Building Energy Management in the FZI House of Living Labs

Birger Becker(✉), Fabian Kern, Manuel Lösch, Ingo Mauser(✉), and Hartmut Schmeck

FZI Research Center for Information Technology,
Haid-und-Neu-Str. 10-14, 76131 Karlsruhe, Germany
`{bbecker,kern,loesch,mauser,schmeck}@fzi.de`
`http://www.fzi.de, http://www.house-of-living-labs.de`

Abstract. The *FZI House of Living Labs* is a research and demonstration environment that facilitates interdisciplinary research, development, and evaluation in real-life scenarios. It consists of various *Living Labs* addressing different research topics. In the *Living Lab smartEnergy*, solutions for the energy system of the future are investigated. For this reason, the whole FZI House of Living Labs has been equipped with building automation, distributed generation, thermal and electrical storage, and technologies that enable the flexibilization of energy supply and demand. The equipment, among others, includes a photovoltaic and battery storage system, a micro combined heat and power plant, and an adsorption chiller. A building energy management system was developed that integrates various communication technologies, and hence enables monitoring, data recording, visualization, and the integrated optimization of the devices and systems. This way, flexibilities can be utilized with regard to different optimization goals such as an increased self-consumption, or the provisioning of grid-supporting services.

Keywords: Energy management · Smart building · Smart home · Building automation · Demand side management

1 Introduction and Motivation

Governments worldwide set the goal to reduce greenhouse gas emissions. The resulting energy transition with an increasing share of renewable energy resources comes along with an intermittent and highly fluctuating energy supply. Hence, as demand and supply within the grid always have to be balanced, one of the key challenges is the efficient utilization of load flexibility. Due to the high energy demand in buildings, *Building Energy Management Systems* (BEMS), which are sometimes also called *Building Operating Systems* [8], bear a great potential for adapting the building's energy load to the global grid state, as well as for providing appropriate ancillary services in future smart grids.

Since 2011, such a BEMS is developed and deployed in the research and demonstration environment *FZI House of Living Labs* (HoLL), which facilitates interdisciplinary research, development, and evaluation in various real-life

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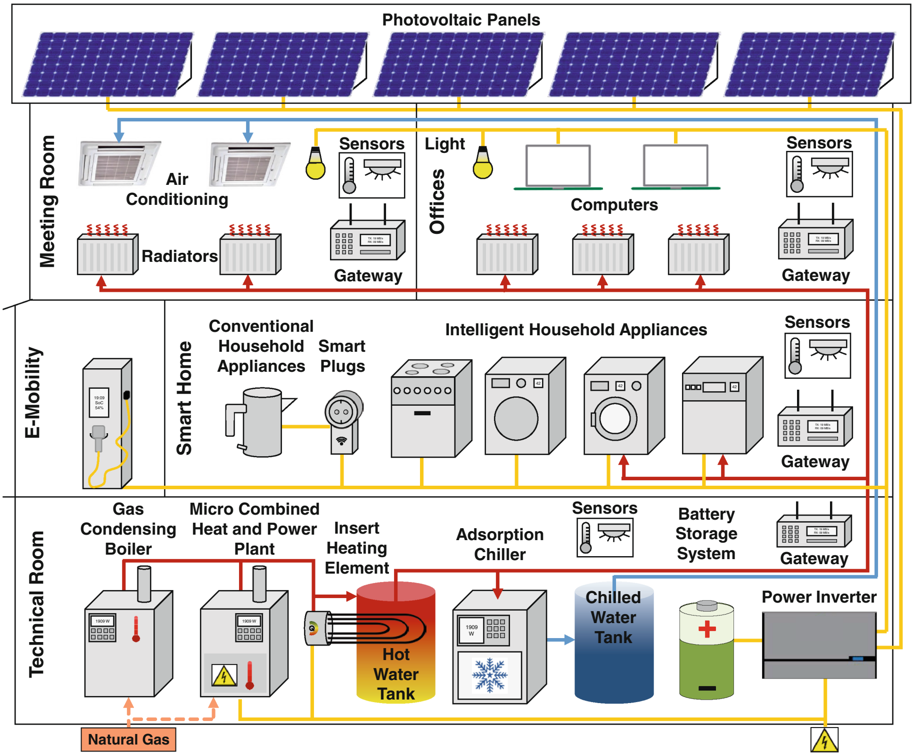

Fig. 1. Structural plan of electrical and thermal equipment of the HoLL

scenarios [17] at the *FZI Research Center for Information Technology* in Karlsruhe, Germany. At the same time, the HoLL also serves as office building for the FZI. In the *Living Lab smartEnergy*, our research focuses on efficient information and communication technologies (ICT) for the integration of heterogeneous components into the BEMS, as well as on optimization strategies and algorithms for energy systems and user interaction interfaces.

With the objective of providing a durable and innovative research lab for energy applications, the HoLL is equipped with state-of-the-art technology that is extended continuously. As the overarching research objective is to provide flexibility for the energy grid, many of the devices and systems provide communication interfaces. The standardized integration of different communication protocols is a major focus of the research in the HoLL. Therefore, it is equipped with heterogeneous communication systems. Since the integrated optimization of various energy carriers is another research focus, energy flows for electric installations, heating, cooling, and natural gas are measured, analyzed, and controlled.

In this paper, the parts of the research environment HoLL that focus on private households and commercial buildings as well as investigated research topics are presented. An overview of the energy equipment and energy flows within the HoLL is illustrated in Fig. 1. The dashed orange lines indicate the supply with natural gas, yellow lines corresponds to electrical energy flows, red and blue lines represent thermal energy flows of hot and chilled water. A large number of different appliances, devices, and building automation technologies provides a suitable research platform for various aspects such as standardized integration, interoperability, smart grid capabilities, and energy management methods. Based on this platform, optimization strategies are developed to cope with different energy management objectives, such as grid support, economic profit, or self-consumption. Due to significant interdependencies of electrical and thermal energy supply, consumption, and storage, which are more closely described in the following sections, their joint management and optimization is done in one BEMS. As the BEMS is integrated into the real operation of the building, valuable data and experience with real-life application are gathered.

Projects that utilize the HoLL for research on energy topics include publicly funded research projects, cooperations with companies of the automation, automotive, electrical equipment, energy, household appliance, and software industry, the *Energy Lab 2.0* of the *Karlsruhe Institute of Technology* (KIT), and the project *Storage and Cross-linked Infrastructures* of the *Helmholtz Association*.

This paper is structured as follows: Sects. 2 and 3 provide an overview of the electrical and thermal equipment that is installed in the HoLL; the installed building automation systems are described in Sect. 4. The software architecture, selected optimization strategies of the BEMS, and concepts for user interaction are depicted in Sect. 5. Section 6 presents exemplary research that is based on the HoLL as well as lessons learned when setting up the environment. An overview of similar research environments is given in Sect. 7. Finally, Sect. 8 summarizes the main aspects and gives an outlook on future work.

2 Electrical Equipment

Various electrical suppliers, consumers, storage systems, and electric vehicles (see Fig. 1 and Table 1) are integrated into the real building operation. Due to the research aspects mentioned, a wide range of devices and systems of different manufacturers have been selected. Each of these devices and systems provides a communication interface, resulting in a heterogeneous system infrastructure.

The *photovoltaic* (PV) system provides up to 15.1 kW using 108 *photovoltaic panels* which are installed on the rooftop. A *battery storage system* with a capacity of 30 kWh is installed. Three *power inverters* convert direct current (DC) provided by the PV panels and the battery storage system into alternating current (AC). A grid outage can be bridged by temporarily providing an islanded AC grid via the power inverters. To increase the autonomy time, the island grid provides power to selected rooms only. The power inverters have an USB communication interface, which enables read and write access to the system. To provide a more generic *Representational State Transfer* (REST) interface for read (e.g., currently generated power) and write (e.g., dynamic control of power factor) access, we have installed an embedded system. This way, the BEMS is able to control the PV system for increasing the consumption of locally generated energy and for providing ancillary services to the power grid, e.g., improving voltage quality or compensating unbalanced phases. Using data recorded in the HoLL, this aspect has been more closely investigated in [5].

Additionally, a gas-fired *micro combined heat and power* unit (µCHP) providing electrical and thermal energy has been installed. The major advantage of the CHP technology is a high overall efficiency by using 12.5 kW waste heat for heating purposes when generating 5.5 kW electrical power. The integration of thermal storage tanks allows for electricity generation by the µCHP unit even when the thermal energy is not consumed at that time (see Sects. 3 and 5).

An electrical *insert heating element* (IHE) is installed in the hot water tank and coupled to the PV system. The objective is to convert surplus electrical energy generated by the PV system into thermal energy instead of feeding the surplus energy into the grid. For this purpose, the PV system has been equipped with additional measurement technology that communicates directly with the IHE.

A major research aspect concerning BEMS is the development of strategies and algorithms to detect and exploit electrical demand and supply flexibility of buildings. To investigate the potential of electrical load management in private households, a *smart home* has been set up within the *Living Lab smartHome/AmbientAssistedLiving*. It is equipped with numerous household appliances of different manufacturers and used by employees of the FZI. Most of the appliances are equipped with communication modules providing an appropriate external communication interface (*intelligent household appliances*). Alternatively, *smart plugs* are installed at the electricity connection of the appliances. Being put between the wall socket and the device plug, they allow to turn connected devices on and off, and to measure their energy consumption. This way, devices that are able to continue their programs at the point where they have been interrupted (fail-over capability) can also be controlled by the BEMS, although not being equipped with communication capabilities by the manufacturer. Besides measuring various devices, this is in particular used to retrofit

Table 1. Technical specifications of selected electrical devices

Device	Specification	Manufacturer and type
PV panels	Electrical power: 15.1 kW_{peak}	108× *Würth Solar WSF0002E140*, CIS
Battery storage	Electrical capacity: 30 kWh	3× *BAE AK40012*, VRLA
Inverters for PV and battery	Max. electrical power: 5 kW per phase	3× *Nedap PowerRouter PR50SB*
µCHP unit	Thermal power: 12.5 kW, Electrical power: 5.5 kW	*Senertec Dachs G 5.5 standard*
Electric vehicles	Max. charging power: 22 kW, Capacity: 15.1 kWh	*Smart Fortwo Electric Drive*
	Max. charging power: 3.6 kW, Capacity: 40.0 kWh	*Peugeot 3008* (modified)

conventional household appliances. The communication modules and the smart plugs are communicating with a dedicated gateway (see Sect. 4). Their integration into the BEMS enables the system to monitor the usage, the state, and the energy profile for each appliance. The research in the smart home focuses on standardized communication and integration including strategies for the automatic control and optimization of appliances.

To take advantage of the energy feed-in and consumption tariffs, we have to distinguish between power of the PV system and power of the µCHP unit as well as grid feed-in and self-consumption. Therefore, we installed a complex metering infrastructure consisting of several (partial two-way) meters, which enables the measurement of the different electrical power flows. In a second step, we integrated the meters into the BEMS using a standardized optical meter interface and the *Device Language Message Specification* (DLMS) protocol.

3 Thermal Equipment

Space heating and air conditioning (see Fig. 1 and Table 2) are done by a system that comprises a gas-fired µCHP unit, an adsorption chiller, a gas-fired condensing boiler, the IHE, as well as storage tanks for hot and chilled water. Such a kind of thermal system is called *trigeneration* or *combined cooling, heat, and power* (CCHP). It combines a µCHP unit, i.e., *cogeneration*, with an adsorption chiller that produces chilled water. Additionally, hot water is also produced by the condensing boiler and the IHE. Generation and consumption of chilled respective hot water are decoupled by the storage tanks.

Two ceiling-mounted cassettes use the chilled water to air-condition a meeting room, which is used by employees of the FZI. The adsorption chiller is mainly powered by hot water supplied by the hot water tank. Bookings of the meeting room trigger air-conditioning requests for the preconditioning in advance to

Table 2. Technical specifications of selected thermal devices

Device	Specification	Interface	Manufacturer and type
Adsorption A/C	Cooling power: 9 kW	Digital I/O	*InvenSor LTC 09*
Gas-fired µCHP unit	Thermal power: 12.5 kW, Electrical power: 5.5 kW	Digital I/O	*Senertec Dachs G 5.5 standard*
Gas-fired condensing boiler	Thermal power: 95 kW	0–10 V	*Elco THISION L 100*
Electric insert heating element	Electrical power: 0, 0.5 ... 3.5 kW	Modbus/Serial	*E.G.O. Smart Heater*
Hot water tank	3250 l	–	Custom-made tank
Chilled water tank	3000 l	–	Custom-made tank
System controller	–	Modbus/TCP	*SolarNext chillii*
Heat flow metering system	–	Meter-Bus (M-Bus)	*Aquametro AMBUS Net*

meetings in the room, when the past outdoor temperatures exceed certain temperature thresholds. The bookings are extracted from the room's calender on the *Microsoft Exchange Server*. An *Energy Management Panel* (see Sect. 5.2) in the meeting room enables the visualization of the bookings and the air conditioning states as well as the adjustment of the room set temperature. The BEMS schedules the operation of the µCHP to provide hot water for the adsorption chiller, the operation of the adsorption chiller to provide chilled water, and the actual air conditioning of the room (see Sect. 5.1).

The heating system utilizes numerous sensors and actuators, such as temperature sensors and heating valves. Some of the sensor data is collected by a subsystem (*SolarNext chillii* system controller), which also controls the release signals for the µCHP unit, the condensing boiler and the adsorption chiller. This subsystem works autonomously when no signal is provided by the BEMS. Comprehensive data of the heating system is retrieved by the BEMS using *Modbus/TCP* to be included into the global optimization of the building's energy management. Additionally, the µCHP unit is equipped with a communication interface that provides a *REST service* for collecting data and receiving control signals directly from the BEMS. On the consumption side, building automation systems are integrated into the BEMS to control the heating for each room of the building individually (see Sect. 4).

In order to gain a more detailed view of the energy flows within the heating and cooling system, we installed six additional heat meters for hot and chilled water. Each of the meters consists of an ultrasonic flow measuring unit and two temperature sensors (flow and return). The meters measure current thermal power flows and thus associated energy demands and supplies. They are connected to a central gateway via *Meter-Bus* (M-Bus), which is integrated into the BEMS using its web service interface. In addition to the information about the energy flows, the basic volume flow data is used for predictive maintenance.

4 Building Automation

A heterogeneous system landscape with multiple building automation technologies has been installed to gain insights into many different existing implementations and their integration, as well as to derive concrete requirements for BEMS. Table 3 provides an overview of the automation technologies deployed in the HoLL. Their usage and integration into the BEMS is subsequently described.

4.1 Wireless Technologies

Bluetooth Smart [6] focuses on radio communication with devices characterized by limited computational power and limited energy supply. It is used to communicate with household appliances that are equipped with a manufacturer-provided communication module providing an external interface. This allows interfering with internal control mechanisms by deferring the appliance operation cycle or even interrupting it. The Bluetooth gateway is implemented on a

Raspberry Pi that is enhanced with a USB-connected Bluetooth radio transmission module.

EnOcean [10] is a communication technology for computationally limited, low-power devices. To operate and communicate, EnOcean devices usually leverage environmental energy wherever possible, such as ambient light and temperature differences. EnOcean is used for controlling the room heating with heating valves for radiators and temperature sensors. The gateway to interact with the BEMS is implemented on a Raspberry Pi that is enhanced with a proprietary general-purpose input/output (GPIO) module for EnOcean radio transmission.

ZigBee [39] focuses on small, low-power devices and allows to increase the range of the radio transmission by passing data through a mesh network of intermediate devices. We use ZigBee smart plugs to monitor the power consumption of household appliances, and for enhancing conventional devices into controllable devices (see Sect. 2). The gateway for interaction with the BEMS is based on a proprietary embedded system comprising a ZigBee radio antenna and provides an EEBus interface.

EEBus [9] is a standardization effort working on a common interface for various devices while relying on existing communication technologies. Its goal is to abstract and translate from various existing standards to a common interface. In our environment, EEBus is used for the interaction with the ZigBee smart plugs and appliances.

Additionally, various *proprietary standalone solutions* are deployed to gain deeper insights via evaluations of technical aspects in real-world scenarios. One

Table 3. Selection of technologies used for building automation and device communication in the HoLL

Technology	Communication link	Integration into BEMS (endpoint)	Usage examples
Bluetooth Smart	Radio (2.4 GHz)	*Raspberry PI* with *Bluetooth* USB module	Household appliances, beacons
EnOcean	Radio (868 MHz)	*Raspberry PI* with *EnOcean* GPIO module	Heating valves, lighting, switches, temperature sensors, window sensors
ZigBee	Radio (2.4 GHz)	Proprietary embedded systems	Household appliances, smart plugs
HabiTeq	Wired	*HabiTeq CTD Controller*	CO_2 sensors, heating valves, light sensors, motion sensors, shutters, switches, temperature sensors, window sensors
KNX	Wired	*tebis KNX Domovea Server*	Fire detectors, heating valves, motion sensors, shutters, switches, temperature sensors, window sensors
EEBus	–	*E.G.O. Smart Gateway*	Household appliances, smart plugs
REST over HTTP	–	Direct connection to local Ethernet	Heat meters, µCHP unit, infrared transceivers

example is a *RWE Smart Home* [33] installation which is used to control lighting in one room and heating in two office rooms. Due to the closed eco-system, the lack of an open local interface, and the limited gains that would be possible, it is not integrated into the BEMS. Furthermore, *en:key* [20], an EnOcean-based solution from *Kieback & Peter*, is used for heating control in the *Living Lab smartEnergy* and in another office room. Based on a motion sensor and a learning algorithm, this system uses historical data to predict occupancy and to heat up the room only when required. Other examples for proprietary stand-alone solutions are *Plugwise* [32] smart plugs, which can be accessed using a USB dongle and a proprietary Plugwise control software. Although the communication protocol is proprietary and closed, a third-party *Java* library is available and used to enable communication between the BEMS and the Plugwise smart plugs.

4.2 Wired Technologies

HabiTeq [16] is a proprietary wired automation technology that is offered by *General Electric* and has originally been developed by *Qbus*. It is used in two office rooms for managing wall switches, lighting, temperature and CO_2 sensors, shutters, and heating valves. HabiTeq can be operated as a standalone solution, as a hardware server enforces the interplay of the different components following predefined rules that have to be specified using a proprietary configuration software. At the same time, the hardware server allows also to access the devices using REST, hence allowing for an integration of the proprietary automation solution into the BEMS.

KNX [21] is a widespread building automation bus. We use a twisted-pair KNX installation in the smart home, which comprises different KNX components, such as controllable shutters, temperature and window sensors. In general, static rules for the interplay between different components can be configured using a client software. In our setup, the additional deployment of a proprietary KNX product, *tebis KNX domovea* from *Hager* that provides a touch panel for direct end-user interaction, and a hardware server make the KNX bus accessible over IP. This way, the hardware server is connected to the BEMS, hence allowing to access, e.g., temperature information and window states.

Additionally, single devices offer an HTTP interface with REST. In these cases, no additional gateways are required for the integration into our BEMS. One example is the µCHP unit, which provides a proprietary REST interface allowing to read various values regarding the µCHP usage and to explicitly trigger a start or stop. Furthermore, several heat meters are installed to study the energetic building performance and to enable thermal predictions. These heat meters are also equipped with a REST interface, which is directly integrated into the BEMS.

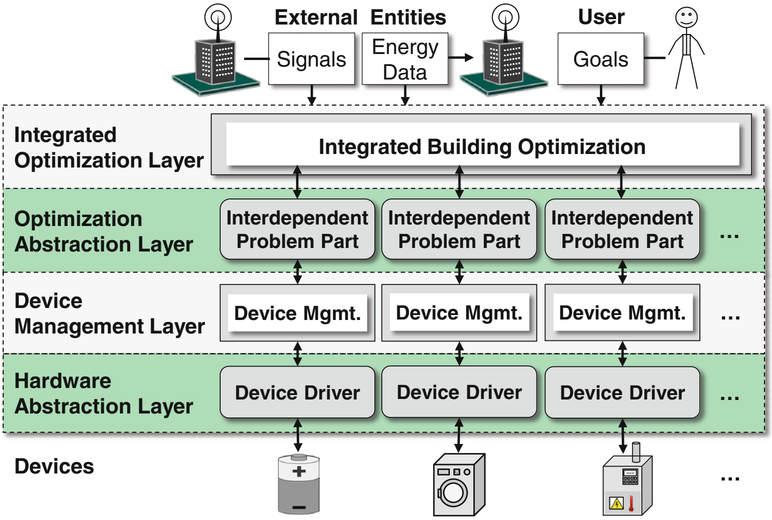

Fig. 2. Overview of organic smart home and its architecture

5 Energy Management and Interaction

This section focuses on the energy management, which is based on the introduced technical equipment as well as the deployed communication technologies and pre-existing automation solutions. It is realized using a building energy management system—the *Organic Smart Home*—and a human machine interface—the *Energy Management Panel*.

5.1 Building Energy Management System

In order to be able to optimize energy flows, an appropriate energy management system that allows for the integration and optimization of the multitude of devices has been developed at FZI and KIT: the *Organic Smart Home*[1] (OSH) [2,27]. It has first been deployed to the *Energy Smart Home Lab* at the KIT [3], where it has been evaluated in multiple evaluation phases [30]. Major advantage of the OSH is its applicability to both, real world energy management and simulations of buildings with different sets of devices in diverse scenarios, enabling the development and testing of control and optimization functionality in simulations before applying them to productive systems. The OSH has already been used to study diverse scenarios of optimizing, e. g., the operation of appliances [2,25], heat-pumps [24], trigeneration [26], and electric vehicles [29]. In order to reach a detailed co-simulation of electrical and thermal energy flows it also has been coupled with the thermal simulation framework TRNSYS [23].

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[1] http://www.organicsmarthome.com.

The trigeneration system involves four main energy carriers: electricity, hot water, chilled water, and natural gas. The devices all work on the same storage tanks and thus their consumption, production, and states are interdependent. Consequently, the OSH considers not only electricity, but also natural gas, hot and chilled water consumption, and emissions of greenhouse gases. Additionally, the inverters of the PV system are capable of adjusting their reactive power to provide ancillary services [5], based on signals that are communicated from external entities to the OSH.

The simplified architecture of the OSH is depicted in Fig. 2 and comprises several layers for abstraction, management, and optimization that are more closely described in [27]. For optimization, a simplified model of the building and the devices is included in the OSH. Usually, systems for building simulation that focus on thermal simulation use time steps on a scale of several minutes [7]. In contrast, when additionally considering electricity, the optimization with respect to variable external signals (e.g., tariffs and load limitations), user preferences (e.g., specified degrees of freedom), and goals (e.g., cost minimization), requires the utilization of shorter time steps in order to take account of short-time consumption and production peaks as well as the actual self-consumption of the generated power [38]. Therefore, the OSH is able to use time steps with a resolution of one second, thus allowing to investigate the optimum time granularity for optimizations [26].

Optimization of a time horizon of several hours would result in mixed integer linear—or nonlinear when also respecting non-linearities—programming with thousands of constraints and variables, which is usually not solved within adequate time on computers with limited resources [1,34]. Additionally, the execution time of the optimization algorithm is crucial, because frequent rescheduling is quite likely and a quick response to user interaction is desirable [30]. Additionally, solving the optimization problem to optimality is only possible when having complete information about future energy flows, which cannot be obtained ex ante. Thus, generating approximate solutions by a heuristic that allows for frequent rescheduling in varying setups promises to be of better use for productive energy management. Therefore, we decided to use a meta-heuristic—an *Evolutionary Algorithm*—with dynamic formulation of the problem instances at runtime of the system to optimize the system heuristically [2,26].

5.2 Energy Management Panel

For covering the entire potential of BEMS in real-life scenarios, the user acceptance of the system plays an important role. On the one hand, most users want a system running automatically without requiring much user interaction. On the other hand, users often want to understand the actions that have been executed automatically by the system and want to be able to override automatic decisions [31]. To meet these requirements, the *Energy Management Panel* (EMP) has been developed for the interaction between the user and the BEMS [4].

The main view of the *visualization* gives an overview of the most important energy flows in the building (see Fig. 3). The upper section focuses on electric

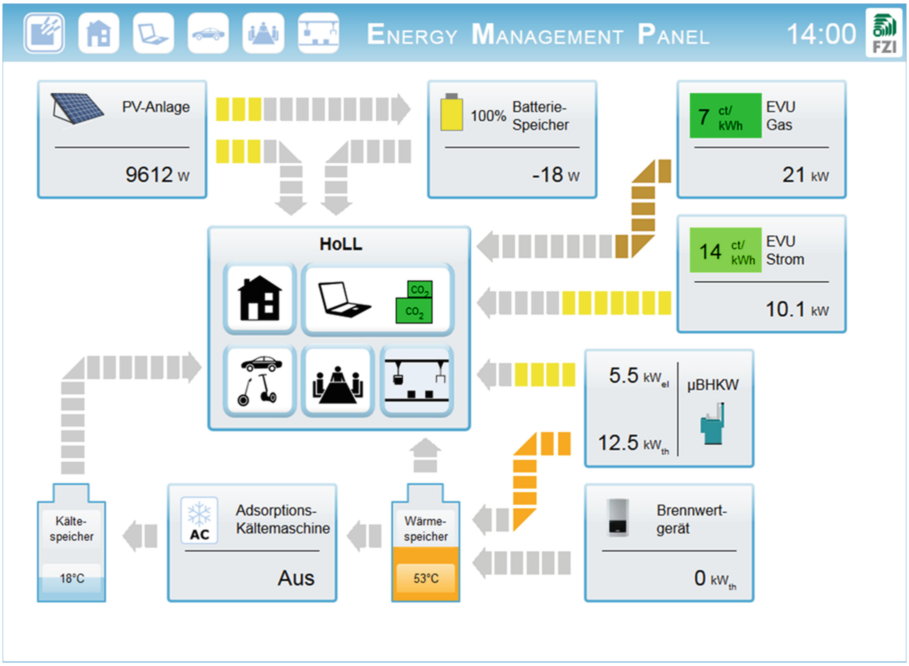

Fig. 3. Energy management panel: visualization of energy flows in the HoLL

energy flows and the lower section highlights thermal energy flows. The user is able to retrieve more detailed information of each component, e.g., energy profile of the PV generation or µCHP unit's operating condition, by selecting relevant detailed views. This overview supports the user to understand the relation between energy supply, consumption, and storage within the building easily.

Additionally, *parametrization* of BEMS is an important feature in the context of user interaction. The EMP enables the user to define certain parameters, which are mandatory for the optimization of the BEMS. The required parametrization ranges from the definition of *degrees of freedom* for load-shifting of appliances to the definition of overall optimization targets, e.g., maximizing the economic benefit or maximizing the usage of renewable energy sources.

In contrast to the parametrization, which is performed at run time of the BEMS, *system configuration* is carried out before the initial start of the BEMS or after major configuration changes. The system configuration enables the adaption of the generic BEMS architecture, components, and drivers to specific requirements and system settings of individual buildings.

Combining visualization, parametrization, and system configuration, the EMP enables the user to get an overview of the energy flows in the building and to understand the mostly automated decisions of the BEMS. Although we found that most users are not willing to control their BEMS manually in the long term, the option for manual interaction with the BEMS increases the user convenience and acceptance significantly [4]. Furthermore, user interaction is able to prevent misunderstandings and increases transparency and traceability. We experienced users being very skeptical about the automatic decisions of the BEMS. They even assumed incorrect decisions (e.g., scheduling the dishwasher to periods of a high electricity price) by the BEMS, because they did not understand the reason for the decisions (e.g., a CHP supplying the building's electricity during this period of high prices). We used these experiences to improve the EMP or even add additional features for user interaction. Thus, the EMP allows the user to adjust the optimization procedures and to adapt the overall system configuration to her individual needs in a very flexible way. In general, user interaction is mandatory for a successful application of BEMS.

6 Exemplary Research and Lessons Learned

Based on the presented systems, devices and technologies, the HoLL builds a sound environment to conduct research and development regarding various *smart building* and *smart grid* topics. Related research conducted in the HoLL includes publicly funded research projects as well as cooperations with companies of the automation, the automotive, the electrical equipment, the energy, the household appliance, and the software industry.

6.1 Exemplary Research

The trigeneration system of the HoLL, consisting of a µCHP unit, an adsorption chiller, and storages tanks for hot and chilled water, has been analyzed, simulated, and optimized in [26]. The results show that an integrated scheduling of the µCHP unit and the adsorption chiller reduces the average total monthly costs on average by about 16 %, in comparison to up to 11 % when scheduling only the µCHP unit respective the adsorption chiller. This supports the approach of an integrated optimization of all devices that are used within a building. In order to enable the successful integration of the multitude of different appliances into one BEMS, the original architecture of the OSH has been enhanced, based on the experience gained in the HoLL [27].

Detailed recorded load profiles of the PV and battery storage system with a resolution of up to one second and corresponding voltage levels have been used in different contexts, such as the optimization of heat pump operation for demand side management [11,24], the optimization of a trigeneration system as depicted in the previous subsection [26,27], the economic evaluation of local PV generation in electric vehicle car parks [35], and the provision of ancillary services by building energy management systems [5].

The EMP is the user interface of the BEMS, i.e., the OSH, in the HoLL. Thus, the BEMS is operating and optimizing the heating and electricity system in combination with several building automation systems and the EMP provides the central user interaction interface of a BEMS in real-life conditions. Since the HoLL is continuously extended by new components and systems, the EMP is also adapted to meet the new requirements, e.g., combining room reservations from the calendar with air conditioning and heating in the meeting room or providing detailed measurement data of the heating and cooling system. Due to the fact that the BEMS is integrated in the real operation, we get feedback from the users who are working every day in the building. Therefore, the EMP is continuously adapted to the available systems and the users' needs.

The *Living Lab smartHome/AmbientAssistedLiving* is used as a development and demonstration platform within various research projects with companies of the automation and the household appliance industry. Conventional and hybrid appliances, i.e., appliances that utilize more than one energy carrier, are equipped with communication modules and integrated into energy management systems [28]. Therefore, suitable interfaces are being developed that enable energy management functionality as well as value-added services in the domains of comfort, safety, and security, based on the insights gained in the HoLL.

6.2 Transfer from Research to Practice

The applied research and development infrastructure, and the continuous interplay of research and practice, allows developing and evaluating innovative smart building solutions. In multiple cooperations with industry partners valuable knowledge regarding the advancement of new technologies are transferred into practice. In one research project with an industry partner, e.g., the energy management concepts developed in and the experiences made with the HoLL are transferred to a large-scale energy management system for a concrete facility. It is composed of about 30 large commercial and industrial buildings with centralized and decentralized energy equipment. The goal is to optimize the interplay of energy supply and demand in order to increase the green energy share and to decrease costs by providing grid-supporting services. In another project, knowledge regarding the control of thermal hardware has been used for the grid-responsive optimization of heat pumps. A predictive control scheme for heat pumps was developed and—in cooperation with an engineering office—realized on real hardware. It allows reacting to demand and supply fluctuations at the energy exchange market. Together with an manufacturer of solar heating solutions and an energy utility, this solution is currently rolled out in up to 20 buildings in order to gain deeper insights. A further project addresses the realization of a market-ready energy management gateway for private as well as for commercial customers. In this context existing equipment, and in particular interdisciplinary knowledge regarding information and communication technologies for the interconnection of various building entities is used for the advancement of real product prototypes.

6.3 Lessons Learned

Due to the large diversity of consumers, suppliers, storage, and automation systems on the market, the standardized and non-proprietary integration of the relevant components into a BEMS is challenging. Although there are several approaches developing communication standards, these are still at their beginning. Therefore, developing the hardware abstraction component of the BEMS operating the HoLL was extensive and complex. Because of the significant interdependencies between thermal and electrical energy flows in a building, optimization strategies of a BEMS have to take different energy carriers into account.

Additionally, research on the needs of users plays an important role regarding user acceptance of, e.g., comfort, safety, and security functions. Research approaches in energy related labs often focus only on one of these aspects independently. Having operated a BEMS and analyzed and controlled numerous components and systems in the HoLL in different conditions during several years, we came to the conclusion that the success of BEMS is enabled by a combination of these features, i.e., standardization, integrated optimization of all energy carriers, and user-centric automatic energy management.

7 Similar Research Environments

Residential as well as commercial building environments are in the focus of the HoLL. Usually, research environments focus either on *smart home* or on *smart building* environments. The term smart home refers to all buildings that are used by private persons, i.e., dwellings, no matter whether it is a single person apartment, a single-, or a multi-family house. In contrast, smart building refers to all buildings that are used commercially, e.g., office buildings, enterprise buildings, and small industrial buildings [37].

Application-oriented and close to the market research in smart home respective smart building environments is done at the two buildings of the *Fraunhofer-inHaus-Zentrum* [13]. Fields of interest are construction systems, living, ambient assisted living, health care, hotel, and office. The buildings are equipped with a geothermal system, a µCHP, phase change material for energy storage, an absorption chiller, and a smart home server with visualization panels. However, the focus lies on technologies targeting at comfort maximization and energy efficient building operation.

A platform for application-oriented research on smart homes with focus on ambient assisted living, energy efficiency, building automation protocols, and *Internet of Things* is provided by the *iHomeLab* [18] of the *Lucerne University of Applied Sciences and Arts*. A personal energy management and visualization infrastructure based on IPv6 is in development in context of the research project *IMPACT*. The energy management focus, however, is on univalent household appliances.

Hands-on experience and research on smart homes in smart microgrids is done at the *Smart Microgrid Lab* [22] of the *Lakeside Labs GmbH*, focusing on smart metering, self-organizing smart appliances, demand response and load scheduling. It is equipped with a PV system, a battery storage system as well as a data acquisition system and can be operated in grid or island mode. Yet, it considers electrical energy and smart homes environments only.

The *SmartHOME* [36] of the German armed forces is a lab environment for research on security, energy efficiency, and comfort in smart homes and smart buildings. It focuses on sensor and actor networks for building automation and the optimization of heating, ventilation, and air-conditioning systems. Integrated multi-energy carrier optimization and intelligent appliances are not considered.

A research and presentation platform for energy management systems is provided by the *IT4Energy Lab* [14] of the *Fraunhofer Institute for Open Communication Systems*. It focuses on building automation, energy management, renewable energy sources, smart metering, and virtual power plants. The project *envyport* aims at the development of an energy management gateway. Nevertheless, the research focuses solely on electricity as energy carrier and lacks an comprehensive view on energy.

Research in the fields of renewable energy sources, energy efficiency, electricity generation, distribution, and storage systems is done at the *ServiceLab Smart Energy* [15] of the *Fraunhofer Institute for Solar Energy Systems*. It aims at products that are close to the market, which require functional, integration, communication, and conformity testing. However, it lacks the integration of heterogeneous building automation systems.

Energy management and building automation in the context of a smart grid is focused on by the *fortiss Smart Energy Living Lab* [12] at the *Technical University Munich*. It consists of a PV and a battery storage system and includes an office environment that is equipped with a control software, which adapts the local energy consumption to the available energy. This lab focuses on electricity and efficient rule-based control strategies.

The *Energy Smart Home Lab* [19] at the KIT is a research and demonstration environment focusing on smart homes as part of a smart grid. It is equipped with a µCHP unit, a PV system, an air conditioner, thermal storage, intelligent appliances and an electric vehicle which are all monitored and controlled by an integrated energy management system. In contrast to the HoLL, the focus is on private households with homogeneous household appliances.

8 Conclusion and Outlook

Currently, energy systems are subject to deep-going changes due to an increasing share of fluctuating renewable energy sources and distributed generation. To cope with these changes, BEMS enable to turn traditionally passive consumers into active grid participants that leverage their local flexibilities according to the grid's needs. In this paper we presented the *FZI House of Living Labs*, a real-world research and demonstration platform. It was shown how it integrates a multitude of different devices and technologies with heterogeneous interfaces and protocols into a single BEMS which enables the flexibilization of demand and supply in the building. This way, a comprehensive research platform is provided for investigating various aspects in the context of smart buildings. This includes in particular the integration of hardware components with heterogeneous protocols and different communication media, as well as software and algorithms for the prediction and efficient optimization of various devices in different scenarios.

Permanent expansions of the HoLL and numerous collaborations with different stakeholders from the domains of smart grids, building automation, energy management, and automotive assure an appropriate up-to-date environment for the development and evaluation of ICT for future buildings in on-going and future projects. In particular, the optimization of the usage of the battery storage system and the hybrid appliances, a more advanced integration of the electric vehicles, as well the extension of optimization algorithms to support additional kinds of demand response will be in focus of future research.

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