Digitalization & Facility Management: Energy Flexibility of Existing Buildings

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Abstract

Future energy systems will require buildings to be able to manage their energy demand and generation in dynamic ways. The technical realization of such energy flexibility in buildings in response to local climate conditions, occupant needs and grid requirements is currently quantified in research and development projects, many of which take place in newly erected buildings as flagships for the related digitalization and seamless automation of technical building services. However, building stock and facility management portfolios tend to consist of existing buildings with differing, highly diverse performance qualities that may pose a problem for generic solutions. The objective of this paper is to highlight potential options, and to sketch an engineering perspective of making existing buildings energy-flexible. For this purpose, on-going work in various control research projects is selected to present issues in (1) the development of a suitable controller, (2) home and building automation design, and (3) building commissioning and diagnostics for future building controls. Non-technical requirements for quality of performance in these cases are summarized. In conclusion, and based on the reviewed projects, a potential strategy for building management is the avoidance of risks and costs associated with the introduction of energy flexibility by using published standards and open protocols for automation, and by documenting their as-operated status in a digital format in all buildings.

Keywords: Energy flexibility, Smart building, Home automation, Building automation

1. Introduction

The integration of renewable energies into existing electrical distribution grids is causing instability in the grid, which cannot be controlled by the existing infrastructure at all times and in all cases. Flexible management of supply and demand of energy at the side of the grid participants aims to optimize grid operation by controlling grid utilization rates within preferred ranges. For decisions on specific strategies for energy flexible operation of individual buildings or building types, large scale models are required, which are based on actual grid data and actual urban environments as built and as operated. For the purpose of this paper, observations and insights from selected projects are used to assess the efforts for making existing buildings energy flexible, and to conclude on how facility resp. building management could provide assistance.

The structure of the paper is as follows: Section 2 is on the potential buildings can offer for grid stabilization: While solutions are in high demand to reach climate goals internationally, they have to be accurately modeled and validated, and project examples are cited that could successfully arrive at strategic constellations of building elements for use in national building stocks. Section 3 is on engineering efforts for energy flexible buildings that are being followed up. Here, current research work related to development of a control mechanism and parameters, their integration and their maintenance is exemplified. These activities take part in different control worlds, namely grid-level control, home and building automation, and building controls, but they share non-technical requirements for quality of performance, discussed in Section 4. Based on these priorities and validated through the projects, recommendations for assistance by building management are formulated.

The so developed recommendations are based on valid and generalizable qualitative indicators, however, their predictive strength, i.e. the potential impact on time and costs of engineering by following up on the recommendations will be addressed in future work.

2. The potential of energy flexibility in existing buildings

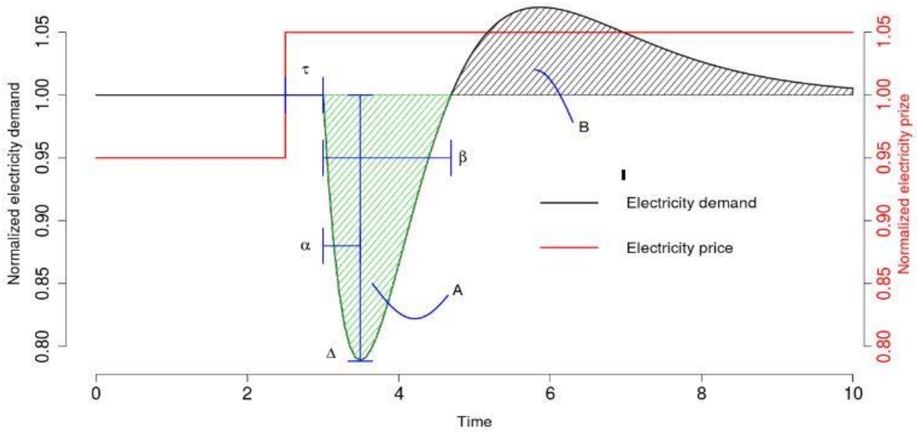
Decisions on load management strategies cannot be based on single buildings, but they require clusters of buildings, such as city quarters, which are typically mixed building stocks. The primary question is whether buildings can contribute the load potential grid operators are looking for. Second, what is a good strategy to reliably deliver this performance? The answers vary with country, grids and building stocks present. There is large interest on the EU level to foster development in buildings that enable grid optimization. In Section 2, information about progress on a methodology for characterization of energy-flexibility is presented. Modeling examples address the potential of heat pumps in smart grids, and of building typologies on a national level suitable for optimizing grid operation.

2.1. Energy flexibility of buildings

In most developed countries, the energy use in buildings accounts for 30-40 % of the total energy consumption (WBCSD 2009), and it is used for space heating, heating of domestic hot water, cooling, ventilation, pumps, control and lighting of rooms, as well as for appliances used by occupants. A large part of the energy demand of buildings may be shifted in time (Le Dréau and Heiselberg 2016), (Reynders et al. 2013), (Patteeuw et al. 2015), and may thus significantly contribute to increase the flexibility of the demand in the energy systems. In particular, the thermal part of the energy demand, e.g. space heating/cooling, ventilation (ventilation is both a thermal and electrical load), domestic hot water, as well as hot water for washing machines, dishwashers, and heat for tumble dryers can be shifted. Energy flexibility of a building can, therefore, be defined as the ability of a building to manage its demand, but also its generation (e.g. from photovoltaics) according to the local climate conditions, user needs and grid requirements. Energy flexibility of buildings will thus allow for demand side management/load control and thereby demand response based on the requirements of the surrounding grids.

That energy flexibility of buildings is an important asset for the future energy systems has also been recognized by the EU commission, as it is proposed to include a smart readiness indicator (SRI) in the upcoming revision of the EPBD (EU 2016a). The purpose of the SRI in EPBD is to *"inform the consumers about the ability of buildings to operate more efficiently, monitor and control energy use and interact with the users and the grid"* (EU 2016b). Furthermore, it is stated that *"A smartness indicator will reflect the ... (iii) readiness of the building to participate in demand response, charge electric vehicles and host energy storage systems"* (EU 2016b). However, as the EU Commission demands a very cheap procedure for the determination of the SRI of a building, it can be feared that the SRI will be of little use. In order for a SRI to be useful for both the building side and the energy network side, there is a need for an approach that takes into account the dynamic behaviour of buildings, rather than a static counting and rating of control devices. It is further important to minimize the CO_2 emission in the overall energy networks, rather than to optimize the energy efficiency of single energy components in a building. Such approach is being developed by IEA EBC Annex 67 Energy flexible buildings (annex67.org), and is described in Junker et al. (2018).

The methodology is a physical data and simulation based approach for quantification of services in use. The general objective is to standardize the external penalty signal to enable comparability of energy flexibility among different buildings (Fig. 1).



Where: τ is the time from the signal is submitted to an action starts
α is the period from start of the response to the max response
Δ is the max response
β is the duration of the response
A is the shifted amount of energy
B is the rebound effect for returning the situation back to "reference"

Fig. 1: Potential of energy flexibility as a function of a building's or system's response to a step change in the external penalty signal (Jensen et al. 2017).

2.2. Demand response of homes and the potential of thermal mass in Belgium

At the building level, many sources exist to offer flexibility to district energy systems. Labeeuw et al. (2014) identified an active demand reduction (ADR) potential of 4 % of the total residential electricity demand using white-good appliances (i.e. dishwashers, tumble-dryers, washing machines). These results are obtained through a large-scale demonstration project monitoring electricity consumption data in 1693 Belgian households between 2006 and 2009, as well as from 500 field surveys. They conclude that, although these white goods can have a significant impact on the electricity consumption with a share equaling the primary reserve capacity, the active demand response of wet appliances does not meet the requirements for response time needed for these power services.

With the electronification of thermal systems in the residential sector, e.g. through the introduction of heat pumps, these systems may as well provide a significant contribution for the demand flexibility needed to optimize electricity networks. At the same time, the interest in 4th generation district heating systems is increasing in heating dominated climates, since these systems promise to provide a sustainable and flexible way of incorporating low-carbon and renewable heat sources such as waste heat from industrial processes, solar, and geothermal energy (Lund et al. 2014).

Patteeuw et al. (2015) evaluated the impact of large scale heat pump integration in the Belgian residential sector analyzing scenarios with and without active demand response (ADR). In the scenario without demand response, heat pumps are controlled to minimize the energy consumption on an individual building level resulting in significant peak demands on cold winter mornings, when all heat pumps operate at the same time. Also, such a control is agnostic for the availability of RES (renewable energy sources) products, hence, it does not contribute to increase RES uptake in the market. Active demand response using the thermal mass of the dwellings as well as the domestic hot water storage tank to decouple the electricity demand from the thermal demand allows to significantly reduce the extra peak capacity required when installing the evaluated 250.000 heat pumps (Fig. 2, below). In the case of buildings equipped with floor heating, almost the entire need for additional peak power plants was avoided, in the case of radiator heated buildings (which represent faster thermal dynamics) on average 30% reduction in peak power was found. At the same time ADR resulted in on average 15 % CO_2 reduction due to increased uptake of renewables.

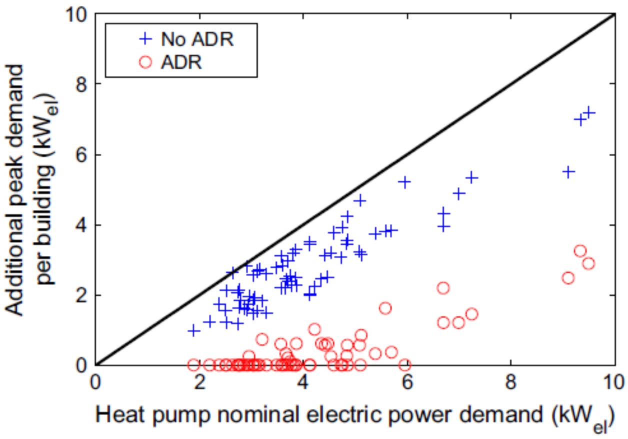


Fig. 2: Performance of ADR in peak-shaving. The electric power that each building is contributing to the demand at peak time is shown with respect to the nominal electric power demand of the heat pump (Patteeuw et al. 2015).

2.3. Simulation of the Austrian building stock

In Austria, heating load management potentials for four representative Austrian building typologies (A, B, C, D – see Fig. 3, below) have been studied using the TABULA dataset (2016). Based on the different insulation levels due to the year of construction, there is a countable influence on the shiftable domestic heating loads when using heavy-weight constructions, optimizing passive solar gains and activating additional thermal storage combined.

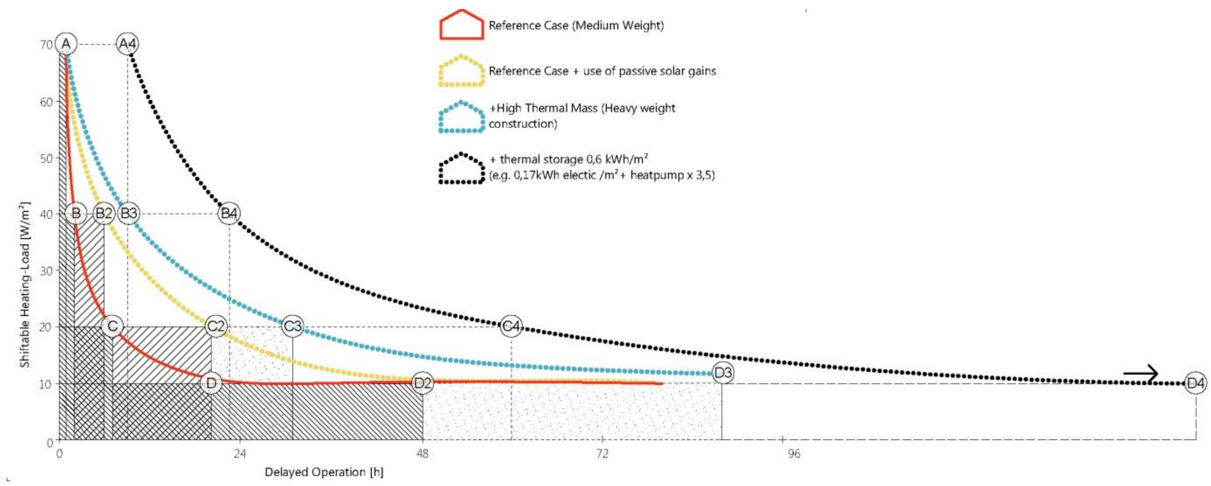


Fig. 3: Load duration curves of four different Austrian typology-buildings showing the potential of shiftable domestic heating load over time by delayed operation (Weiss et al. 2018)

Load shift periods were evaluated for a cold week of January with the following assumptions:

- an indoor operating temperature range of 19..22°C
- the heating system with simple radiators as heat dissipation system is switched off at 22°C and cools down until the temperature reaches the lower limit of its setpoint

The cooling curve thus describes the ratio between the heating load in each type of building of a cold week in January per square meter of treated floor area [W/m²] and time [h] during which the operative temperature is ranging within the predefined 19°C..22°C.

The **blue curve** indicates the potential of these buildings with an increase of the specifically effective heat storage capacity of the primary construction per square meter treated floor area, from approx. 60 Wh/m²K for the reference buildings (medium brick construction) to 110 Wh/m²K (heavy reinforced concrete construction). The **black curve** shows the increase in flexibility when approximately 0.6 kWh/m²a of thermal energy can be stored.

Basically, the curve can be used for any day / season of the year (assuming the heating power at the time is known) to roughly describe the ratio of heating load to time within the set comfort limit, including thermal mass and additional storage. The curves can be used to estimate the impact of different building technologies on the shiftable heating load of different building types (see Weiss et al. 2018).

3. Technologies for realization of energy flexibility in research studies

In this section, research efforts in engineering of energy flexible buildings are introduced. They represent activities for development of a suitable controller, the integration of controller functionality in buildings, and commissioning and maintenance of the integrated controls.

3.1. A dynamic CO_2-based control of a swimming pool heating system

This example is a part of the Danish CITIES Project (www.smart-cities-centre.org) and the EU H2020 SmartNet project (www.smartnet-project.org). The purpose of this project is to demonstrate the flexibility of summer houses with a swimming pool. Swimming pools are flexible in the sense that due to their thermal inertia, it takes a rather long time for them to heat and cool. In CITIES, the objective has been to minimize emissions while still respecting comfort requirements. In the SmartNet project, the same setup is used for price-based control, and the prices are selected such that the total system can provide various grid services as described in (Madsen et al. 2015).

In the setup, the controller for heating the pools can be formulated in a way which minimizes the total CO_2 emission. Alternatively, the same setup can be used to do price-based control. This also gives the opportunity to solve some ancillary service problems in e.g. low voltage grids (DSO grids as described in (De Zotti et al. 2018)).

In the future electric energy system, one of the main challenges will be to keep the voltage level in weak DSO (low voltage grids) areas close to the reference. This challenge is even more pronounced in areas with a lot of summerhouses, since the use of the houses is less predictable, and because the electricity grid here is often rather weak. However, summerhouses with swimming pools constitute large energy storages, which can be used for solving some of the issues related to the electricity grid.

In the following, we will focus on a setup of model predictive control of the heating of the swimming pools, which aims at minimizing the CO_2 emission. The houses considered here are using a heat pump.

The share of renewable-based electricity in Denmark varies significantly and rapidly, as seen in Fig. 4 for a week around December 1st, 2016.

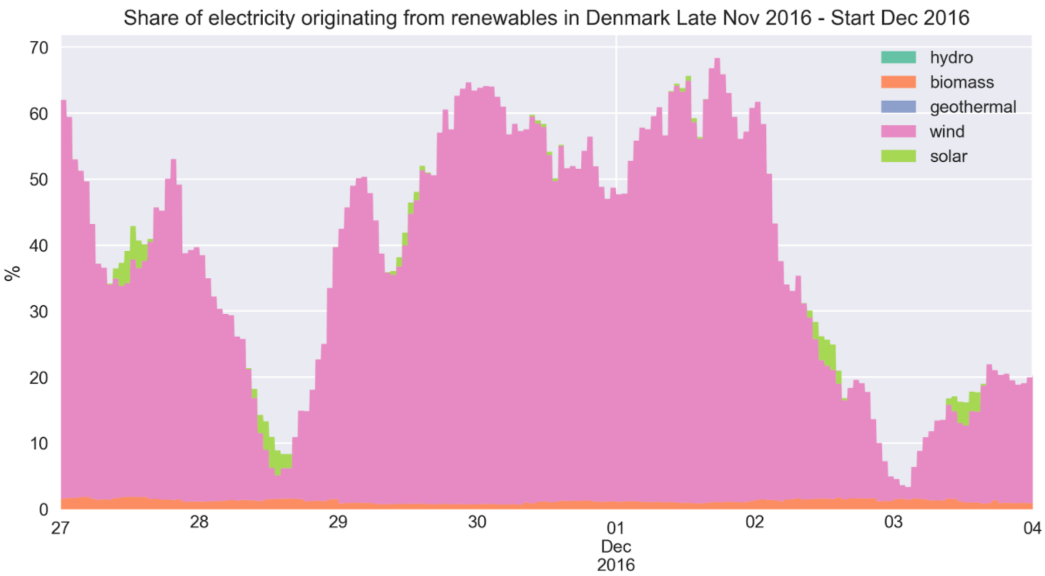


Fig. 4: Share of electricity originating from renewables during a one-week period around December 1st, 2016. Data is computed based on historical data from http://www.electricitymap.org. This translates into a very volatile carbon intensity (i.e. the overall emissions required to produce 1 kWh of electricity).

It therefore makes sense to optimize with respect to total emissions, by incentivizing flexible devices to consume when the carbon intensity is low.

In the setup, the actuator is a controllable thermostat listening to a signal from a local controller (called SN-10). The SN-10 unit controls the actuator in order to keep the controlled pool temperature (outgoing water temperature) close to a setpoint. That setpoint can be lowered or increased temporarily in order to save energy or to preheat, depending on the expected CO_2 intensity of electricity consumed.

- **Forecasting and Control**

In the initial settings, the models used are of the ARX type (see Madsen 2008), whereas regime switching models will be considered at a later stage. The need for the regime based models arrives due to the fact that the dynamics of the house and the pool will depend on the use of the summerhouse and maybe also on the number of people and/or the activity levels. The algorithms for forecasting and control are implemented at the DMS and cloud computing facility operated by ENFOR. Forecasts of the expected CO_2 emission related to the power mix are provided by the the company Tomorrow.

- **Data Management System and Cloud Computing**

The Data Management System is hosted by ENFOR (www.enfor.dk), so all the data is hosted here, and the interaction with the system takes place via this setup. The Cloud Computing facility at ENFOR also hosts the controllers.

The ENFOR services, illustrated in the figure below, consist roughly of the following parts:

1. Web-service: Supports requests for data upload from FlexGrid, ie. the house data, and requests the latest house state from Novasol.
2. Tomorrow client: Fetches CO_2 forecasts made by Tomorrow
3. FlexGrid client: Uploads water temperature setpoints and pump status to FlexGrid
4. Novasol client: Fetches availability schedules from Novasol web-service
5. Weather forecasts: Provides local weather forecasts
6. Algorithms: Forecasts and control based on house data and the weather forecasts
7. Data storage and management: Includes a graphical user interface

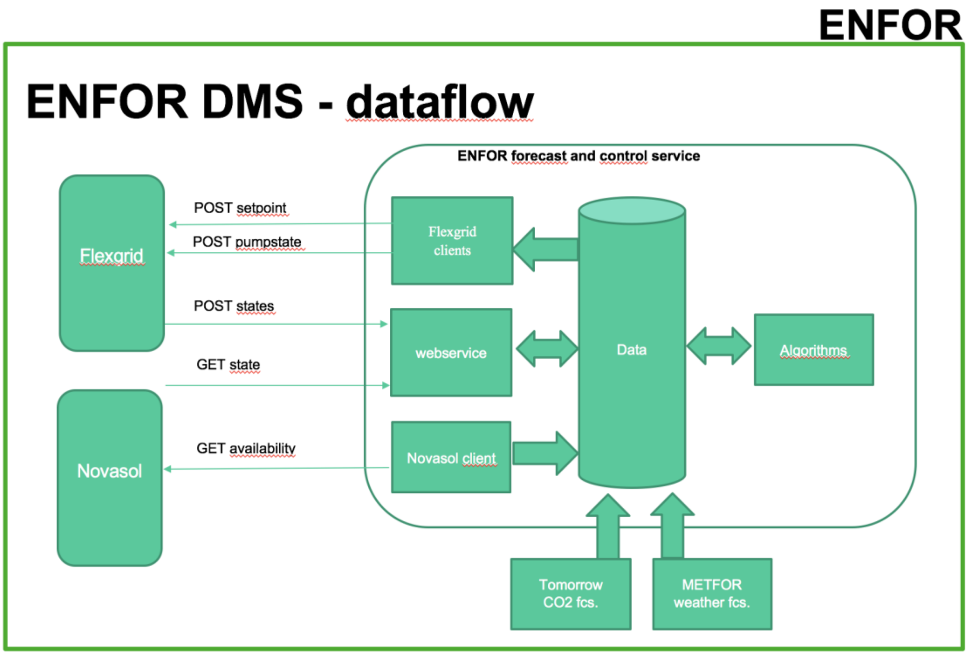


Fig. 5: Data management architecture.

The users of the cloud based controllers can switch between being 1) Energy Efficient (the energy consumption is minimized), 2) Cost Efficient (the total cost is minimized), and 3) Emission Efficient (the total CO_2 emission is minimize) - see Junker et al. (2018).

- **Some results**

In the following, two houses are considered. The first house D7811 is using CO_2-based control, and consequently the total CO_2 emission of the related power production is minimized. Fig. 6 shows a screen plot from the controller of the ENFOR smart house portal. The blue lines are the lower and upper limits of the pool temperature. The red vertical line show the actual time, and we can see that the controller decides to overheat the pool within the next hours, since the CO_2 emission is expected to be low for these hours, while we expect a much higher CO_2 emission for the following hours.

Fig. 6: A house (D7811) using CO_2-based control. This minimizes the total CO_2 emission related to heating up the swimming pool.

The second house (P32788) is using price-based control, and here, Fig. 7 shows the measurement of the ENFOR smart house portal. We have shown a period with negative power prices as indicated around the period marked with a green dashed ellipsoid. It is clearly seen that, as a result of the negative power prices, the controller is heating up the pool to the maximum water temperature. Due to the large inertia of the pool, the preheating under the period with negative prices implies that the summer house does not need to use power for heating for a rather long time.

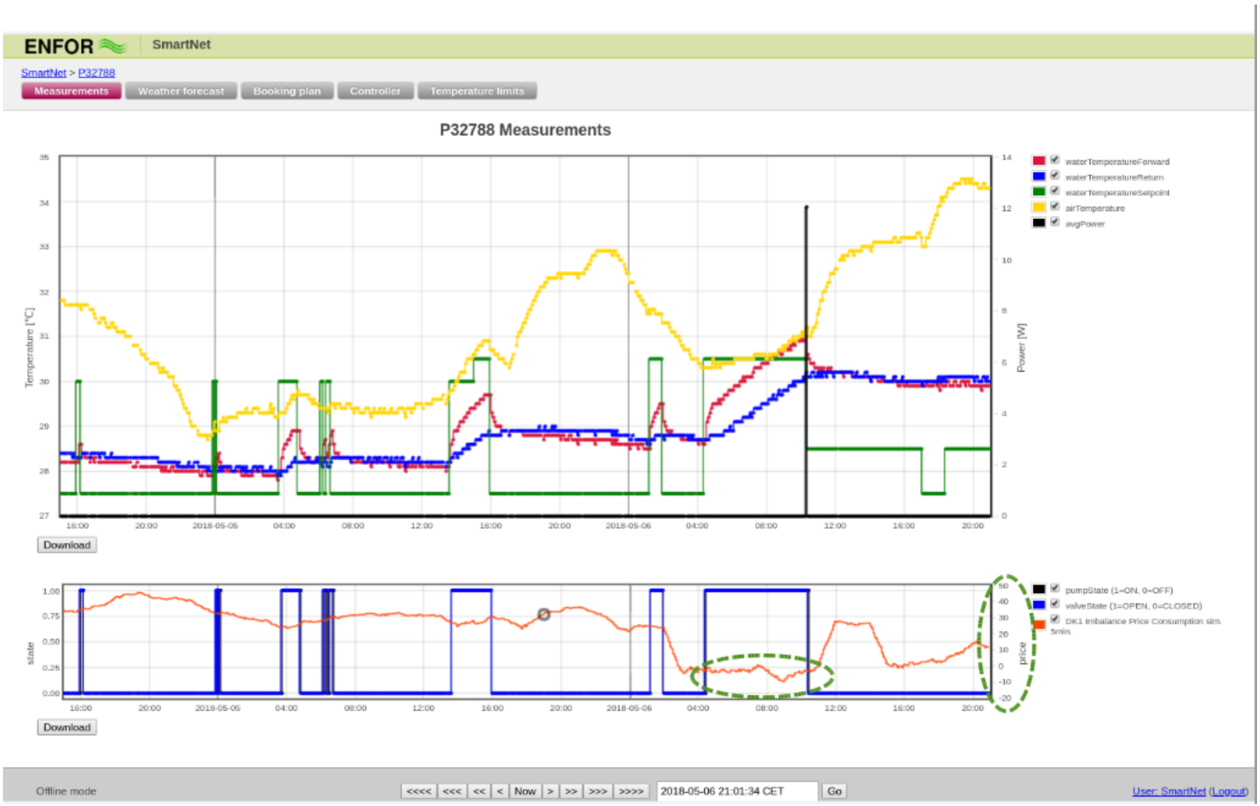


Fig. 7: A house (D32788) using price-based control. This minimizes the total costs related to heating up the swimming pool. This screen plot contains a period with negative power prices (green ellipsoid).

3.2. Complexity and integration of information models for building-to-grid services

In building-to-grid processes, buildings act as end nodes in the smart grid. Since their physical integration requires investment costs and novel technology concepts, it is important to quantify *how* buildings can play a critical role in the grid nationally.

A potential improvement for demand side management through building-based load forecasts was investigated in a study on building information systems, where building energy performance was characterized with a novel method involving a complex thermo-dynamic building model (Metzger et al.). A controlled flexibility study with a cluster of 500 apartments in Vienna, Austria, showed that, with the improved model compared to a linear model used for smart grid simulations at the time, 33% more events suitable for load shifting could have been offered to the grid within the specified indoor temperature control limits (Table 1, below).

Tab. 1: Distribution of load shifting decisions. The linear model compared to the improved model overpredicted comfort violations (329 of 1000 analyzed events) (Metzger et al.)

Decision	Outcome	Occurrence
Shed load	Comfort Violated	329
	Comfort ok	61
Do not shed load	Comfort would have been ok	137
	Either not possible or comfort would have been violated	473

While a complex energy model brings about higher quality for planning of forecasts, it also potentially means an increase in monitoring effort on site. Hence, in theory, an efficient implementation that builds on existing infrastructure and information in already installed devices and systems, such as smart meters and building and home automation systems would be ideal. This ideal is challenged in the real world by the uncertainty of installed infrastructure in individual buildings and homes of modeled clusters and requirements for unobtrusiveness of the in-situ measurements in operating buildings. In a case study in a new campus building of the University of Innsbruck, these challenges acted as barriers for optimized field measurements, despite the fact that most of the required sensors were already installed and integrated in regular building operations (Pfluger et al. 2017, pp. 45-51).

Following up on these results, the Automation Systems Group of TU Wien, Austria, is currently developing a virtual solution with laboratory simulated performance and optimization of control networks, which holds the capability for comparison of different scenarios. Fig. 8 shows an overview of the system architecture for validation of the optimized information model from the study on building-based load forecasts, which assumed utility-driven demand response (Metzger et al.). The building measurement layout for the forecasts in this study could be minimized to one indoor temperature sensor per apartment and computation of apartment heat load, the latter of which could be acquired from data of the apartment's smart meter, for instance. Additional quality of service information of the tested layout has to be accounted for in any optimization step, pictured here as a stand-alone implementation on a local field computer. The method for optimization requires a generic model for evaluation of different infrastructure typologies with sufficient modularity for further optimization steps.

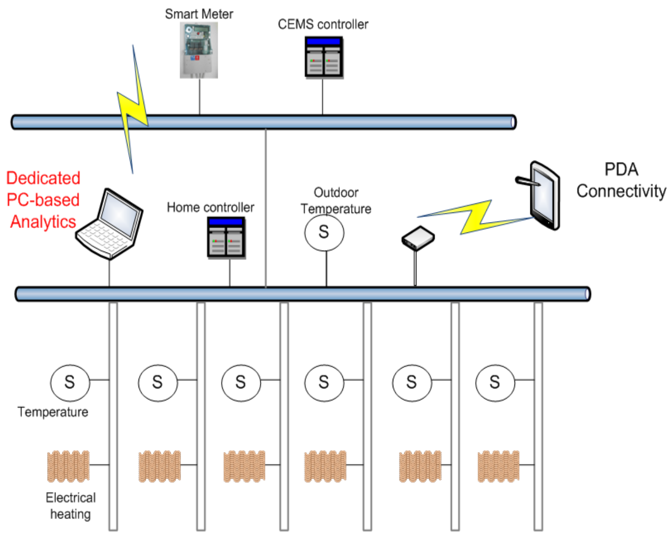


Fig. 8: Overview of systems architecture for field validation as part of an integrated home automation system. Each apartment building has 6 separate apartments.

Furthermore, a concept for evaluation of information privacy and security of the planned field layouts is part of the proposed solution, partially based on experiences from the development of a cybersecurity module for the user role in indirect control of energy flexibility:

To address the desire and to support the end-users' claim of more self-control and energy efficiency, the Automation Systems Group is part of the project "Adaptable Platform for Active Services Exchange" (AnyPLACE, www.anyplace2020.org/). The project addresses a modular, secure and flexible energy management system deployed in local field computer ("smart hub"). The developed platform comprises a bidirectional service exchange gateway with management and control functionalities enabling the interaction between end-users, market representatives, electricity networks operators and ICT providers (Fig. 9). Among other features, it allows end-users to manage their energy expenditure and take advantage of dynamic price tariffs to minimize their energy costs.

To protect users from malicious attacks and data abuse, security and privacy aspects needed to be included in the design and implementation of the platform from the very beginning. To this end, an analysis of EU-wide regulations regarding security and privacy was conducted. From there, requirements for the development of the platform were derived. As core component of the AnyPLACE solution, a cybersecurity module was developed responsible for storing the key material used to protect the platform. With this module, data and communication can be signed/verified and de/encrypted. This way, the core principles of information security (confidentiality, integrity and authenticity) can be provided. To secure the platform and its application, the secure development lifecycle (SDL) was followed comprising of five consecutive phases: (1) definition of security requirements, (2) design & implementation, (3) security testing & verification, (4) release, and (5) security response. In addition to laboratory testing and validation of the developed platform, a field trial was started at the end of 2017 in the area of Dörentrup, Kreis Lippe (Germany).

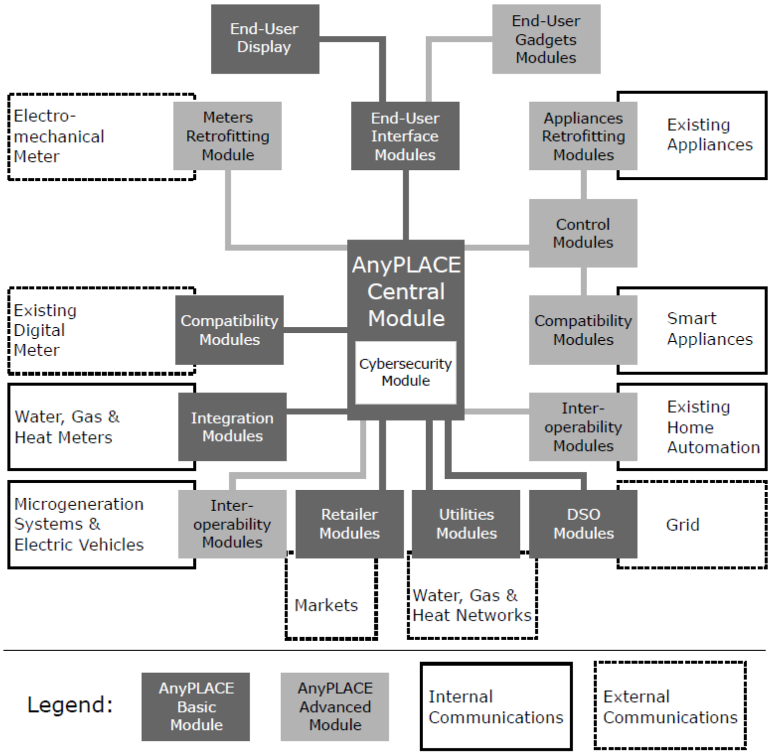


Fig. 9: AnyPLACE architecture (Henneke et al. 2016)

3.3. An automated and continuous performance testing framework for office buildings

As part of the international research project COORDICY (COORDICY 2018), an online building energy performance monitoring and evaluation tool (ObepME) was developed aiming to better monitor, characterize and evaluate building energy performance, and ensure a proper operation (Jradi et al. 2018). The tool includes a set of building performance tests serving as a basis for fault detection and diagnostics throughout the building operational and management phases and forming a backbone for an automatic and continuous building commissioning and evaluation. In addition to performance testing and monitoring, the tool is intended to be used for investigation and evaluation of various energy systems operational patterns and modes, including control strategies and DR events.

An overview of the processes of the tool is shown in Fig. 10. An overall building 3D architectural model is developed. Then, building specifications and characteristics along with the 3D model are used to develop a holistic dynamic energy model in EnergyPlus, capable of simulating building performance. Data collected from the building including weather conditions, occupancy profiles, systems operational parameters and set points, and energy consumption reported by different meters are used to calibrate the developed holistic energy model. Using the calibrated model, simulations are carried out automatically and continuously on a daily basis to predict the building performance. Simulations are compared to actual data collected from building meters. When a performance gap is detected, an overall fault detection and diagnosis process is implemented to identify any underperformance issues and system faults.

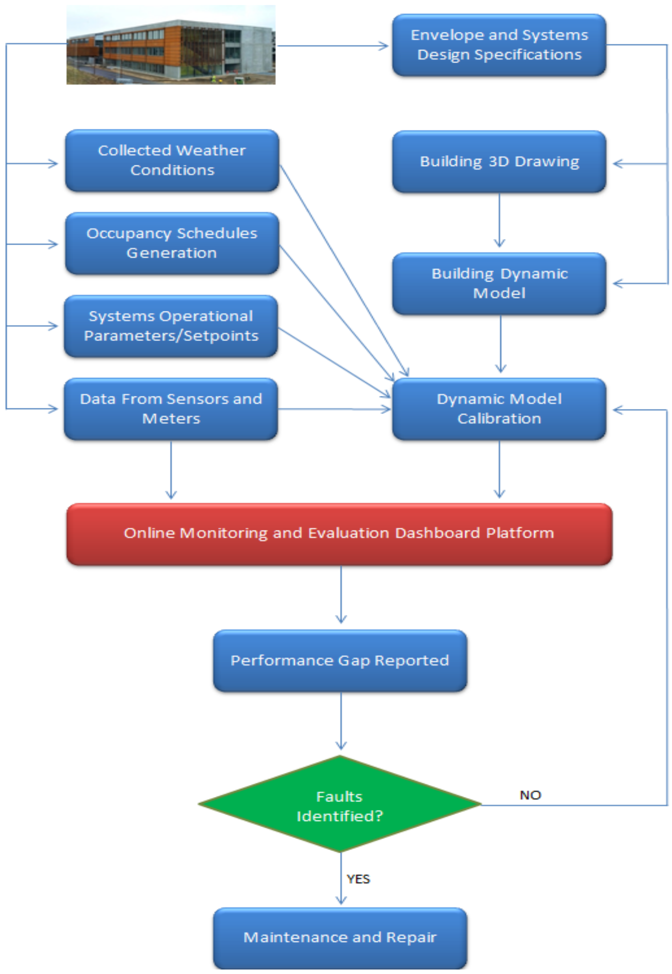


Fig. 10: ObepME Tool Framework (Jradi et.al 2018)

The EnergyPlus building model is implemented into the ObepME tool using Functional Mock-Up Interface (FMI) (FMI, 2010). FMI serves as an open co-simulation protocol allowing models developed in various modeling and simulation environments to communicate with each other, or to connect with third-party software. The dynamic building model is exported to a self-contained file, Functional Mock-Up Unit (FMU) that can be run by any FMI compatible framework (EnergyPlusToFMU, 2018). Selected input and output variables are exposed in the interface, and are mapped to the corresponding data streams from the data collection platform.

With the aid of the FMI, ObepME is completely model-agnostic needing only an FMU and mappings for the selected variables to data streams. The online energy simulation architecture is shown in Fig. 11, where data are accessed via sMAP and the simulation engine is embedded in a FMU, and run through FMI.

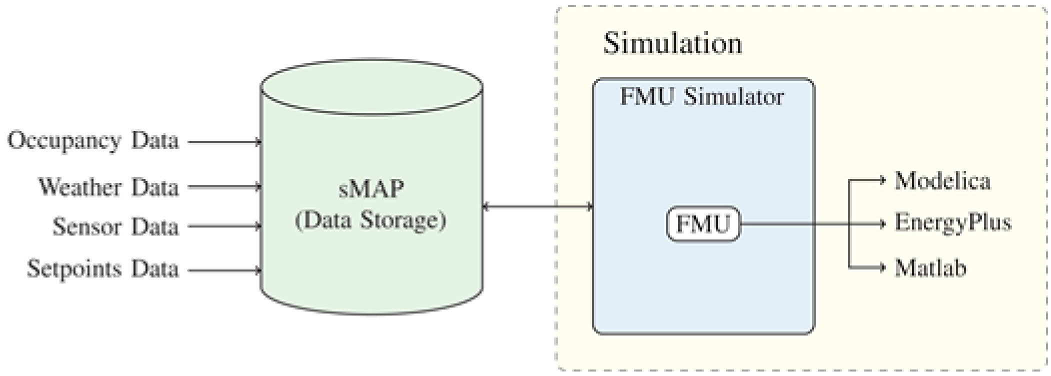


Fig. 11: Online Energy Simulation Architecture (Mattera et.al 2018)

The ObepME tool is configured and currently running in the OU44 building on an automatic and continuous manner. The building has a Schneider Electric building management system (BMS) capable of controlling and optimizing different energy systems operation on different building levels. All the sensors in the building are accessible through a KNX bus, transferring records to the BMS based on the configuration. Various data collected from meters around the building are fetched from the BMS into a centralized database platform using Simple Measurement and Actuation Profile (sMAP) protocol. The OU44 building instrumentation publishes sensor data through a publish-subscribe substrate. A set of processes each subscribe to a subset of these data streams and publish streams representing a key performance indicator (KPI) to the same substrate. Whenever a new value is received on either of the inputs, an output is generated. A dashboard application subscribes to these KPIs, and updates a visual representation each time a value is received.

Combining real-time measurements onsite with calibrated dynamic energy performance model simulations is key to improve the overall energy efficiency and the operation scheme of different energy supply systems. This is in addition to enhancing the building flexibility quotient through the testing and implementation of effective operation management and control strategies in the building. This was highlighted by Li (2014), and demonstrated in a case study of Sutarja Daj Hall at UC Berkeley, where the calibrated dynamic energy model along with real-time data were used to implement and test different energy efficient measures, in addition to demand response events and scenarios for heating, cooling, and lighting systems. Moreover, the dynamic energy performance model could aid implementing an online model predictive control, as reported by Henze and Krarti (2005) and by May-Ostendorp et al (2011). In overall, one of the main features of flexible buildings is providing the opportunity for owners and occupants to implement functional and operational strategies targeting various energy supply systems without comprising indoor thermal comfort and energy consumption baselines. This would require a continuous performance monitoring and a platform to test such strategies. Thus, the proposed framework and the developed tool serves as a basis to test and implement operational methodologies, and control approaches including DR events aiming to optimize the energy performance of various energy supply systems.

4. Discussion

As shown above, engineering for energy flexible buildings takes part in specialized control technologies at the grid-level, in home and building automation, and in building controls. What unites them is that they share priorities for quality of performance in engineered services, which have to be complied with in design. These are discussed below.

For technical facility management, critical requirements for information and control systems related to energy flexibility have to be satisfied in existing buildings. To estimate the effort of adaptation of building operation to energy flexible operation, the principles of energy flexible operation, as well as the requirements for predictive and dynamic management of energy consumption have to be understood. Overall, it can be described as a dedicated service with the following tasks:

1) Energy forecasts have to be produced, and a schedule for e.g. next day operation prepared and communicated to the grid entity.
2) Related devices are distributed, and must be (made) capable of acting together in controlling the building systems under reduced power conditions, and for feeding back surplus energy into the grid.
3) Reduced power conditions may come from two different contracts:
    a. *Direct control* is a utility-initiated operation, where building operations respond to requests for immediate power reduction that originate in smart grid operation.
    b. *Indirect control* is an occupant-initiated operation, where building operations respond to requests for scheduled operation of devices to avoid economic penalties, such as energy price or carbon dioxide emissions.

Research steps in this regard are to find a representation of sufficient quality, implement this model in a distributed system, operate it in a decentralized way, and – different from legacy automation - maintain and optimize it to ensure its quality over the building life cycle.

Ideally, these new solutions are built on top of an existing infrastructure. Independent of the complexity of implementations, and as a point of view of the authors' research experience in buildings, providing for the following technical, non-functional engineering requirements can lower cost and risk associated with the introduction of energy flexible operation:

- *Testability of buildings and systems*

In research projects, often, simplified controls layouts are used to be able to focus on the research question at hand, which often results in only minimal requirements for access to building systems during tests. Examples of the type and timing of **access to building systems** in energy flexibility studies are setpoint modulation, on/off control of a ventilation system, or testing a reduced scope of building operation (e.g. at construction before occupancy, or forecasting services only). In contrast, fully functional energy flexibility processes will be complex and highly networked in the future, and will affect operating buildings at all scales. While, during building adaptation to energy flexibility, unobtrusiveness will be critical to minimize costs and risk, it has to be taken into consideration, that most existing buildings may not be built and equipped for testing in the way RD&D (research, development and demonstration) buildings are, for instance. Therefore, test methods, which function under conditions of minimal access to building systems or with abilities to model building parts out of reach of sensors, will be advantageous. On the other hand, such services have their limitations when it comes to **training staff and occupants** to familiarize with the new operations and technologies, partly because most of their processes cannot be visualized for user information or feedback. For this purpose, simplified and first generation tests might provide customizable functionalities for user learning and exploring.

- *Quality of representation*

For improved **testability** in buildings, accurate **documentation** of the building “as-operated” is vital. In larger buildings, local control systems may be **interoperable** and already share information in a network that is also already visualized for user control. However, existing networks have to be based on **open or published standards and protocols** to be able to reuse the infrastructure. Any information and control systems, existing as well as future, will have to be **scalable** to be economic (“added value”) in a smart city and smart grid environment, where an increasing number of devices and buildings will be networked in clusters of sizes that cannot be predicted at the beginning.

- *Quality of building models*

The role of using **dynamic energy performance models** as a basis for testing and implementing various operation management and control strategies in buildings was demonstrated and highlighted. This will lead to an overall energy efficiency improvement in addition to enhancing the building flexibility quotient. Moreover, to satisfy this role, such dynamic models need to be combined with real-time measurements on-site aiding the calibration process and allowing validation of the impact of implemented strategies. However, to save time and resources in development of such dynamic building energy models, requirements for digital models need to be developed and implemented for allowing a smooth transfer from building information models (BIM) to building energy models (BEM). Such reequipment is currently implemented in Denmark, where all new public buildings need to be digitally managed and interchanged with a **reequipment of digital models** to be delivered in the handover phase (Svidt and Christiansson, 2008).

- *Quality of service over time*

It is clear to most that controlling building power and heat at the grid side are **mission-critical** operations that require robust and well understood methods. For energy flexibility in buildings, this mission-criticality now also applies to the control networks servicing the installed building hardware. Engineered systems have to be designed for **dependability**, so their runtime does not have to be interrupted to recover from an operations error. For dynamic processes, control networks have to be designed for **availability** to ensure the quality of service of the communication flow between existing and new components. When engineered control networks are also designed for **maintainability**, not only the integration of new components and functionality is quality-controlled, but they could also support remote maintenance in regular operations, if desired. A resilient grid performance is required for national security of energy systems. When buildings connect to the grid, their communications have to be **secure** at a similar level to avoid performance gaps that could be used for attacks on the grid. On a personal level, **information protection** and **privacy of information** will be critical for the acceptability of energy flexible services, as first experiences with the roll-out of smart meters have shown. Last but not least, **efficiency** in control networks and solutions will be critical, not only in terms of sampling efficiency, but particularly **energy efficiency** of services to ensure that the energy saved during the load management operations is not consumed by the information, communication and controls processes in existing buildings.

In summary, the realization of energy flexible building management involves testing controls and automation solutions as a function of building performance. In this context, information on building performance and access to it acted as constraints to the solutions developed for energy flexibility. Hence, building management could improve the testability of buildings and building systems by providing this information in a digital format, and by adopting a policy of exclusively implementing protocols for automation that are "open".

5. Conclusions

For energy flexibility in residential, commercial and institutional buildings, the following can be concluded:

- A proposed methodology for computation of the potential energy flexibility performance of buildings is available, which includes the ability to compare buildings' performance in this regard independent from their individual differences.
- In contrast, implemented solutions for participation in demand response programs will be diverse and building-specific due to the individuality of buildings and operated building solutions. While the complexity of control processes involved in coupling the building sector to the grid becomes evident, formal evaluations of implemented solutions down to the last building meter are slowly evolving.
- Providing for improved testability of a building and its systems can lower costs and risk involved in adapting to energy flexibility. Exercising existing best-practice strategies, such as adoption of published standards and open protocols for automation, and accurate documentation of the as-operated status in a digital format in all buildings, would support several requirements for quality of service simultaneously.

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