is alleged to have said, *"We cannot solve our problems with the same thinking we used when we created them".*

Many industries have been transformed to meet new performance, quality, safety, cost, and time-to-market requirements of complex products and services, and they offer methods and processes we can learn from and be inspired by. For example, the semiconductor industry underwent fundamental changes to provide products and services that could not have been anticipated twenty years ago. Underlying this type of industrial transformation was the introduction of a rigorous design methodology that constrained the design space and, by doing so, allowed verification using computer models that could perform automatic and optimized translation from schematics to layout and from layout to manufacturing instructions. This design methodology evolved over the years to take into consideration reuse (intellectual property blocks) and higher levels of abstraction. Such an evolution can be cast in the platform-based design (PBD) framework (see Appendix A.2 for a summary of PBD) that distills the basic tenets and can be used in other industrial and application domains such as the transportation domain. The framework allows efficient handling of system design complexity, enabling rapid scaling and agile, continuous system innovation. This paper describes how PBD can be adapted to the energy sector, in particular, for distributed energy resources, to achieve a fast and reliable transformation from fossil fuel–based to fully renewable energy systems.

Here we address the challenges and the current state of energy system design, present a new design framework that combines PBD and energy hub principles, and demonstrate the practical application of the PBD concept using a real-world example.

1.2. Challenges of energy system design

1.2.1. Urgency of defossilization

Fossil fuels still predominate in the energy supply, accounting for over 82% of the primary energy share in 2021,[3] even as countries across the globe establish policies to reach a zero-carbon emission society [6]. The European Green Deal [7,8], for example, expresses this objective in its ambitious program to defossilize the building sector. Approximately 250 million existing buildings in the EU [9] must be retrofitted urgently in order to reach net-zero in 2050. The U.S. Department of Energy (DOE) is also working to support grid-interactive buildings for renewable integration. It estimates that the national adoption of such buildings could be worth $100-$200 billion in U.S. electric power system cost savings over the next two decades. DOE's National Roadmap for Grid-Interactive Efficient Buildings aims to triple the energy efficiency and demand flexibility of the buildings sector by 2030 relative to 2020 levels. For industry, the DOE [10] lays out a path to decarbonize the sector by 2050 through multiple decarbonization technologies and approaches including carbon capture, utilization and sequestration, industrial electrification and low-carbon fuels, feedstock and energy sources, and energy efficiency. The defossilization of energy systems is also a critical element of the Swiss energy strategy 2050 [11], which outlines efforts to integrate renewables, enhance efficiency through electrification, and utilize synergies through sector coupling [11,12].

The defossilization of energy systems is a tremendous global challenge, requiring urgent measures to address it due to the postponed and delayed actions against climate change [13].[4] **Countries' current efforts are necessary and important, but are unable to scale and accelerate the transformation to the degree required.**

[1] The reason for using the term *defossilization* arises from the emerging sectors of synthetic fuels and platform chemicals for industrial processes. In both sectors, carbon is used to produce green, climate-neutral goods. Thus, decarbonization may not occur, but fossil resource abandonment must occur to achieve net-zero carbon emissions.

[2] The energy hub concept is defined as a central nexus where various energy carriers converge. At this hub, energy flows are transformed, conditioned, stored, and eventually distributed to meet demand requirements optimally. The modeling of an energy hub delineates the relationship between input and output energy flows, aiding in the optimization of energy consumption during both planning and operation [3].

[3] See https://ourworldindata.org/energy-production--consumption (accessed June 6, 2023)

[4] See also the upcoming UN Global Sustainable Development Report 2023.

1.2.2. Transformation of the energy system

The energy systems' current defossilization progresses too slowly to achieve net-zero carbon emissions in 2050 [14]. Despite the effort in research and development of new technology, the dissemination or uptake in the industry is modest. There are impressive pilot and demonstration projects in operation; however, the wide application is delayed [15].

One of the key elements for defossilization is the integration of distributed energy resources[5] and waste heat sources into the energy system. This integration shifts the current centralized energy system architecture toward decentralized energy systems [16–18]. The proximity of various technologies and infrastructures in local areas allows the creation of energy hubs as an effective concept for decentralized energy systems [19]. Energy hubs on the scale of a neighborhood, district, or city can share investment costs and maximize the utilization of expensive technologies. Large energy systems, such as seasonal energy storage or *energy-to-X*[6] conversion paths, can serve many consumers, resulting in a low-cost energy supply [20,21].

In addition to the technical transformation, non-negligible socio-economic and institutional aspects also affect the reconstruction of our energy systems [22,23]. Energy hubs are, therefore, a complex socio-technical system consisting of multiple actors, various decision-making entities, and technological artifacts governed by energy policy in a multi-level institutional space [24,25].

The transformation pathway for renewable energy systems must deal with increased complexity and rapid implementation, or else we will neither be able to reduce greenhouse gas emissions fast enough nor ensure affordable energy prices and reliable supply [26].

1.3. The current state and future pitfalls of energy system design

The current design process for building and district energy systems is based on a *waterfall* concept [27].[7] ASHRAE GreenGuide [28], and comparable standards in Germany (DIN 276:2018-12) and Switzerland (SIA 112:2014), defines the design process accordingly, and industry largely adopted it to plan energy infrastructure. This approach focuses linear and sequential processes, where each phase of the project life-cycle is discrete, and you must complete one phase before moving on to the next. It does not consider modular, reusable elements, which facilitates immediate feedback when testing individual modules or when adapting the elements for a specific use case.

In recent decades, integral design principles have been added to the waterfall design process for buildings to meet the requirements of a more holistic system design. Coordinators were introduced into the design process to leverage synergies between disciplines [28]. They are primarily concerned that intersections are managed and clashes prevented between disciplines. But there is little effort to optimize buildings and their energy infrastructure in a holistic, systemic approach that allows reusability of components and tracking the performance of the integrated system at each stage of the design process.

Despite efforts to overcome disciplinary silos, the building design process is still organized around disciplines, such as mechanical, electrical, control, or architectural design. Typically, a mechanical engineer develops the building's heating, ventilation, and air conditioning (HVAC) system based on the architect's specifications and in compliance with the current regulations. Their system specification is then passed on to the control engineer, who in turn tries to find the best control design for the given specification. There is no or little interaction among disciplines to co-design buildings or energy infrastructure as a holistic system. PBD has been suggested as an integrated workflow to overcome the silos between HVAC and control systems design [29]; however, the focus is on building and equipment scales and does not consider the higher levels of neighborhood, district, and city scales for energy system defossilization.

The technology mix of renewable energy systems is more diverse than today's energy system, which still relies to a large degree on fossil fuels. To use multiple energy sources, and to match supply to demand, a wide range of technical solutions is needed: solar systems, geothermal probes, storage systems, heat pumps, combined heat and power plants, and/or district heating systems, to name a few. In addition, these technologies require advanced controls that respond to weather, loads, prices, or carbon intensity, and manage multiple energy carriers and stakeholders' needs. Such dynamic decisions not only affect operations but must be taken into account in the planning phase for system configuration and technology sizing to achieve resilient energy system designs. Managing and de-risking the complexity of integrated solutions is essential to ensure fast time-to-market and affordable solutions.

The challenges that energy system design workflows will face in the future include increasing complexity, broadening interdisciplinary collaboration, and consideration of the entire life cycle: design, build, operate, and dismantle.

1.4. Inspiration from other industries

The energy sector is undergoing a similar transformation in performance requirements and system complexity as the semiconductor or automotive industries did a few decades ago. These industries were the first to apply PBD, revolutionizing the way chips and automobiles are manufactured. In light of how this new approach to design has changed the value chain of entire industries, it is highly likely that such a development could be very productively used in the energy industry.

1.4.1. Semiconductor industry

The semiconductor industry's principal approach to meet cost, performance, and time-to-market was – and still is – design automation [27], which allowed the industry to go from a few hundred handcrafted transistor chips of the 1970s to the billion transistor chips of today. The PBD approach was developed to distill the principles of electronic design automation to provide a rigorous framework where reusability, abstraction, and refinement – the separation of concerns between what a system is supposed to do and how it does it – play a fundamental role. This methodology is used to provide directives on how to extend the design of a chip into a system-on-a-chip and multi-chip packaging. PBD can determine trade-offs between various aspects of manufacturing costs, nonrecurring costs, and design productivity. This approach is key to reuse, flexibility, and efficiency in design and production [30].

1.4.2. Automotive industry

Automotive electronic system design was the first extension to another industrial domain of PBD. Cost pressure, flexibility, extensibility, and the need to cope with increased functional complexity are changing the fundamental paradigms for the definition of an electronic architecture in automotive and aeronautics systems. Today's automobiles are required to support an ever-increasing number of functions, such as active cruise control, lane departure warning, and collision avoidance, made possible by the semiconductor evolution. These functions are complex, distributed, interdependent, and time–critical. The integration of these commands requires several stages of planning and arbitration and an unprecedented level of integration and cross-dependency among functions and systems [31].

PBD was introduced in this industrial domain to decouple the hardware architecture from functional requirements, allow the migration

[5] See also https://www.energy.gov/femp/distributed-energy-resources-resilience# (accessed June 6, 2023).

[6] Energy-to-X is used as a synonym for power-to-X.

[7] The waterfall model originates from the construction and production process, where highly structured procedures must be followed, as late changes are expensive or even impossible.

from one hardware architecture to another quickly and inexpensively, and favor the reuse of software functions and hardware components. The principles of PBD are an integral part of the definition of the AUTOSAR architecture that has become pervasive in the automotive domain.[8]

In conclusion, digitized industries have successfully undergone their transformation thanks to new design processes.

1.5. The role of digitalization in energy system transformation

Digitalization pushes today's energy systems into cyber–physical systems. This by itself creates possible systems with higher complexity given the critical interfaces between the digital and the physical components. On the other hand, a digitalized workflow (i.e., design process), if correctly developed, can help manage cyber–physical system design and operation. Thus, digitalization presents great challenges but also great opportunities in several large industries, including electronics, automotive, defense and aerospace, telecommunications, instrumentation, and industrial automation [32]. The energy sector stands to benefit from their experience.

The emergent cloud computing and the Internet of Things (IoT) are prerequisites for a cyber–physical energy system. Future energy systems will access various distributed sensors and contextual data of generation, conversion, and storage technologies as well as networks and appliances [33]. However, new requirements for the design of energy systems arise due to growing quantities of data and the need to extract actionable insights. *Digital twins* can help overcome these challenges, as they can integrate various datasets and can be regularly updated using real-time measurement data. Digital twins are built using distinct multi-physics or data-driven models to cover the entire lifecycle of the energy systems or their components [34,35]. The emerging concept of digital twin will provide a holistic information basis — setting the *single source of truth* for all design and operational aspects and allowing collaborative planning and effective decision-making with all actors [36].

In today's energy planning processes, digitalization is usually considered an additional feature or separated discipline (federated architecture) [37] rather than an integral element of a system design [38].

Driven by digitalization, model-based design for energy systems is evolving but still a niche, applied for highly specialized processes, e.g., thermal process design in the chemical industry. However, this emerging design process establishes a foundation for new design principles to address holistic energy system design [39].

2. Concept of PBD for energy systems

Today's energy system design processes cannot cope with the challenges outlined above. We argue that this shortcoming can be addressed by developing a PBD framework that integrates energy hub principles. This framework:

- Improves scalability: PBD enables the creation of modular, reusable components based on energy hub principles that can be combined and scaled to reduce time-to-market and implementation risk.
- Enhances interoperability: PBD in combination with energy hub principles enables holistic design among different sectors, domains, and disciplines and their seamless operation.
- Propels innovation: PBD facilitates innovation by enabling developers to build on existing platforms and leverage existing components, subsystems, and tools.
- Promotes reliability: PBD builds on verified components and subsystems to deploy reliable new energy systems.
- Increases flexibility: PBD in combination with energy hub principles enables energy systems to be customized and adapted to meet the specific needs of different stakeholders and applications.

Overall, applying a PBD-Energy hub framework will improve efficiency, innovation, and quality in the energy sector, leading to more sustainable, affordable, and resilient energy systems. The explanations in the following section assume an understanding of PBD principles. The PBD concept is well documented, both in the method and in various case studies [39–41]. A summary of the PBD key principles can be found in the Appendix A.2.

2.1. Platforms for energy system design

Applying PBD requires careful system design thinking. Progressing from the basic requirements toward implementation requires intermediate design stages or platform layers to effectively explore the design space. Intermediate platform layers have to follow the PBD rules of structuring the design process into independent aspects [39]. The challenge of finding an appropriate platform stack with its intermediate platform layers is to specify only as many layers as necessary and as few as possible, in the interest of reusability, flexibility, and rapid design-space exploration.

A promising platform stack for designing decentralized energy systems is oriented on its spatial resolution (Fig. 1). Such a structure is currently applied to develop geo-coupled energy systems in urban areas.[9]

The spatial resolution depicted in Fig. 1 is consistent with the abstraction levels of energy systems: Technical equipment, such as pumps, valves, heat exchanger, and controllers, at the equipment scale can be combined into building energy systems such as energy transfer stations, and HVAC systems at the building scale. These systems, in turn, can be connected by different types of networks, such as electrical, thermal, or gas grids, forming district energy systems at the corresponding scale. Multiple district energy systems form the energy system of a city or community. At each level of abstraction or platform, the system is characterized by its components and properties. On the highest layer, the City Energy System Platform layer, components and properties are then typically expressed by specific performance indicators, as we observe in energy master planning tasks [42].

This *bottom-up* process can be applied to analyze either a single building or a whole city energy system, depending on which level of abstraction the analysis process stops. Moving from lower to higher levels of abstraction, a project can be studied at each scale in terms of its behavior and performance. Building stock dynamics and their impact on the energy demand, for example, can be systematically modeled and studied by conducting such an abstraction process [43]. Typically, the bottom-up process establishes a model framework of the current situation on which a top-down refining process can develop future transformation scenarios.

A *top-down* process can then be applied to develop energy systems for either single buildings or whole cities, again, depending at which level of abstraction the design process stops. In any case, system design should always start at the highest level of abstraction at which decisions can be made, relating to the functional requirements at this corresponding level [39]. The mapped solution on the starting level provides requirements to the subsequent lower-level platform, which analyzes how its solution can meet the requirements with refined components. At the very end of such a refinement process, the most suitable specification level for the energy system to be analyzed is reached and

[8] https://www.autosar.org/ (accessed July 11, 2023).

[9] See, Horizon2020, ERA-Net - Geothermica Project GOES, https://www.goes-project.info/ (accessed July 14, 2023).

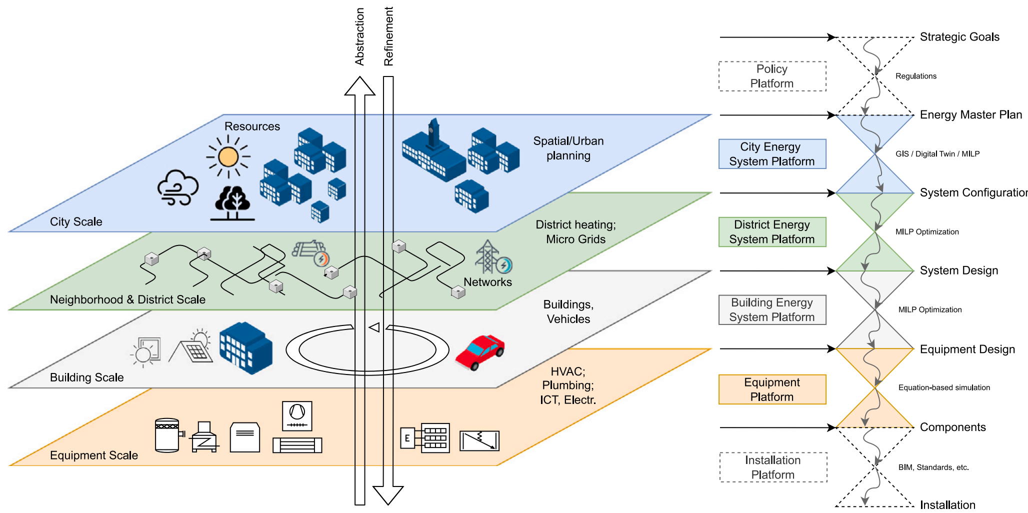


Fig. 1. Spatial scales of decentralized energy systems. On the right, the different scales are assigned to their corresponding Platforms or Layers, defining the Platform Stack of decentralized energy systems. The tools mentioned on each platform are exemplary and serve for a better understanding in the following illustrative example.

its components are defined accordingly — ready for implementation. At this stage, the components are regarded as *atomic components* on which no further decomposition will take place. There might be some components that reach their *atomic* stage at an early level of abstraction if they are fully specified and available.

In general, the relevant boundary conditions, such as policy, regulation, standards, social norms, and spatial constraints, must be considered as the system's environment that affects the solution at each scale and hence the requirements on the subsequent layer. The platform stack with its intermediate layer defines the design exploration space, which is framed by the system boundary conditions, forming a holistic PBD framework for energy system design.

2.2. Combining PBD and energy hub principles

On each Platform, the decentralized energy system can be represented as an energy hub, which is composed of various architectural components. An energy hub is, by definition, not limited to traditional trade, such as HVAC and electrical systems, or information and communications technology, but can consider any energy assets in a holistic framework. The functional requirements will define the configuration and specification of an energy hub. Its design process is conducted by mapping functional to architectural components, and the solution is represented as a platform instance or as an energy hub specification. Energy hubs comply with the basic principles of PBD not to neglect interdependent components or systems, but rather to separate the design tasks into functional requirements and architectural components.

For abstraction or refinement, multiple hubs on a particular platform layer can be aggregated into a single hub on the next higher level. Or conversely, an energy hub can be decomposed into multiple hubs on the lower level of abstraction. On the level where the refinement cannot be expressed as an energy hub, the hub has then to be fully decomposed in its equipment.[10] Applying energy hub concepts by using PBD combines two powerful concepts to tackle the energy system transformation. Fig. 2 shows an example of the energy hub concept applied in a PBD process.

The energy hub concept also accounts for the principles of *orthogonalization of concerns* [39]. On a specific level of abstraction, energy hubs can be developed separately, according to their technical or spatial domain. On the next higher level, these separated hubs can be aggregated, either within the same domain or among different domains. For example, various buildings in a particular neighborhood can be designed as individual energy hubs. District heating networks and electrical microgrids connect these energy hubs and establish an interrelationship. At the neighborhood level, the buildings (hubs) and grids (networks) are aggregated into the same spatial domain as a single hub to analyze the district energy system. Moreover, the aggregation of different domains, i.e. independent neighborhoods, into a city-scale energy hub enables the analysis of utility-scale technologies, e.g., large combined heat and power facilities, utility batteries, and superordinate heating networks.

In every technical or spatial domain, energy hubs can be designed separately and aggregated at the appropriate level of abstraction. Such a structure enables holistic decentralized energy system design while managing its technological, economic, and spatial complexity.

2.3. Digitalization leveraging PBD in the energy sector

The rapid expansion of available data sets allows us to describe and model energy systems at every level of abstraction. The functional description, representation of architectural elements, and the *meet-in-the-middle* mapping process can be automated according to the PBD principles. Moreover, cyber–physical elements allow energy system designs that are adaptive and reusable. Software, as part of the cyber elements, enables customization to satisfy different functional requirements by reusing hardware. Configurable energy systems or subsystems can be implemented in various sites by simply reprogramming the system's behavior. Hence, energy systems that are built according to PBD principles have a great potential to scale.

In Fig. 3 we indicate how architectural elements (Library) could be described or modeled and how requirements (Functional space) can be mapped (Tools) to find platform instances by a digitalized workflow. The Platforms presented in Fig. 3 and their Functional and Architectural elements are exemplary and non-exhaustive.

3. Illustrative example for an energy system design

To demonstrate the PBD process, we will design an energy system for a virtual neighborhood with three clusters of residential, office, and hospital buildings, representing a typical mixed-use area in Zurich, Switzerland (Fig. 4). Details about space heating and domestic hot water, cooling demand, and technical specifications can be found in [44].

[10] Every piece of equipment (or Atomic Component) could also be developed using its own separate PBD process. This would be conducted outside of our design space.

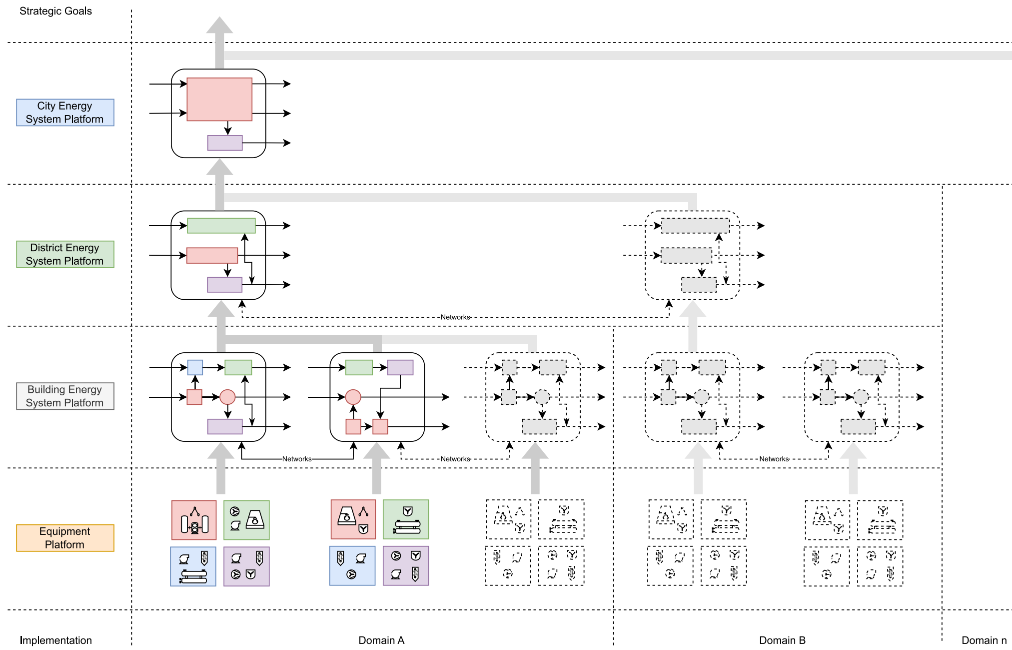


Fig. 2. The energy hub concept applied in a PBD process. The layer above a given layer abstracts the energy hub or aggregates multiple energy hubs below. Energy hubs from different domains can be aggregated on subsequent higher-level energy hubs. Networks can build interrelationships between energy hubs at a given level of abstraction. At the lowest level, where implementation occurs, energy hubs are decomposed into specific types of equipment and controls.

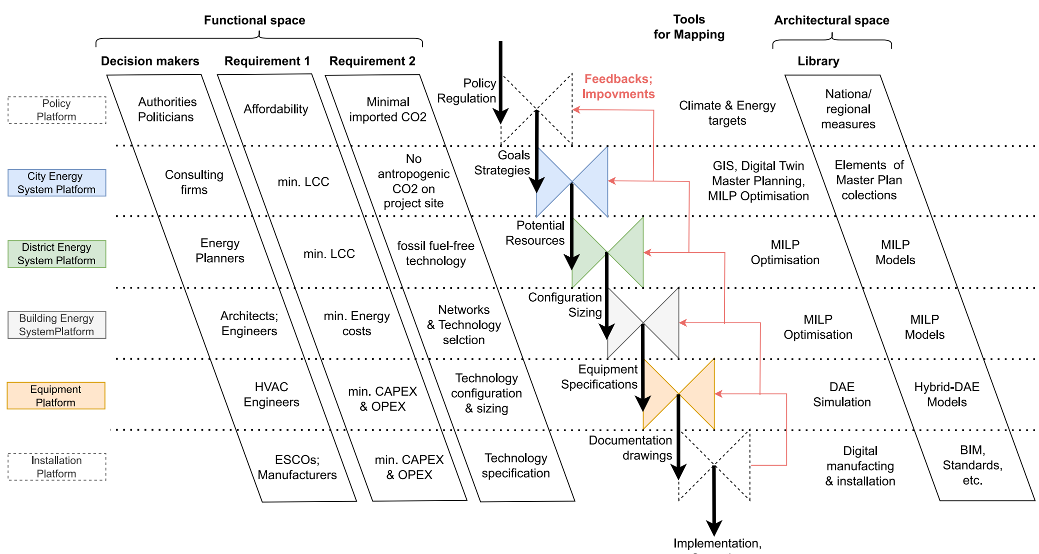


Fig. 3. Exemplary PBD process for decentralized energy systems and typical elements of the functional and architectural space which support a digital workflow.

We also considered electricity demand for general appliances by applying the standard values (20-30 kWh/m^2) for new Swiss buildings and rooftop area for solar installation (5 m^2 per inhabitant).[11] The illustrative example cannot exhaustively demonstrate the advantages of PBD in tackling complex design challenges; however, the example allows us to see how PBD can be used to design a decentralized energy system that is Pareto-optimal with respect to system cost and CO_2 emissions.

The energy hub concept is used to describe the energy system at different levels of abstraction. We start the PBD process at the city scale, which is our highest level of abstraction on this project, addressing the decision-making of city authorities. At the City Energy System Platform, the energy hub represents the city's energy master plan, whose creation is typically led by consulting firms [19]. Following the PBD process principle of refinement, we refined the City Energy System Platform Instance into the District Energy System Platform, which deals with network technologies such as district heating systems. In order for the energy planners to find the most appropriate solution at this level of abstraction, the single hub can be decomposed into multiple hubs representing the three building clusters and the water treatment plant. The next level of abstraction is the Building Energy System Platform, where architects and consulting engineers can optimize the building envelope and the energy system for each hub. Next, at the Equipment Platform, the energy hubs will be decomposed into their HVAC systems, components, and control logic, which will then be fully specified by HVAC engineers — ready for implementation (see also Fig. 2). In the following section, the detailed process steps are described.

[11] See Appendix A.1.

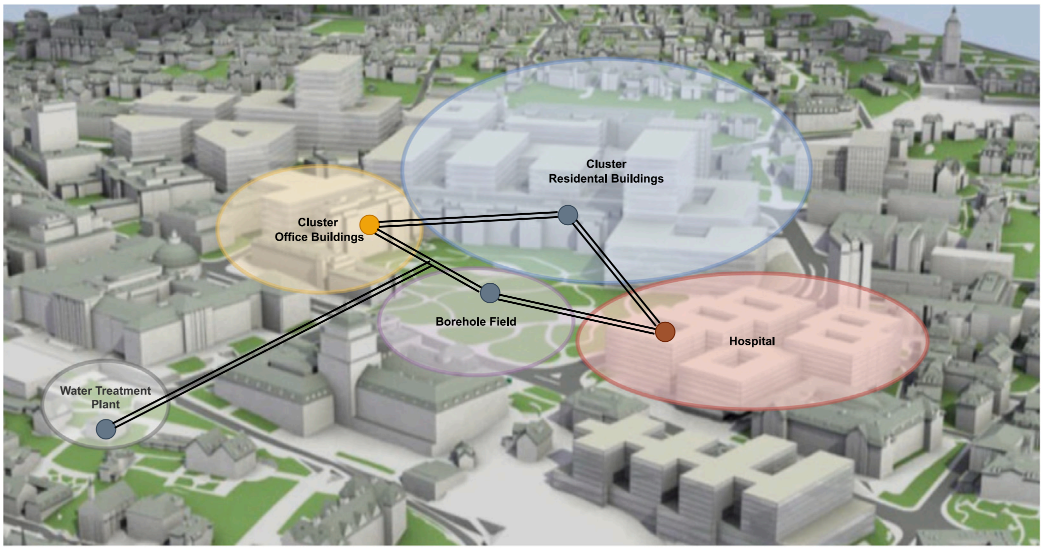


Fig. 4. Layout of a virtual neighborhood in Zurich, Switzerland (visualization Kanton/Stadt Zürich).

3.1. City energy system platform

This platform is the starting point, where the community's requirements are defined as providing an affordable, reliable, and carbon-free energy supply, as set forth by the city of Zurich [26].[12] The to-be-developed energy master plan can be modeled as an aggregated energy hub. Candidates for the city energy hub, defining the architectural space, are: (a) available energy resources, (b) future heating, cooling, and other electricity demand, and (c) prospective types of energy infrastructure. Mapping requirements and architectural components to find the most appropriate energy master plan is done by multi-objective optimization using mixed-integer linear programming (MILP) [45,46]. Fig. 5 shows the energy hub of the neighborhood on the city scale, which formulates the MILP model.[13] In order to analyze the optimal transition of today's infrastructure, the hub model also considers oil and gas boilers (grey-shaded boxes in Fig. 5). As a result, Fig. 6, (a) shows the entire Pareto front from the highest (red dot) to the lowest (green dot) CO_2 emission solutions. As we shift from today's high-emission energy system to a low-emission one, Pareto point (1) delineates the required system transformation, representing an optimized energy master plan.

The mapped solution, i.e., the Platform Instance (Pareto point (1) in Fig. 6), reveals an energy master plan that promotes district heating and cooling (DHC) utilizing geothermal heat, waste heat from the water treatment plant, and photovoltaics (PV) to facilitate local self-consumption (Fig. 5, colored components). At the city scale, the aggregated and hence abstracted technology models are sufficiently accurate for master planning and to set the requirements for the District Energy System Platform.

Pareto point (1) meets the criteria for a carbon-free city that specifies ensuring minimal imported CO_2 and affordability: Switching from today's natural gas and oil boiler-dominated heating infrastructure to a renewable-based energy system reduces the CO_2 emissions by ~75%, causing a green premium, payment of 156 CHF per reduced metric ton of CO_2 [47], see Fig. 6(a).[14] To ensure affordability, the green premium has to be lower than the expected carbon tax of 168 CHF per metric ton [20].

3.2. District energy system platform

The solution of the City Energy System Platform is now passed to the District Energy System Platform as its requirements: district heating and cooling system, solar PV system, zero carbon emissions inside the project perimeter, minimal imported CO_2 emissions, and minimal life cycle costs. Refined requirements that result from this solution are allowable CO_2 emissions and maximum equipment cost and capacities. If a smaller heat pump with a larger buffer tank, for example, satisfies the emission target while meeting the load, then such a system design can be selected.

In the architectural space of this platform, there are still spatially related but refined options,[15] These options include (1) boreholes down to 300 m in depth, (2) roof-top PV systems, (3) DHC sizes, (4) connections to the public electrical grid, (5) thermal and electric storage systems, and (6) waste heat at 15 °C supplied by the adjacent water treatment plant with a maximum capacity of 350 kW.

The use of wood-fired boilers, air-source heat pumps, or electrical chillers are not an option anymore as these technologies have been eliminated in the City Energy System Platform.

The mapping of the requirements to the architectural components (1) through (6) creates hundreds of promising system combinations and equipment sizes for analysis. Finding the Pareto-optimal solution can again be conducted using MILP optimization of the refined energy hub model as shown in colored components of Fig. 5. Choosing the most appropriate solution, Pareto point (2) on the Pareto front of the refined energy hub optimization (Fig. 6(b)) defines the Platform Instance. In

[12] No CO_2 emissions at the city scale, according to the City of Zurich's phase-out regulation of fossil fuels. To comply with the national carbon policy, imported CO_2 emissions have to be minimized.

[13] The MILP model was built with software from Urban Sympheny AG (https://www.sympheny.com/#1), a spin-off of the Empa — Swiss Federal Laboratories for Materials Science and Technology and solved by the Gurobi Solver (https://www.gurobi.com).

[14] The green premium refers to the price difference between a service that emits carbon and its carbon-reduced or carbon-free alternative. In other words, it is the extra cost one would have to pay to get an energy system in a way that releases less or no greenhouse gases compared to the fossil-fueled system.

[15] The refinement leads to increasingly detailed models. For instance, a PV system modeled at the city scale represents a consolidated area with a single orientation, one slope, and a consistent conversion rate. When viewed at the district scale, the PV system is depicted as areas with varied orientations and slopes. However, at the building scale, a PV system is portrayed as a rooftop system that mirrors the actual orientation and slope of the roof. Additionally, panels and inverters are individually modeled based on their efficiency rates.

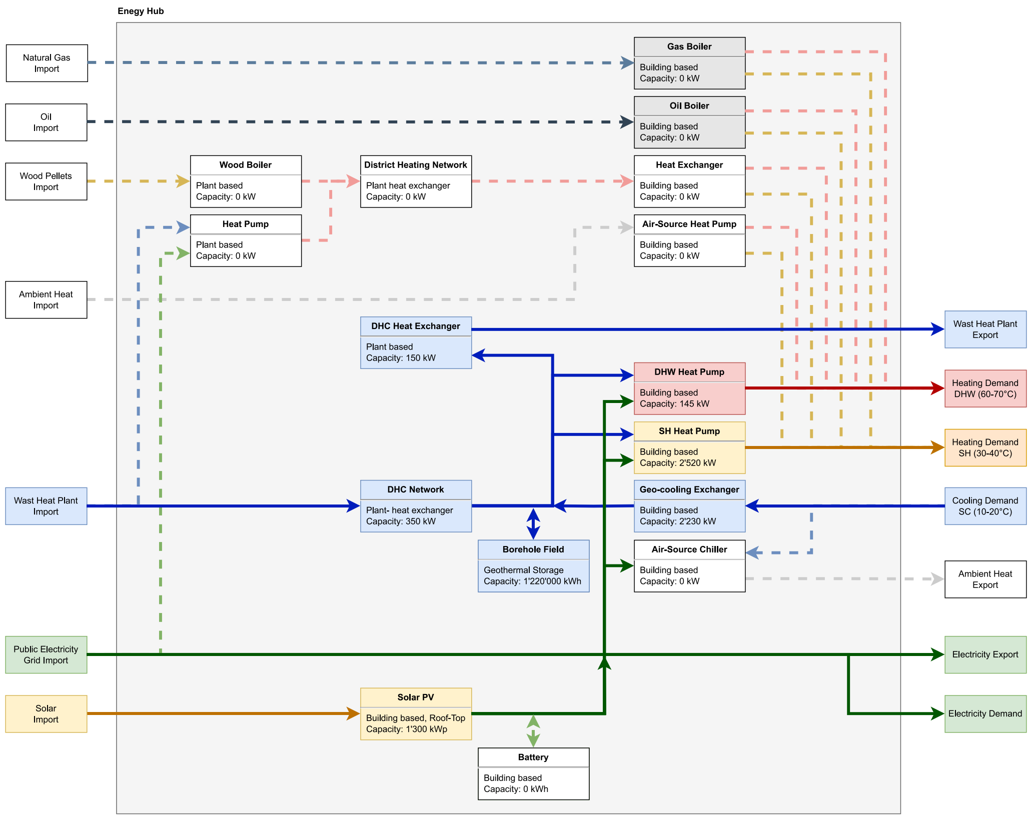


Fig. 5. Aggregated energy hub of the neighborhood scale in the City Energy System Platform. The technologies highlighted with different colors have been selected by the mapping process and represent the Pareto point (1) in Fig. 6. White and grey boxes indicate technologies that were not selected and hence will be removed from further consideration. The grey-shaded technologies represent the fossil-fuel-dominated heating systems common today (the red dot in Fig. 6).

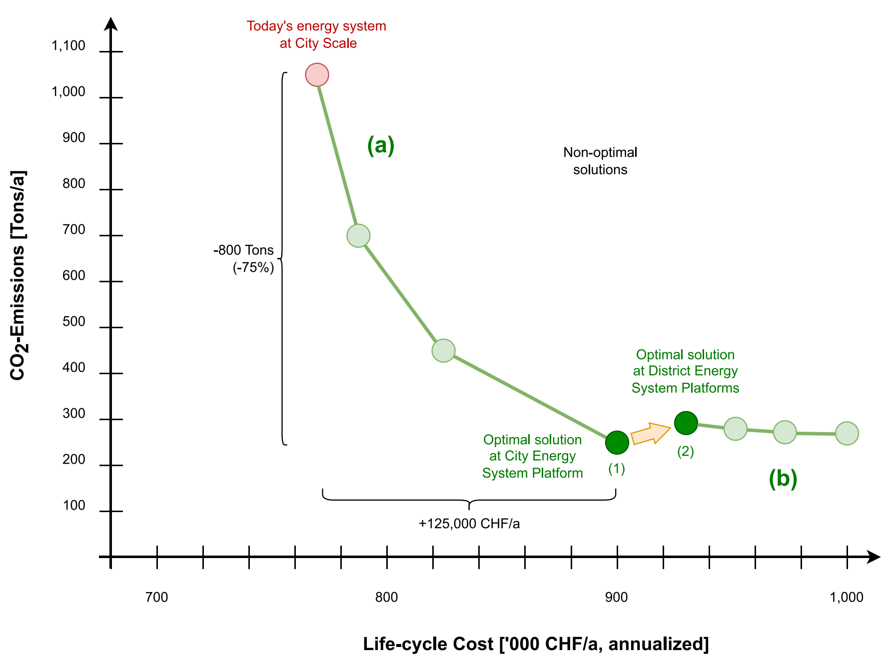


Fig. 6. Pareto fronts of the energy hub at the City (a) and District (b) Energy System Platforms. The Pareto point 'Today's energy system' (red dot) represents the technology installed in the neighborhood. The Pareto point (1) with the lowest CO_2 emissions (dark green) represents the City Energy System Platform instance. Light green colored Pareto points represent other optimal solutions that we did not select for further refinement. The deviation between the City (Pareto point (1)) and District (Pareto point (2)) Energy System Platform instance (yellow arrow) is due to the refinement process. The changes in CO_2 emissions and life-cycle costs (brackets) represent the green premium.

our case, it is the Pareto point with the lowest life cycle cost, as it will fulfill the requirement of the city's carbon emissions and affordability. There are Pareto-optimal solutions with fewer CO_2 emissions. However, the green premiums for these solutions are exceptionally high and do not comply with the affordability requirement.

In Fig. 6, Pareto points (1) and (2) depict identical energy system solutions. Their differing life-cycle costs and CO_2 emissions, indicated by the orange arrow, arise from refinements made between the city-scale and district-scale energy hubs.[16]

The selected solution is the one that combines a district heating and cooling system with the following conversion technologies: energy transfer stations totaling 2,520 kW space heating (SH) capacity, 2,230 kW cooling capacity, and, for domestic hot water (DHW), 145 kW heating capacity; heat pumps with a seasonal performance factor above 2.5 (DHW) and 5.3 (SH), which was an assumption of the MILP; roof-top photovoltaics (PV) totaling 1,300 kW_p; and waste heat supply from or rejection to the water treatment plant with about 350 kW load capacity. As far as storage technologies, the optimal design selects no batteries but rather a borehole field that uses the ground as seasonal heat storage with multiple probes, with a maximum capacity of 1,220 MWh. The buildings are connected to the public electrical grid, which results in 110 g of imported CO_2 emissions per supplied kWh. The tariff is 0.24 CHF/kWh for supply and 0.14 CHF/kWh for feed-in.

3.3. Building energy system platform

The mapped solution at the District scale provides the functional requirements for the Building Energy System Platform, where the previously analyzed energy hub is decomposed into four sub-hubs, representing the residential, office, and hospital buildings, as well as the water treatment plant and the borehole field used for seasonal storage. In each sub-hub, there are multiple options to configure the building's energy transfer station or the connection to the DHC system. To keep the illustrative example simple, we assumed a fixed DHC design according to [44]. Fig. 7 shows the four decomposed energy hubs at the building scale with the DHC and electricity networks.

The resulting Platform Instance at the Building Energy System Platform describes the DHC system as an ambient-temperature grid with decentralized heat pumps (the 5th generation of DHC systems [44]). The PV system assigned to each building maximizes the self-consumption of these prosumers, which is further supported by the use of the thermal storage capacity of the DHW tanks. The specification of each building's energy transfer station, the water treatment plant with its connected borehole field, and the DHC network can now be passed as functional requirements onto the subsequent Equipment Platform. In addition, the upper limits of CO_2 emissions (300 tons/a), caused by imported electricity, and life-cycle costs (1,000,000 CHF/a) set the boundary conditions for the following refinement step (see Fig. 6, Pareto point (2)).

3.4. Equipment platform

The architectural space of the Equipment Platform contains various detailed designs of components representing heat pumps, heat exchangers, valves, pipes, and controls. These components may also differ according to their manufacturers. Equation-based simulation (using Modelica, in this case) provides an effective and efficient approach to find (i.e., map) the optimal selection of components and the best system configuration according to the functional requirements. At this level, system simulations are conducted to solve the system of differential–algebraic equations of the thermal network, fluid network, and electrical system, coupled to feedback control. This gives detailed electricity use, heat requirements, and mass flow rates, and informs the selection of components and the design of the control logic. A typical mapping task is described in [44], explaining how increased pipe diameter and improved control logic of the main pump achieve maximum efficiency and thus minimize operation costs. The Platform Instance found with Modelica is shown in Fig. 8.

The refinement of the model in the Equipment Platform yields the following performance, where values in parentheses are the requirements from the Building Energy System Platform: boreholes with a depth of 300 m (300 m); energy transfer stations totaling 2,529 kW (2,520 kW) heating capacity, 2,129 kW (2,230 kW) cooling capacity, and 141 kW (145 kW) for DHW water; heat pumps with a seasonal performance factor of 5.9 SH (5.3) and 2.6 DHW (2.5); roof-top PV totaling 1,355 kW_p (1,300 kW_p); and waste heat supply from or rejection to the water treatment plant with maximal 322 kW (350 kW). The following storage technologies are chosen for the optimal design: no batteries and a borehole field of 1,442 MWh (1,220 MWh) capacity. The boundary conditions of CO_2 emissions and life-cycle costs establised by Building Energy System Platform need to be proven by post-calculations and, if necessary, improved by iteration.

Hypothetically, if the requirements cannot be met (as not illustrated in this example), the instance on the higher platform has to be renegotiated, or the system has to be redesigned. For example, choosing a heat pump with a higher seasonal performance factor from an innovative manufacturer on the Equipment Platform results in additional heat supply by the low-temperature DHC network, as presented in [48]. Hence, the DHC system must be redesigned, and the expected increase in efficiency must be proven on the higher-level Building Energy System Platform.

The specifications of all components, connections, controls, etc. that define the detailed design of the neighborhood's energy system can then be passed to the *Installation Platform*. The fully described energy system can be mapped to Building Information Model (BIM) elements, listed in the architectural space providing the necessary procurement and installation information. The control logic of the system can also be passed through a mapping process through the use of the Control Description Languages (CDL) [49,50], thereby ensuring a high quality of implementation, commissioning, and operation. In this way, PBD allows equipment suppliers to efficiently customize their components, ready to be installed by ESCOs and ready for operation.

4. Discussion

4.1. The need for a new system design workflow

In today's energy system design process, the system solution is usually determined by first choosing from two to four variants. Based on the selected variant, the required technologies, layouts, requirements, and functions are then separately specified in the basic design phase for each discipline — such as mechanical, electrical, control, or architectural design. In the detailed design phase, precise drawings, schematics, and descriptions are prepared for each discipline, which can then be tendered. During the construction and commissioning phase, cost and quality control are performed.

Moreover, today's waterfall model forces system design from *macro- to micro-granularity* information of each component. Interactions are rarely considered among subsystems or components that facilitate system-level optimization. It is rather a discipline-specific design process that fails to consider all of the systemic interactions between disciplines or even between domains. And, there are no principles to effectively abstract or refine a system during the design process. Requirements are typically expressed only vaguely, and there is little if any feedback from detailed design back to conceptual design. The waterfall model also does not support the reuse of architectural components. All steps have to be repeated by every project again and again.

[16] The increase in life-cycle costs for the refined analysis is specific to this example. In a different analysis, a more detailed approach might result in lower life-cycle costs.

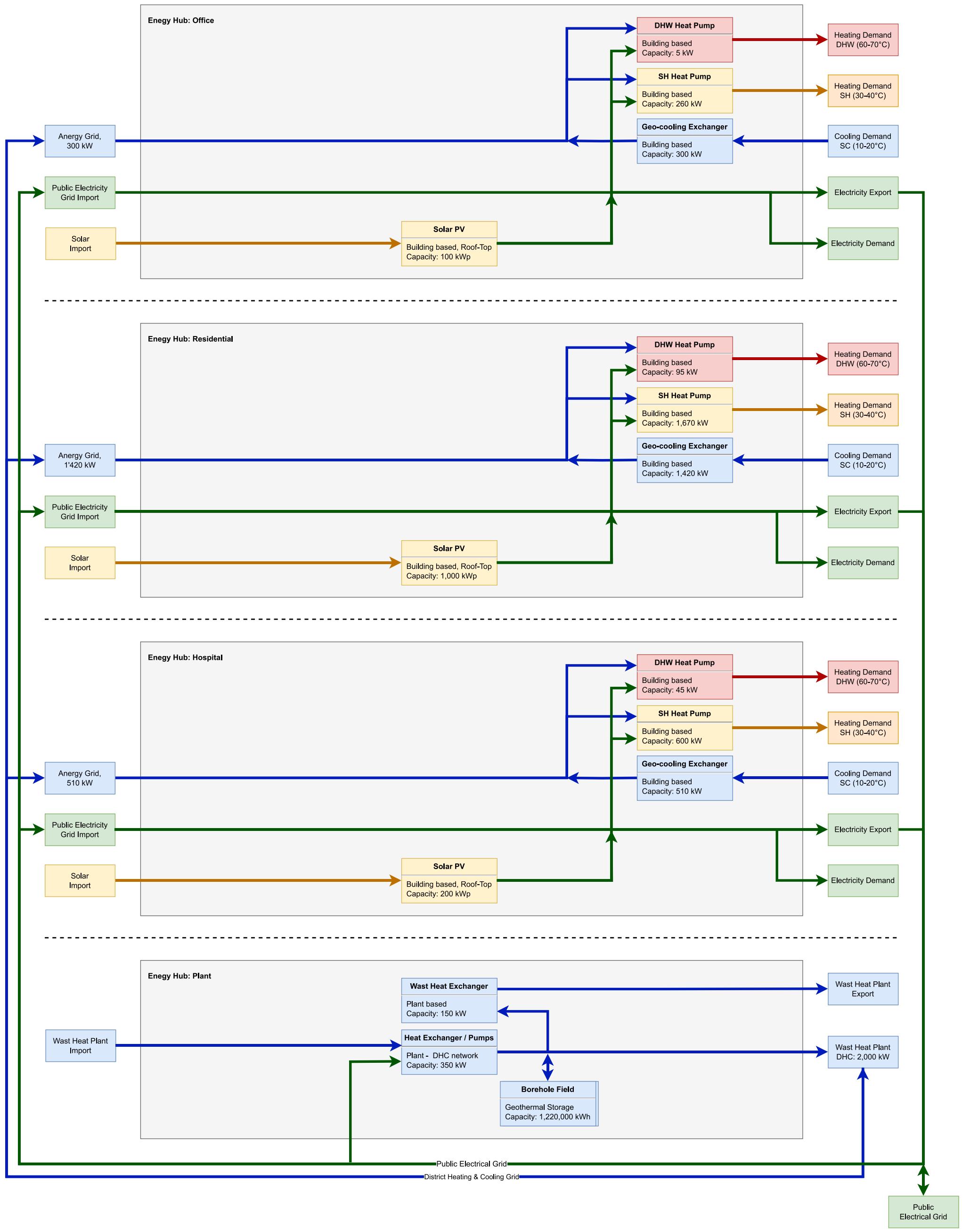


Fig. 7. Decomposed energy hubs for the three building clusters and the water treatment plant, showing the technologies that were mapped on the aggregated energy hub at the District Energy System Platform.

Principles for automation or scalability – essential if we are to address the challenges of the future energy system design – are missing.

Moving from a discipline-specific waterfall model to the PBD-Energy Hub framework presented here addresses the challenges of urgency and complexity as identified in Section 1.2:

- **PBD enables an automated system design and hence accelerates the defossilization of energy systems.** At each platform data, models and tools can be applied to support uniformed decision-making, i.e., a meet-in-the-middle process. This, in turn, allows platforms to be interconnected, establishing a holistic digitalized design workflow. In addition, PBD process encourages the continuous improvement of components and subsystems in the architectural components library. Feedback loops with standardized interfaces between the design steps are a crucial feature of PBD. A recognized failure observed, for example, in the construction or operation phase is reported back and leads to improvements at the particular level of abstraction. Such an implicit learning curve will also reduce the time-to-market.
- **PBD embraces the increased complexity of renewable-based, decentralized energy systems and provides a full exploration of the design space, and hence drives innovation from design to implementation.** The energy system design is no longer limited to a particular degree of complexity that can be overseen by one expert or inspired by well-known solutions. Multiple stakeholders contribute their knowledge at the appropriate level of abstraction. The unified PBD principles allow expert inputs to be

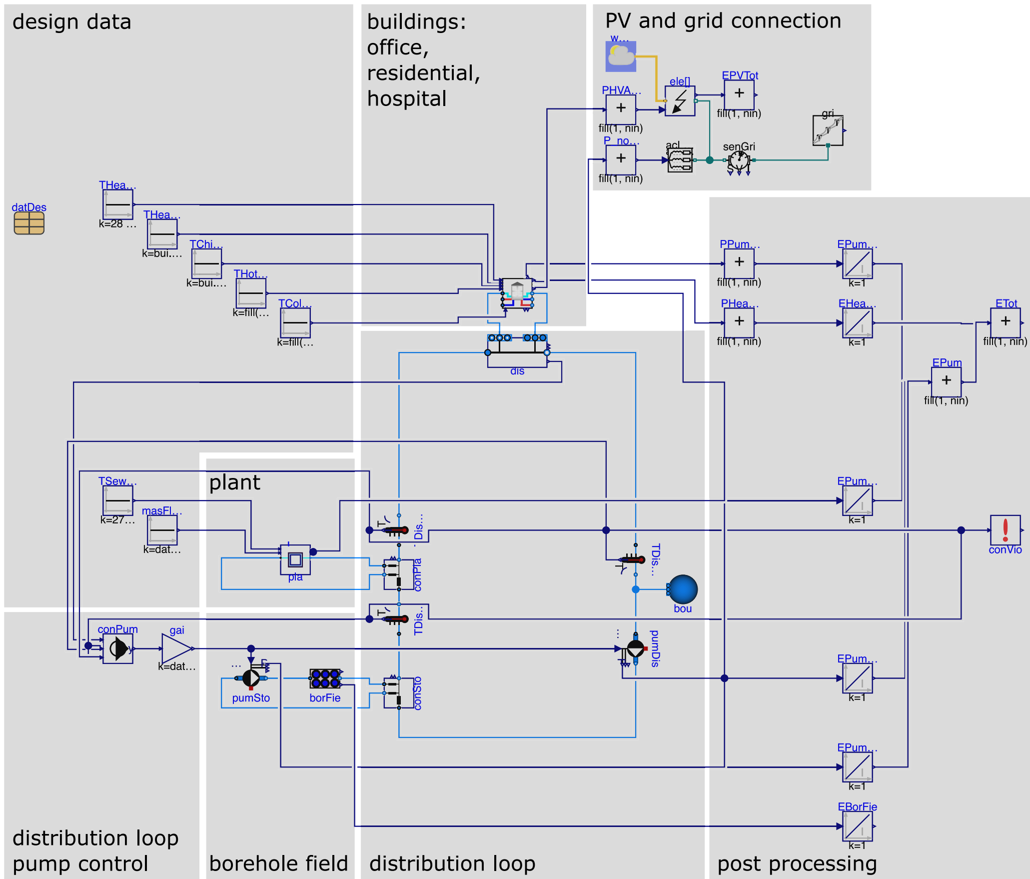


Fig. 8. Modelica model of the neighborhood's energy system on the Building Energy System Platform. Details of this model can be found in Appendix A.1.

abstracted or refined during the design process to ensure efficient collaboration.[17]

In general, The PBD-Energy Hub workflow enhances the industrialization of energy systems, leading to improved quality, reduced implementation time, and greater affordability. Establishing reusable independent components for architectural libraries, which can be customized to a project's functional requirements at every level of abstraction, is the key to scalable services and products.

4.2. Additional value creation by design principles

Along the value chain of energy system implementation, innovation can be facilitated at various stages to reduce costs and increase customer benefits. The following design principles used in PBD-Energy Hub leverage such value creation:

- **PBD facilitates rapid component innovation**. At every platform, virtual architectural components can be introduced, representing the necessary innovation to improve the energy system further [39]. Because of the strict separation of function and architecture, the innovation can be conducted independently of the project design or neighboring platforms. Conversely, new products can be integrated into the corresponding architectural library and are thus available for all upcoming projects — immediately.
- **PBD integrates BIM to automate the design process**. PBD and the energy hub concept can provide a framework for the design process that unleashes the full potential of BIM. Emerging BIMs establish a comprehensive data framework that allows the exchange of information among different stakeholders, domains, and disciplines within the building sector [51]. But even as BIM, and its fast-developing tools, transform the craft-dominated construction industry into a digitalized, automated industry, the design, construction, and operational processes are not evolving accordingly. Today, BIM is more of an add-on to existing processes than a fully integrated part, but PBD-Energy Hub is poised to change that.
- **It enables effective risk mitigation**. The energy hub concept considers the whole system in an interdisciplinary environment at every platform layer, capturing the full complexity of a system. Thus, the holistic nature of PBD and energy hub principles enable de-risked system implementation by considering relevant interactions and interference between domains, disciplines, and components as early as possible in the design process. A robust design must begin at the highest level of abstraction to ensure reliable operation at the end of the design process.
- **It allows contractual collaboration of multiple project partners**. Structuring the design tasks into connected platforms (Fig. 3) defines a clear design process in which the solution from the previous platform acts as a functional input into the next platform. The transition from a higher-level to a lower-level platform is defined by contracts [32,52], which allow specifying the desired function. Given the functional specification of a contract, the contracted platform can find the most appropriate architectural solution through its *meet-in-the-middle* process. Contracts between platforms might also reflect the industry's structure,

[17] For example, implementing new innovations in buildings' protection from solar gain or insulation levels to reduce first cost will flow back to reassessing its impact on already agreed-upon HVAC system choices and operational performance, which also impacts the district energy system.

as different companies can offer a service at different levels of abstraction. PBD with its contractual feature could strengthen the collaboration between industry partners.[18]

In general, interoperability within and between platforms is one of the crucial prerequisites for developing an effective and highly automatized PBD process that leads to the above value creation. On every platform, common semantics and formats to exchange information must be defined to map functional requirements and architectural components to platform instances. To pass an instance to the next platform, the information exchange among platforms also has to be harmonized. Applying a powerful data framework that defines formats, semantics, and ontologies is a major challenge for PBD. Developments toward the interoperability of models and data sets can be seen in [53,54].

5. Outlook

5.1. Potential impact on the value chain

The successful dissemination and scaling of PBD will rely heavily on the value the market players can generate. How will system designers adapt their business models based on these new insights? How will PBD affect the energy system value chains? What workforce skills or level of expertise is needed to operate PBD processes on particular platforms? Further investigations in the field of socio-economic science are needed.

PBD, as presented here is not limited to the energy sector; rather, it is a sub-process of an even more holistic infrastructure design. A first attempt to describe PBD for the building sector is presented in [55]. Other adjacent industries in the energy and building sector can be further integrated with the PBD concept, allowing exploration of an even broader solutions space to reach ambitious goals faster, at lower cost, and with higher resilience.

5.2. Levers for dissemination

Ongoing digitalization connects a wide range of elements in the urban area to the cloud. The resulting cyber–physical elements use these vast and growing data and allow customization and new applications by providing software-embedded systems to the building industry. A major advantage of this trend is the reuse of physical and digital components. Unlocking the strength of embedded systems in energy or other building system design, PBD is a process that has been proven in various industries and should be adapted and further developed to support the building and energy industry in its digital transformation.

One of the greatest challenges is to develop common semantic domains to exchange information between components, platforms, domains, and disciplines. System representations are being developed that allow a high level of automation in the deployment and configuration of software for building controls and analytics. They range from languages to express the semantic information of building energy systems [56] to languages for expressing the building control logic in a control/vendor-independent format [49]. These can serve as a basis to digitize control specification, delivery, and verification [50,54] and to deploy analytics in a building-agnostic way [57]. These languages are now being standardized through ASHRAE Standard 223P and 231P, and complement existing data representations such as Industry Foundation Classes (IFC, ISO 16739-1:2018). As our research proceeds, we will build PBD in combination with energy hub principles on these upcoming data representations.

[18] Moreover, the fee for the different design steps in the PBD process can be easily calculated according to the functional description of each platform (see, for example, SIA Norms Leistungs- und Honorarordnungen (LHO) from 101 to 118, http://shop.sia.ch/normenwerk/D/SubGroups)

5.3. Potential impact of PBD

We have shown how an industry in transition facing increasing complexities, innovation needs, and market dynamics could address its challenges by rethinking the design process. In particular, if the US and Europe replace all fossil fuel–supplied energy systems in buildings by 2050, a retrofit rate of roughly 3% will be required.[19] In other words, more than 40,000 building energy systems have to be transformed every working day, starting today. A new energy system design process is necessary to accelerate the massive deployment. Digital transformation, PBD, and energy hub principles, hand in hand, provide a solution.

In the Horizon2020 - ERA-Net Smart-Energy-System project, Geothermal-Based Optimized Energy Systems (GOES)[20] we are developing, testing, and validating a PBD-Energy hub framework in several different regions (US, Denmark, Germany, Austria, and Switzerland) for different projects (schools, homes, and offices) and for multiple scales (campuses, neighborhoods, buildings). The insights gained from these projects will support the development of PBD and its dissemination in the energy industry. Moreover, the application for energy system design will showcase the ability of PBD to transform system design in the built environment.

6. Conclusion

Inspired by the semiconductor and automotive industries, the energy sector facing similar transformation challenges. An industry undergoing transformation not only needs innovation for new products, services, and business models, but also needs new design processes to enhance its value chain. The combination of PBD with the energy hub framework can be used to fundamentally improve the process of planning future energy systems. PBD, with the integrated energy hub principles, manages and de-risks the complexity of integrated solutions, enables fast time-to-market, and leads to affordable solutions due to the inherent techno-economic analysis that underlies the decision-making.

The major advantage of PBD over the current design process is the rigorous distinction between functional requirements and architectural components, allowing the reuse of architectural components in other projects. Successfully applied components or subsystems, like heat pumps with seasonal borehole storage systems, can be incorporated into upcoming projects by simply parameterizing the subsystem.

Moreover, PBD separates the steps of the design process into different platforms, allowing independent design decisions to be made at the right level of abstraction while maintaining a holistic view and overarching requirements. This allows for effective design space exploration and handling of the complexity of energy systems in ways that are untenable in current approaches.

A current response to the increased complexity of innovation in the energy sector is *focalization* [58]. Firms, but also funding agencies, regulators and politicians, are focusing on the innovation of parts or components of an energy system. However, the vertical and horizontal disintegration of the industry's value chain calls for a reorganization of the design process: Discipline- and domain-specific consulting, engineering, architecture, and construction firms must collaborate with each other as part of an integrated design process. Co-design and integrated concurrent engineering are established methods that tackle certain challenges of integrated system design, and thus, could be significant contributors to PBD development. PBD, with its contractual

[19] In the US, 65 to 70% of all commercial and residential buildings (approximately 135 million) are supplied by fossil fuels (US Energy Information Administration, https://www.eia.gov/consumption/), and 75% of all buildings in the EU (approximately 230 million) are supplied by fossil fuels (Buildings Performance Institute Europe, https://www.bpie.eu/).

[20] (http://www.geothermica.eu/projects/joint-call-2021/goes/ and https://www.goes-project.info/)

approach that bridges various disciplines and domains, offers a comprehensive process for industry and stakeholder collaboration. As a result, spatial planning, architecture, and civil engineering can be seamlessly integrated into a holistic design workflow using the PBD concept.

PBD and energy hub design principles can transform the current prevailing waterfall model into a holistic, comprehensive, and collaborative method for energy system design that enables design automation. In view of the pace and challenge of defossilization, such a process transformation is critical to achieve governments' ambitious goals for net-zero carbon emissions by 2050.

CRediT authorship contribution statement

Matthias Sulzer: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Michael Wetter:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Robin Mutschler:** Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing. **Alberto Sangiovanni-Vincentelli:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Matthias Sulzer reports financial support was provided by E O Lawrence Berkeley National Laboratory and Empa Materials Science and Technology. Michael Wetter reports financial support was provided by E O Lawrence Berkeley National Laboratory. Robin Mutschler reports financial support was provided by Empa Materials Science and Technology.

Data availability

The models are available at https://www.github.com/lbl-srg/modelica-sympheny-district-pub(commit c8015c8).

Appendix

A.1. Data availability

The MILP optimizations were conducted with Sympheny https://www.sympheny.com. The Modelica simulations were conducted with Dymola 2023x on Linux Ubuntu 20.04. The models are available at https://www.github.com/lbl-srg/modelica-sympheny-district-pub (commit c8015c8).

A.2. The general concept of PBD

The PBD concept is well documented, both the method itself and in various case studies. The basic principles of PBD [39–41] are to:

1. Start at the highest level of abstraction.
2. Hide unnecessary details of implementation.
3. Summarize the important parameters of the implementation in an abstract model.
4. Limit the design space exploration to a set of available components.
5. Carry out the design as a sequence of "refinement" steps that go from the initial specification toward the final implementation using platforms at various levels of abstraction.

An essential characteristic of the PBD paradigm is the orthogonalization of concerns, which allows the separation of the design space aspects: The functionality (what the system is supposed to do) is separated from the architecture (how the system does what it is supposed to do). This allows a more effective and efficient exploration of the architectural space that supports the required functionality. Hence, mapping functions to architectural solutions will become an essential step in the process from conception to implementation [39].

The following description of PBD concept, i.e. platform, mapping, design and modeling principles, is extracted from [31,39,41].

A.2.1. Platform principles

A platform is a library of components that can be assembled to generate a system design at a particular level of abstraction. Such a design library contains not only mathematical models, representing physical and digital components that perform in a quantifiable manner, but also communication components that are used to interconnect components to form a system.

It is important to keep physical, digital, and communication components well separated so that different methods for representing and refining systems can be applied. Design by aggregation of components (abstraction) requires great care in defining the communication mechanisms as they may facilitate or hinder design reuse. Unexpected behavior of the system configuration is often due to negligence in defining the interfaces and the communication among the components.

In general, each library component is characterized in terms of performance parameters and the functionality it can support. Not all components in the library are pre-existing components. Some library components can be "virtual components", which are placeholders for yet-to-be-developed components. Virtual components provide flexibility of customization or express the need to innovate new components as part of the design process.

A.2.2. Mapping principles

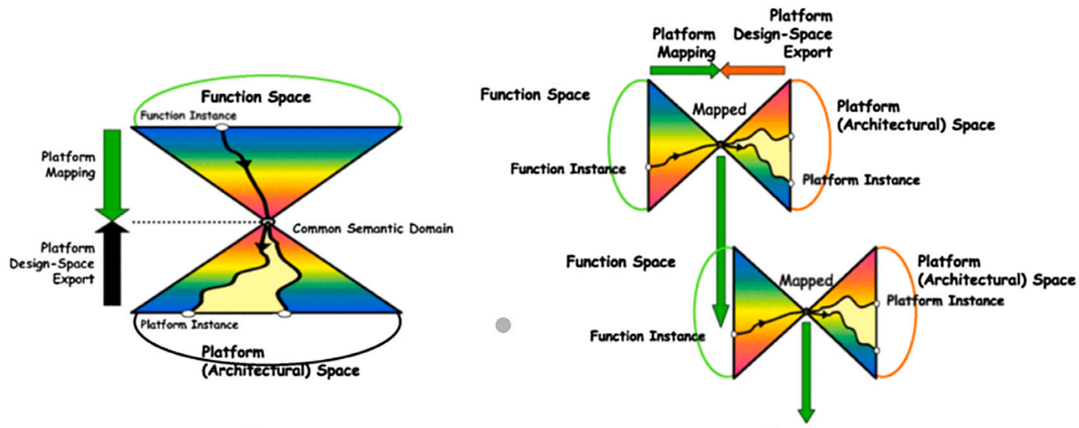
Platforms represent a particular family of solutions that share common architectural features, i.e., components of the platform. Hence, components of a platform can be reused to form various system solutions. Since the notion of a platform is associated with a set of potential solutions to a design problem, the process of mapping a functionality (what the system is supposed to do) with the platform elements that will be used to build a platform instance or an "architecture" (how the system does what it is supposed to do) is crucial. This mapping process is the essential step for refinement and provides a mechanism to proceed toward implementation in a structured way.

The PBD design process is neither a fully top-down nor a fully bottom-up approach in the traditional sense; rather, it is a *meet-in-the-middle* process (see Fig. A.9(a)) as it can be seen as a combination of both:

- A top-down approach maps an instance of the required functionality of the design into an instance of the platform (architecture) and propagates constraints.
- A bottom-up approach builds a platform by choosing components of the library to form a system that characterizes it and an associated performance abstraction, e.g., a seasonal performance factor of a heat pump.

The *middle* is where functionality meets the architectural configuration, which represents the solution or instance of the platform. Given the original semantic difference between the two, the meeting place must be described with a common semantic domain so that the mapping of functionality to components of the platform, to yield an implementation, can be formalized and automated.

A prerequisite for the adoption of the PBD and of the meet-in-the-middle approach is the definition of the right models and abstractions for the description of the functional specification at the top and for



(a) (b)

Fig. A.9. The PBD concept: (a) a generic platform, (b) the PBD process.

the architecture solutions at the bottom of the hourglass of Fig. A.9(a). The platform interface must be isolated from lower-level details but, at the same time, must provide enough information to allow design space exploration with a fairly accurate prediction of the properties of the implementation.

A.2.3. Design principles

To better represent the refinement process and to stress that platforms may pre-exist the functionality of the system to be designed, we turn the triangles on their sides and represent the *middle* as the mapped functionality. Then, the refinement process takes place on the mapped functionality that becomes the *function* at the lower level of the refinement. Another platform is then considered *underneath* with the mapped instance, and the process is iterated until all the architectural components are implemented in their final form. This process is applied at all levels of abstraction, demonstrating what we call the *fractal nature of design* — the design problem repeats itself at every level of the hierarchy. The resulting Fig. A.9(b) exemplifies this aspect of the design methodology.

The result of the mapping process from functionality to architecture can be interpreted as functionality at a lower level of abstraction where a new set of components, interconnections, and composition rules are identified. To progress in the design, the new functionality has to be mapped to the new set of architectural components. If the previous step used an architectural component that was fully instantiated,[21] then that part of the design is considered concluded and the mapping process involves only the parts that have not been fully specified yet.

Establishing the number, location, and components of intermediate platforms is the essence of the PBD process. In fact, designs with different requirements and specifications may use different intermediate platforms, hence different layers of regularity and design-space constraints. The trade-offs involved in selecting the number and characteristics of platforms relate to the size of the design space to be explored and the accuracy of the estimation of the characteristics of the solution adopted.

The choice of the intermediate platforms may also be dictated by business concerns and by the common agreement of the supply chain in specific industrial segments. However, degrees of freedom should be exploited inside any of the companies in the supply chain and in the definition of the components even across company boundaries.

A.3. Glossary

See Table A.1.

[21] The component reaches its *atomic* stage, and its decomposition stops.

Table A.1
Glossary.

Cyber–physical elements	Interacting digital, analog, physical, and human components engineered to provide functionality through integrated physics and logic[a]
Design space	The space of all possible solutions to a problem
Specification	Description of what a system must do; it could include multiple layers of abstraction
Behavior	Representation of what a system does at each level of abstraction
Property	A subset of behaviors that characterizes a system
Component	Function, model, or communication element representing physical or computational items
Atomic component	The element on the lowest level of abstraction, where the decomposition stops
Element	A component
Functional component	Description of the behavior of a component[b]
Architectural component	Description of the physical, digital, or virtual component to be used to build a system[c]
Communication component	Connection among architectural elements used to form a system, such as a bus or network. Communication components also include connections among functional elements that are used to decompose a high-level task, e.g., protocols, adaptors, and channels
Virtual component	Placeholder in a system for a yet-to-be-developed architectural component
Library	A set of components that contains available functional, architectural, communication, and virtual components that can be reused
Platform	The set of architectures that can be assembled using the library of components to generate a design
Platform layer	A layer that represents an intermediate platform at a particular level of abstraction, one that structures and constrains the design space
Platform stack	A set of platforms that contains multiple intermediate platform layers representing the whole design
Platform instance	A specified architecture that defines the system (how the system does what is supposed to do)
Model	Software representing components in a virtual environment using equations

(continued on next page)

Table A.1 (*continued*).

Digital twin	A virtual representation of an object or system that spans its lifecycle, which is updated using real-time data and uses simulation, system identification, and reasoning to assist decision-making[d]
Application	An operational program that performs a function by executing software
Domain	Independent activity or system, especially one which has its own control, influence, or rights
Semantic domain	A mathematical characterization of a language. Defining a common semantic domain between functional and architectural components allows the optimized mapping of function to architecture
Discipline	A subdivision of knowledge or expertise applied to the performance of professional tasks in a particular field
Energy hub	A set of consumers, producers, storage, transmission, conversion, control, and communication components, assembled to form an energy system
Reusability	A feature of PBD that allows the "recycling" of a component or a part of a component
Partitioning	An artifact that allows part of a set of components to be reused
Pareto-optimal	The optimal configuration where it is impossible to reconfigure them without worsening one of the considered requirements

[a] According to M. Bartock, J. Cichonski, M. Souppaya, M. Smith, G. Witte, and K. Scarfone, 'Guide for cybersecurity event recovery', National Institute of Standards and Technology, Gaithersburg, MD, NIST SP 800-184, Dec. 2016. doi: 10.6028/NIST.SP.800-184.

[b] What the system is supposed to do?

[c] Software provides the operational support to perform a function on a chosen architecture (hardware).

[d] IBM. What is a digital twin? 2021. https://www.ibm.com/topics/what-is-a-digital-twin (accessed Mai 29, 2023).

References

[1] Geidl M, Koeppel G, Favre-Perrod P, Klockl B, Andersson G, Frohlich K. Energy hubs for the future. IEEE Power Energy Mag 2007;5(1):24–30. http://dx.doi.org/10.1109/MPAE.2007.264850, URL http://ieeexplore.ieee.org/document/4042137/.

[2] Walker S, Labeodan T, Maassen W, Zeiler W. A review study of the current research on energy hub for energy positive neighborhoods. Energy Procedia 2017;122:727–32. http://dx.doi.org/10.1016/j.egypro.2017.07.387, URL https://linkinghub.elsevier.com/retrieve/pii/S1876610217329910.

[3] Geidl M, Andersson G. Optimal coupling of energy infrastructures. In: 2007 IEEE Lausanne power tech. Lausanne, Switzerland: IEEE; 2007, p. 1398–403. http://dx.doi.org/10.1109/PCT.2007.4538520, URL http://ieeexplore.ieee.org/document/4538520/.

[4] Amir Mansouri S, Javadi MS, Ahmarinejad A, Nematbakhsh E, Zare A, Catalão JP. A coordinated energy management framework for industrial, residential and commercial energy hubs considering demand response programs. Sustain Energy Technol Assess 2021;47:101376. http://dx.doi.org/10.1016/j.seta.2021.101376, URL https://linkinghub.elsevier.com/retrieve/pii/S2213138821003866.

[5] Eladl AA, El-Afifi MI, El-Saadawi MM, Sedhom BE. A review on energy hubs: Models, methods, classification, applications, and future trends. Alex Eng J 2023;68:315–42. http://dx.doi.org/10.1016/j.aej.2023.01.021, URL https://linkinghub.elsevier.com/retrieve/pii/S1110016823000364.

[6] United Nations. Paris agreement to the united nations framework convention on climate change. 2015.

[7] European Commission. European green deal. 2019, URL https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en.

[8] European Commission, COM 37. Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Commission Work Programme 2020. 2020, URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0037.

[9] European Commission C. Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. 2020, URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0662.

[10] US Department of Energy, DOE/EE-2635. Industrial decarbonization roadmap. 2022, URL https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf.

[11] Swiss Federal Office of Energy. Energy Strategy 2050. 2021, URL https://www.bfe.admin.ch/bfe/de/home/politik/energiestrategie-2050.html,

[12] Koirala B, Hers S, Morales-España G, Özdemir O, Sijm J, Weeda M. Integrated electricity, hydrogen and methane system modelling framework: Application to the Dutch infrastructure outlook 2050. Appl Energy 2021;289:116713. http://dx.doi.org/10.1016/j.apenergy.2021.116713, URL https://linkinghub.elsevier.com/retrieve/pii/S0306261921002336.

[13] United Nations. Global sustainable development report 2019: The future is now - science for achieving sustainable development. Global sustainable development report, UN; 2019, http://dx.doi.org/10.18356/5d04ad97-en, URL https://www.un-ilibrary.org/content/books/9789210045919.

[14] IEA. World energy outlook 2022. 2022, p. 121–2, URL https://www.iea.org/reports/world-energy-outlook-2022.

[15] Muench S, Thuss S, Guenther E. What hampers energy system transformations? The case of smart grids. Energy Policy 2014;73:80–92. http://dx.doi.org/10.1016/j.enpol.2014.05.051, URL https://linkinghub.elsevier.com/retrieve/pii/S0301421514003668.

[16] Alanne K, Saari A. Distributed energy generation and sustainable development. Renew Sustain Energy Rev 2006;10(6):539–58. http://dx.doi.org/10.1016/j.rser.2004.11.004, URL https://linkinghub.elsevier.com/retrieve/pii/S1364032105000043.

[17] Mancarella P. MES (multi-energy systems): An overview of concepts and evaluation models. Energy 2014;65:1–17. http://dx.doi.org/10.1016/j.energy.2013.10.041, URL https://linkinghub.elsevier.com/retrieve/pii/S0360544213008931.

[18] Mavromatidis G, Orehounig K, Carmeliet J. A review of uncertainty characterisation approaches for the optimal design of distributed energy systems. Renew Sustain Energy Rev 2018;88:258–77. http://dx.doi.org/10.1016/j.rser.2018.02.021, URL https://linkinghub.elsevier.com/retrieve/pii/S1364032118300510.

[19] Sulzer M, Bollinger A, Oerhounig K. Energy hubs – Ein Beitrag Zur energiewende. Aqua Gas 2019;14–21.

[20] Marti T, Sulzer M, Rüdisüli M. Energieversorgung der Schweiz bis 2050. Zusammenfassung von Ergebnissen und Grundlagen. 2022, URL https://www.dora.lib4ri.ch/empa/islandora/object/empa%3A32267. https://www.energiezukunft2050.ch.

[21] Quiquerez L, Lachal B, Monnard M, Faessler J. The role of district heating in achieving sustainable cities: Comparative analysis of different heat scenarios for Geneva. Energy Procedia 2017;116:78–90. http://dx.doi.org/10.1016/j.egypro.2017.05.057, URL https://linkinghub.elsevier.com/retrieve/pii/S1876610217322646.

[22] Koirala BP, van Oost E, van der Windt H. Community energy storage: A responsible innovation towards a sustainable energy system? Appl Energy 2018;231:570–85. http://dx.doi.org/10.1016/j.apenergy.2018.09.163, URL https://linkinghub.elsevier.com/retrieve/pii/S0306261918314740.

[23] Koirala BP, Koliou E, Friege J, Hakvoort RA, Herder PM. Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems. Renew Sustain Energy Rev 2016;56:722–44. http://dx.doi.org/10.1016/j.rser.2015.11.080, URL https://linkinghub.elsevier.com/retrieve/pii/S1364032115013477.

[24] Hoven Jvd, Vermaas PE, Poel Ivd. Handbook of ethics, values, and technological design: Sources, theory, values and application domains. Dordrecht: SpringerReference; 2015.

[25] Künneke R. Critical infrastructures: Aligning institutions and technology. 2013, URL http://resolver.tudelft.nl/uuid:20a4706e-d2dc-483e-a0d0-279875d98681.

[26] Council WE. World energy trilemma index. 2022, URL https://www.worldenergy.org/transition-toolkit/world-energy-trilemma-index.

[27] Wikipedia. Waterfall Model. 2023, URL https://en.wikipedia.org/wiki/Waterfall_model.

[28] ASHRAE greenguide: Design, construction, and operation of sustainable buildings, 5th ed.. Atlanta, GA: ASHRAE; 2018, OCLC 1023844014.

[29] Jia R, Jin B, Jin M, Zhou Y, Konstantakopoulos IC, Zou H, et al. Design automation for smart building systems. Proc IEEE 2018;106(9):1680–99. http://dx.doi.org/10.1109/JPROC.2018.2856932, URL https://ieeexplore.ieee.org/document/8466990/.

[30] Sangiovanni-Vincentelli A, Martin G. Platform-based design and software design methodology for embedded systems. IEEE Des Test Comput 2001;18(6):23–33. http://dx.doi.org/10.1109/54.970421, URL http://ieeexplore.ieee.org/document/970421/.

[31] Di Natale M, Sangiovanni-Vincentelli A. Moving from federated to integrated architectures in automotive: The role of standards, methods and tools. Proc IEEE 2010;98(4):603–20. http://dx.doi.org/10.1109/JPROC.2009.2039550, URL http://ieeexplore.ieee.org/document/5440059/.

[32] Sangiovanni-Vincentelli A, Damm W, Passerone R. Taming Dr. Frankenstein: Contract-based design for cyber-physical systems*. Eur J Control 2012;18(3):217–38. http://dx.doi.org/10.3166/ejc.18.217-238, URL https://linkinghub.elsevier.com/retrieve/pii/S0947358012709433.

[33] Pileggi P, Verriet J, Broekhuijsen J, van Leeuwen C, Wijbrandi W, Konsman M. A digital twin for cyber-physical energy systems. In: 2019 7th workshop on modeling and simulation of cyber-physical energy systems. Montreal, QC, Canada: IEEE; 2019, p. 1–6. http://dx.doi.org/10.1109/MSCPES.2019.8738792, URL https://ieeexplore.ieee.org/document/8738792/.

[34] Wright L, Davidson S. How to tell the difference between a model and a digital twin. Adv Model Simul Eng Sci 2020;7(1):13. http://dx.doi.org/10.1186/s40323-020-00147-4, URL https://amses-journal.springeropen.com/articles/10.1186/s40323-020-00147-4.

[35] Onile AE, Machlev R, Petlenkov E, Levron Y, Belikov J. Uses of the digital twins concept for energy services, intelligent recommendation systems, and demand side management: A review. Energy Rep 2021;7:997–1015. http://dx.doi.org/10.1016/j.egyr.2021.01.090, URL https://linkinghub.elsevier.com/retrieve/pii/S2352484721000913.

[36] Jones D, Snider C, Nassehi A, Yon J, Hicks B. Characterising the digital twin: A systematic literature review. CIRP J Manuf Sci Technol 2020;29:36–52. http://dx.doi.org/10.1016/j.cirpj.2020.02.002, URL https://linkinghub.elsevier.com/retrieve/pii/S1755581720300110.

[37] Boje C, Guerriero A, Kubicki S, Rezgui Y. Towards a semantic construction digital twin: Directions for future research. Autom Constr 2020;114:103179. http://dx.doi.org/10.1016/j.autcon.2020.103179, URL https://linkinghub.elsevier.com/retrieve/pii/S0926580519314785.

[38] Ferrari A, Sangiovanni-Vincentelli A. System design: Traditional concepts and new paradigms. In: Proceedings 1999 IEEE international conference on computer design: VLSI in computers and processors (Cat. No.99CB37040). Austin, TX, USA: IEEE Comput. Soc; 1999, p. 2–12. http://dx.doi.org/10.1109/ICCD.1999.808256, URL http://ieeexplore.ieee.org/document/808256/.

[39] Sangiovanni-Vincentelli A. Quo Vadis, SLD? Reasoning about the trends and challenges of system level design. Proc IEEE 2007;95(3):467–506. http://dx.doi.org/10.1109/JPROC.2006.890107, URL http://ieeexplore.ieee.org/document/4167779/.

[40] Balarin F, Chiodo M, Giusto P, Hsieh H, Jurecska A, Lavagno L, et al. Hardware-software co-design of embedded systems. Boston, MA: Springer US; 1997, http://dx.doi.org/10.1007/978-1-4615-6127-9, URL http://link.springer.com/10.1007/978-1-4615-6127-9.

[41] Keutzer K, Newton A, Rabaey J, Sangiovanni-Vincentelli A. System-level design: Orthogonalization of concerns and platform-based design. IEEE Trans Comput-Aided Des Integr Circuits Syst 2000;19(12):1523–43. http://dx.doi.org/10.1109/43.898830, URL http://ieeexplore.ieee.org/document/898830/.

[42] Charani Shandiz S, Rismanchi B, Foliente G. Energy master planning for net-zero emission communities: State of the art and research challenges. Renew Sustain Energy Rev 2021;137:110600. http://dx.doi.org/10.1016/j.rser.2020.110600, URL https://linkinghub.elsevier.com/retrieve/pii/S1364032120308844.

[43] Eggimann S, Vulic N, Rüdisüli M, Mutschler R, Orehounig K, Sulzer M. Spatiotemporal upscaling errors of building stock clustering for energy demand simulation. Energy Build 2022;111844. http://dx.doi.org/10.1016/J.ENBUILD.2022.111844, URL https://linkinghub.elsevier.com/retrieve/pii/S0378778822000159.

[44] Sommer T, Sulzer M, Wetter M, Sotnikov A, Mennel S, Stettler C. The reservoir network: A new network topology for district heating and cooling. Energy 2020;199:117418. http://dx.doi.org/10.1016/j.energy.2020.117418, URL https://linkinghub.elsevier.com/retrieve/pii/S0360544220305259.

[45] Andrew Bollinger L, Marquant J, Sulzer M. Optimization-based planning of local energy systems -bridging the research-practice gap. IOP Conf Ser: Earth Environ Sci 2019;323(1):012077. http://dx.doi.org/10.1088/1755-1315/323/1/012077, URL https://iopscience.iop.org/article/10.1088/1755-1315/323/1/012077.

[46] Evins R, Orehounig K, Dorer V, Carmeliet J. New formulations of the 'energy hub' model to address operational constraints. Energy 2014;73:387–98. http://dx.doi.org/10.1016/j.energy.2014.06.029, URL https://linkinghub.elsevier.com/retrieve/pii/S0360544214007270.

[47] Gates B. How to avoid a climate disaster: The solutions we have and the breakthroughs we need. 1st ed.. New York: Alfred A. Knopf; 2021, OCLC: on1122802121.

[48] Maccarini A, Sotnikov A, Sommer T, Wetter M, Sulzer M, Afshari A. Influence of building heat distribution temperatures on the energy performance and sizing of 5th generation district heating and cooling networks. Energy 2023;275:127457. http://dx.doi.org/10.1016/j.energy.2023.127457, URL https://linkinghub.elsevier.com/retrieve/pii/S0360544223008514.

[49] Wetter M, Grahovac M, Hu J. Control description language. 2019, p. 17–26. http://dx.doi.org/10.3384/ecp1815417, URL https://ep.liu.se/en/conference-article.aspx?series=ecp&issue=154&Article_No=2.

[50] Wetter M, Ehrlich P, Gautier A, Grahovac M, Haves P, Hu J, et al. OpenBuildingControl: Digitizing the control delivery from building energy modeling to specification, implementation and formal verification. Energy 2022;238:121501. http://dx.doi.org/10.1016/j.energy.2021.121501, URL https://linkinghub.elsevier.com/retrieve/pii/S0360544221017497.

[51] Volk R, Stengel J, Schultmann F. Building information modeling (BIM) for existing buildings — Literature review and future needs. Autom Constr 2014;38:109–27. http://dx.doi.org/10.1016/j.autcon.2013.10.023, URL https://linkinghub.elsevier.com/retrieve/pii/S092658051300191X.

[52] Nuzzo P, Sangiovanni-Vincentelli AL, Bresolin D, Geretti L, Villa T. A platform-based design methodology with contracts and related tools for the design of cyber-Physical systems. Proc IEEE 2015;103(11):2104–32. http://dx.doi.org/10.1109/JPROC.2015.2453253, URL http://ieeexplore.ieee.org/document/7268792/.

[53] Pritoni M, Paine D, Fierro G, Mosiman C, Poplawski M, Saha A, et al. Metadata schemas and ontologies for building energy applications: A critical review and use case analysis. Energies 2021;14(7):2024. http://dx.doi.org/10.3390/en14072024, URL https://www.mdpi.com/1996-1073/14/7/2024.

[54] Roth A, Wetter M, Benne K, Blum D, Chen Y, Fierro G, et al. Towards digital and performance-based supervisory HVAC control delivery. 2022, http://dx.doi.org/10.20357/B70G62, Publisher: Lawrence Berkeley National Laboratory, URL https://escholarship.org/uc/item/59z6d46m.

[55] Lin Y-W, Tang TLE, Schiavon S, Spanos CJ. Toward platform-based building design. 2023, URL http://arxiv.org/abs/2305.10949. arXiv:2305.10949 [cs].

[56] Balaji B, Bhattacharya A, Fierro G, Gao J, Gluck J, Hong D, et al. Brick : Metadata schema for portable smart building applications. Appl Energy 2018;226:1273–92. http://dx.doi.org/10.1016/j.apenergy.2018.02.091, URL https://linkinghub.elsevier.com/retrieve/pii/S0306261918302162.

[57] Fierro G, Pritoni M, AbdelBaky M, Raftery P, Peffer T, Thomson G, et al. Mortar: An open testbed for portable building analytics. In: Proceedings of the 5th conference on systems for built environments. Shenzen China: ACM; 2018, p. 172–81. http://dx.doi.org/10.1145/3276774.3276796, URL https://dl.acm.org/doi/10.1145/3276774.3276796.

[58] Barjak F, Foray D, Wörter M. Mastering multiple complexities – A rising challenge for Swiss innovation models. Report ISSN: 2296-3871, Switzerland: The State Secretariat for Education, Research and Innovation, SERI; 2023, p. 59.