Multi-Commodity Energy Management Applied to Micro CHPs and Electrical Heaters in Smart Buildings

Christian Gitte · Huiwen Xu · Fabian Rigoll · Joeri van Eekelen · Michael Kaisers

Abstract - Energy management on a residential level can provide supplementary load shifting flexibility for upcoming smart grids, supporting increased energy efficiency by aligning load with surplus energy generated from renewables. This paper presents results from the EIT Digital Project HEGRID, in which a multi-commodity test-bed has been evaluated in Karlsruhe, Germany. The system architecture is based on the EF-Pi framework (Energy Flexibility Platform and Interface) and integrates different energy carriers (natural gas, electricity, heat). We present the device driver architecture, user interface, simulation capabilities, and energy management through drivers of device categories. Our experiments validate this multi-commodity scenario and its components in a real device test-bed and provide lessons learned from a prototype implementation of the entire stack, thus decoupling hardware-specific devices through software drivers from energy management.

Keywords Energy Management · Hybrid Energy · Multi-Commodity · Power Generation Economics · Smart Homes

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1. Introduction

With the growing percentage of electrical energy from renewable energy sources, solutions for managing and integrating hybrid energy approaches [6, 14, 15], which utilize more than one energy source to decrease generation dependability, are becoming more and more popular in order to ensure stable and constant power supply. In this paper, we present a prototype which instead of focusing on the level of generation, puts the vision to the management and optimization of multi-commodity (electricity, gas, and thermal energy) within residential households, as introduced in related work [7, 8]. We present the results of the EIT Digital[1] HEGRID (Hybrid Energy Grid Management) which focuses on hybrid energy management on the consumer side with innovative ICT concepts.

Most other energy management systems on the market or under development consider single commodities only. Even if multi-commodity management is supported, it is usually divided into separate approaches for each commodity. For example, HomeOS [2] provides a PC-like abstraction for home technology. It provides common APIs for applications to conduct tasks involving multiple devices. Current applications developed on this system are electricity oriented and are used to implement functionality of home automation. As another approach, the Organic Smart Home (OSH) is based on the observer/controller architecture. OSH optimizes the schedule of appliances so as to minimize energy costs for residents [1]. The platform has been further developed to support multi-commodity scenarios and optimization of energy usage powered by evolutionary algorithms [7, 8]. Further work has presented an intelli-

[1] https://www.eitdigital.eu

gent home energy management algorithm for demand response applications [9]. The algorithm generates decisions for sending signals to change the appliance status by combining load priority and customers' preference settings. In essence, it implements the generation of heat and electricity by using a single commodity only (electricity) through turning on or off power switches of different appliances. A scenario, in which a general system and a mathematical model for energy management in multi-commodity energy systems are built, is available as well [10]. Its objective is to minimize the electricity exchanged with the grid connection. The closest related work to the test-bed described in this paper is another test-bed of the HEGRID project [12], which developed an optimization approach based on dynamic programming and the Energy Flexibility Platform and Interface (EF-Pi).

Parts of the following results have been compiled into internal research reports, restricted to EIT community [5, 3, 4]. In this paper, the work is published for the first time.

2. Scenario Description

In this paper, we utilize the EF-Pi framework [13] for the implementation and evaluation of a real device multi-commodity energy management scenario. EF-Pi connects energy devices to demand side management concepts. These concepts are implemented in form of so called energy apps, provided by demand side managers (e. g. energy retailers). The term app is not related to mobile apps, one could name it service, module or software package. EF-Pi acts as a middleware system for smart buildings in our scenario. The optimization scenario assumes a residential customer and an energy retailer selling gas and electricity to this customer. Our scenario comprises a multi-commodity device in form of a micro combined heat and power unit (μCHP) with additional electrical heating, as a bivalent domestic heating system. In such a scenario heat can be generated by gas or by electricity. Furthermore, heating by gas produces electricity at the same time, which may be sold back to the grid in case that electricity production exceeds demand. Demand side management is integrated in form of algorithms provided by the energy retailer's app. The optimization approach is based on static or dynamic prices for multiple commodities, provided by the retailer in the form of a real time tariff. The management algorithms have been specifically extended to support multiple commodities in order to be applicable to our scenarios.

The real device test-bed is provided by the Energy Smart Home Lab at the Karlsruhe Institute of Technology (KIT). It offers a running and testing environment for the prototype. This lab is a two bedroom apartment of 60 m^2. In addition to basic measurable and controllable household appliances, like dish washer and washing machine, the lab is also equipped with PV panels, batteries, a charging station for electric vehicles, etc. Particularly, a μCHP is also available in the lab. With natural gas fueling its Otto engine, the μCHP with a water storage of 750 liters is able to produce electricity and heat simultaneously. In order to enhance its functionality, the water storage of the μCHP is extended with an electrically driven heating coil as an alternative actuator to produce heat. As for the hardware installation, the μCHP provided by KIT's Energy Smart Home Lab, named Dachs, is a product of the German company Senertec, and the heating coil is a product of the German company Eltra. Due to the hybrid energy features, the μCHPis bivalent and plays a key role in our hybrid energy management scenario. Figure 1 represents a physical model of the μCHP. It shows the different kinds of energy transitions possible (e. g. electricity to heat). These different energy transitions reveal capabilities of the μCHP to leverage the hybrid energy potential. Furthermore, not only flows of energy but also flows of water are indicated.

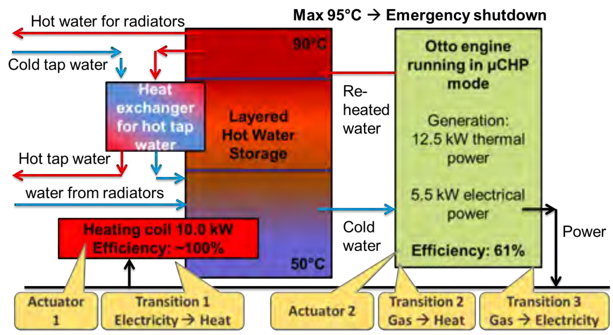

Fig. 1 The physical model of the bivalent μCHP *[4].*

Instead of directly utilizing expensive and maintenance-intensive real hardware, a simulation environment is needed in order to pre-test the performance of the optimization solutions. This simulation environment should correctly reflect the behavior of the μCHP and hybrid energy demand in the household. Therefore, the simulation environment as outlined in Figure 2 has been created, which can approximately simulate the real environment of the household in our prototype. This simulation model consists of three main parts: a μCHP simulation, an energy app, and a building model.

The μCHP driver provides the core functionality for observation and control of real μCHPs. It can not only reflect the behavior of the μCHP but is also capable of running in a simulation mode. It hides the technical

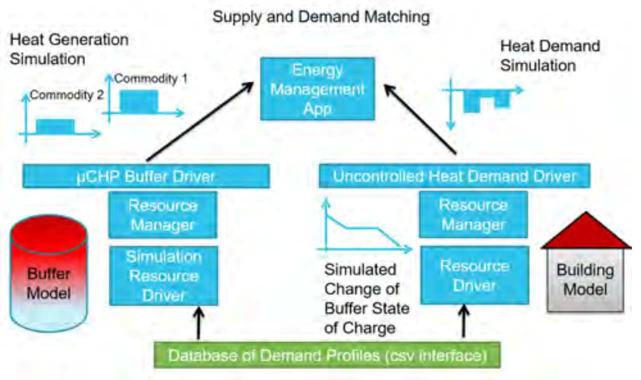

Fig. 2 The model of the simulation environment [cf. 4]: The μCHP driver represents the buffer storage. Possible generation loads are communicated to the central energy app. A building model is used for heat demand simulation, corresponding needs are communicated to the energy app. Heat and demand matching is performed by the app.

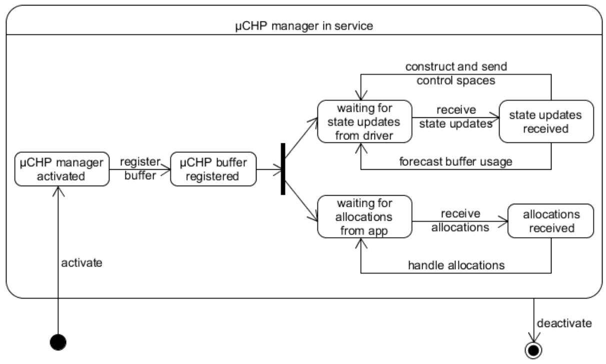

Fig. 3 The state machine diagram of the μCHP manager.

details of the μCHP and provides a common interface for energy apps. The driver stores states of the μCHP for forecasting purposes. Furthermore, it can do simple forecasts itself based on the day before.

The energy app contains an optimization component, which integrates price models and a cost model. It collects newest states periodically from the μCHP driver and receives simulated hybrid energy demand from the building model. Taking all those factors into consideration, the energy app is able to exploit energy flexibility (e. g. flexible loads or storage availability) and make optimized decisions for the selection of the best energy carrier to satisfy the demand for heat, or to intelligently control the battery.

In the simulation environment, the building model simulates the energy demand within the household. In order to make the simulation more realistic, we used demand profiles from the Energy Smart Home Lab. Based on these profiles, the building model provides simulated heat and electricity demand in the household to the energy management app during the cost-optimized hybrid energy management scenario. Note that the drivers implemented within the EF-Pi framework provide a form of categorical device abstraction. The energy app is only aware of these drivers and the communicated information of the devices through these drivers. Thus, our work investigates the practicality of such a decoupling in our implementation.

3. Implementation

The prototype is based on the EF-Pi framework, a middleware platform for smart grid integration of decentralized energy resources. Within the EF-Pi framework, an appliance's energy flexibility is expressed in a generic structure, called control space. Devices are classified according to their characteristics of offering energy flexibility, and are cast into one of four kinds of control spaces: uncontrollable, time shiftable, buffer/storage, and unconstrained. A buffer control space, which is used for the presented work, consists of buffer leakage function, fill level information, power values for the gas burner, power values for the heating coil, minimum/maximum runtimes and charging behavior profiles. By modeling all sorts of appliances in generic control spaces, energy apps can be developed against a collection of the control space categories, and without explicit knowledge about particular devices. As a response to receiving control spaces from appliances, energy apps optimize schedules of appliances and send so called allocations to the appliances. Similar to control spaces, allocations are also generic structures, generated by energy apps to interact with different appliances. Allocations respect the constraints expressed in control spaces and indicate how the energy flexibility is to be exploited [cf. 13].

As the μCHP has a water storage, it can act as a buffer to store thermal energy by heating water. The Otto engine and the heating coil, as mentioned in the last section, are two actuators that can charge the heat buffer by using different energy carriers. The driver interface of a buffer includes the state of charge of the buffer, current running mode, leakage function, actuator behaviors, and others. Furthermore, the driver collects current states of the μCHP and compiles control spaces for the energy app. It receives and translates allocations from the energy app and further passes specific instructions on to the device. Internally, the driver consists of a driver class and a manager class. The state machine diagram of the μCHP manager class is displayed in Figure 3.

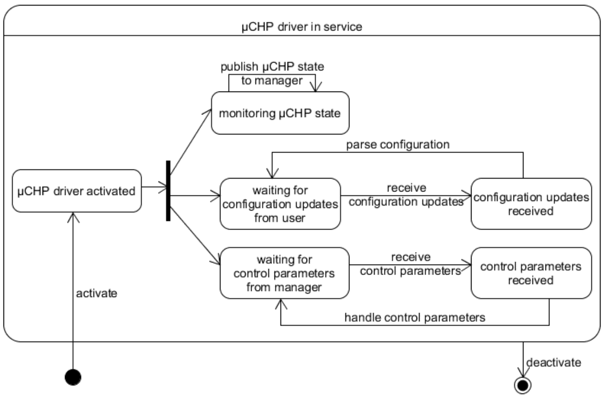

Fig. 4 The state machine diagram of the µCHP driver.

With the two aforementioned actuators (Otto engine and heating coil), the µCHP can operate in one of the following running modes:

- Idle mode
- Otto engine activated mode
- Heating coil activated mode
- Otto engine and heating coil activated mode
- Otto engine activated for legionella protection mode

With the aim of minimizing costs of procurement of energy carriers, the energy app determines the specific running mode of the µCHP. However, as a legionella protection mechanism, the device can start itself automatically if necessary. The energy app should be aware of the mode in time and adapt its optimization model accordingly.

Figure 4 shows the state machine diagram of the µCHP driver class. The specific running mode determined by the energy app is sent by the manager class as control parameters to the driver class. The driver class keeps monitoring the µCHP by periodically reporting the newest state of the device to the energy app and waiting for the target running mode from the energy app. Under the premise of satisfying the current operational constraints, e. g., the Otto engine has to run ten minutes without interruption once started up, the driver would turn to the required running mode after getting a control parameter from the manager class.

Visualization of real time device states is done via a lightweight widget-based user interface as shown in Figure 5. It presents the temperature of different parts as well as detailed real-time operational parameters of the µCHP both in reality and in simulation.

Fig. 5 The user interface of the µCHP [3].

4. Evaluation

4.1 Drivers and Simulation

The implementation of the prototype of our hybrid energy management system currently runs on an off-the-shelf x86-computer which is connected to the Home Area Network. Based on positive simulation results, testing on real hardware was promising and the drivers and observation user interface have been tested with real hardware successfully [5]. Due to the fact that all devices are off-the-shelf products, the developed prototype implementation can be considered ready for commercial utilization. The combination of simulation functionality and real hardware enables powerful hardware-in-the-loop evaluations. The EF-Pi ecosystem provides several different resource apps for the simulation of devices. Based on the hybrid scenario described and further simulated components the following results have been generated, using both simulated as well as real devices.

4.2 Energy Management and Demand Response

The energy management app observes the system state by processing the retailer tariff and messages coming from all device drivers that are present in the scenario. The retailer tariff is considered to be communicated outside the EF-Pi framework, possibly through proprietary prototcols, since our scenario foresees energy management applications to be developed by the retailers, therefore making it possible to encode any desirable tariff. In contrast, the device messages are exclusively using the EF-Pi messaging protocols. A complete system state is composed by initial device registration messages and updated over time as devices signal new information, such as control spaces or updated forecasts.

The decision problem that the energy management application faces is essentially an allocation or scheduling problem with uncertainty. The app uses the system state and available forecasts indicating demand of heat and future electricity load, and computes an allocation. In our experiments, the application receives heat and electricity demand through uncontrollable EF-Pi drivers. Similarly, the PV solar generation and its forecasts are communicated as uncontrollable. In addition, the μCHP and the battery are represented as a buffer driver. Both the μCHP and the battery have several running modes that can be controlled by allocations. The initial registration messages describe the available run modes and corresponding energy consumption and state-of-charge effects (i. e., charging or discharging the heat or battery storage). The energy management application complements the forecasts of demand with forecasts of the demand of controllable devices by projecting the energy consumption and state-of-charge effects of the current run mode into the future. If no allocations are being sent, the devices simply switch run modes according to their pre-programmed behavior. In case of the battery, it remains idle. In case of the μCHP, it switches into legionella protection mode if the temperature (communicated as state of charge in the driver) drops below a critical threshold for a certain period of time. Albeit this behavior is not known or communicated explicitly to the energy management app, the run mode specific state transitions are dependent on the state of charge and imply the default behavior.

For the purpose of the demonstration in this article, the management application preforms a heuristic optimization of the allocation problem under two external tariffs from the retailer. Both tariffs use a static gas price of 0.60 Euro/m^3, since gas can easily be stored and may thus be less likely to fluctuate, especially on the short term. In addition, the first tariff comprises a static electricity tariff of 0.22 Euro/kWh for consumption and no reimbursement of feed-in, while the second tariff employs a time-dependent dynamic price signal for both consumption and feed-in of electricity. The dynamic price signal has been derived from imbalance market data, since the purpose of energy management by the retailer is supposed to aid in the balancing of the future smart grid. More precisely, the dynamic price signal is taken from 2014 data of the Dutch imbalance market operated by TenneT [11], and rescaled to the

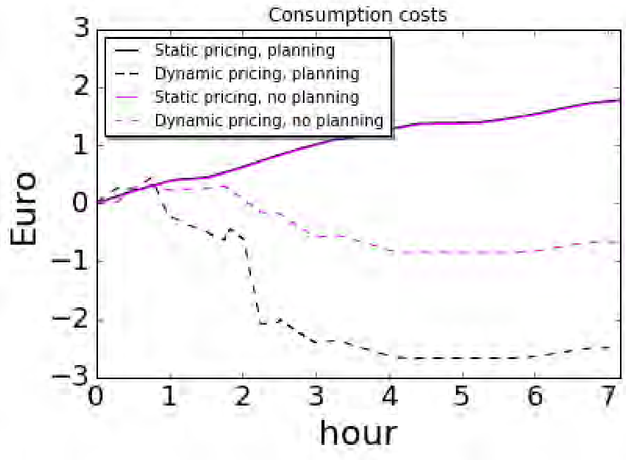

Fig. 6 *Comparison of overall consumption costs between different scenarios. Du to the feed-in tariff, overall costs could be negative (profits). Graphs for static pricing are overlapping.*

average of 22 Euro cents per kWh. In line with the imbalance market, these prices are assumed to correspond to 15 minute intervals.

The remainder of this section presents simulation results of energy management against the simulated μCHP driver, which has been validated against a real μCHP device as described in the previous section. To this end, we first present the comparison of the end-effect of energy management on costs under two energy tariffs. Subsequently, we proceed to present plots that elucidate the behavioral effect of energy management, and which explain how and when the gains have been achieved.

The empirical results comprise four scenario runs of approximately the same length. The cost comparison is depicted in Figure 6. Each label shows one of the two tariffs, which differ by and are labeled by the electricity pricing rule (static or dynamic), and either indicates planning to imply that the energy management has sent allocations, or no planning, indicating that it has only observed the system state without interference with the default behavior. Negative consumption costs indicate reimbursement for feed-in of electricity.

The first observation is that the dynamic price tariff comes out fortunate for the consumer, whether or not energy management is applied. This is largely due to the fact that feed-in in the static case has not been reimbursed. Second, energy management does not lead to significant savings under static pricing. Our experiment corresponds to a winter day, starting at 9:00, hence PV generation does not exceed demand, which eliminates the only way of saving in this scenario. However, under dynamic electricity prices, both the battery and the heating coil can be used in times of negative or very low

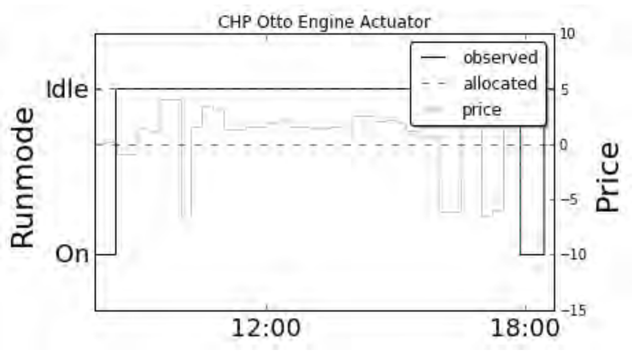

Fig. 7 Runmode changes of the μCHP's Otto engine, under intelligent management and static prices.

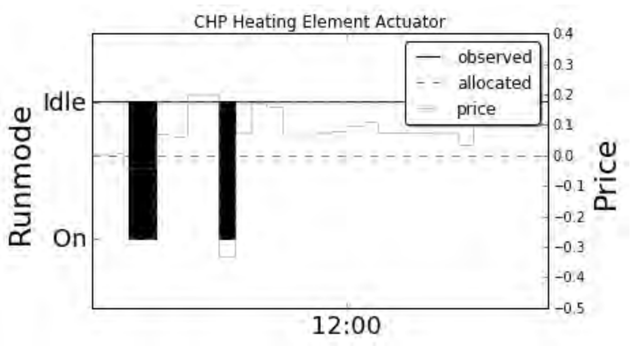

Fig. 8 Runmode changes of the μCHP's heating element, un-der intelligent management and dynamic prices. Black shaded area indicates the actual runtime.

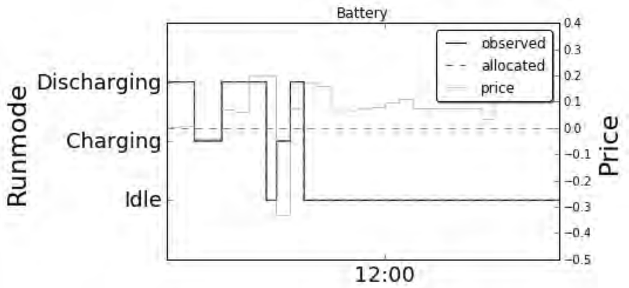

Fig. 9 Runmode changes of battery under intelligent management and dynamic prices.

prices to reduce costs. Since the cause of negative prices in the imbalance market is over-production (e. g., due to the national actual PV generation exceeding forecasted supply), the residential flexibility in this case aids the balancing of the envisioned smart grid. At the same time, the local increase of load charges the battery or the heat buffer of the μCHP and thereby prepares for later savings by deferring the time at which the heat needs to be topped up by the gas-driven Otto engine or discharging the battery to meet local electricity demand.

The demand response induced by energy management can be inspected in detail by studying the running modes over time, as allocated and observed by the energy management application. The reference scenario does not show any runmode changes for the battery or heat coil, and only shows periodical forced activation of the legionella protection for the μCHP. Since there are no incentives for demand response under static prices, the behavior is equivalent, except for μCHP run mode changes now not being forced by the device, but being allocated by the management application. The following plots therefore focus on the energy management allocations under dynamic prices, which are most illustrative. For reference, the energy price has been overlayed in gray to aid in the interpretation of the behavior.

Figure 7 shows the behavior of the μCHP's Otto engine. Since the simulation is started near the legionella protection limit of the heat buffer, the energy management initially allocates the activation of the heat buffer, and then reverts to recommending idle mode. The device has a minimum running time of 30 minutes, which has not been communicated and evaluated in the prototype implementation, which explains the discrepancy between allocation and observation following the brief activation impulse by the energy management app.

The behavior of the heat coil is shown in Figure 8. At the times of negative prices the energy management application sends and observes activation of the heat coil. In line with the hardware device's parameters, the heat coil can be cycled quickly. Due to an interaction of the messaging protocol and the hardware driver, the device must be reactivated regularly to stay in operational on mode, which explains the apparent black bar in the activation times.

Finally, Figure 9 illustrates the charging and discharging behavior of the battery. The demand response behavior follows the intuition that the battery charges in times of negative prices and discharges as soon and as long as possible thereafter.

Overall, these results show that intelligent energy management is possible through the device driver abstraction of the EF-Pi framework. The management heuristic has been able to perform cost-savings as long as profitable incentives are provided by the external tariff, here in the form of a dynamic price signal. Practical limitations of hardware control, especially regarding minimum runtimes, require careful calibration of the drivers. In addition, system state aggregation and aggregate forecasts projecting current run modes into the future are common functionalities that were implemented in our energy management application but would be a valuable part of any energy management framework.

5. Conclusion

This article provides an overview of a residential multi-commodity energy management scenario, and its prototype implementation with a decoupled stack of energy management against EF-Pi device driver categories, abstracting simulated and real hardware devices. By executing integration tests we have shown the practicality of such a driver-based decoupling of energy management and hardware control, using flexibility categories provided by EF-Pi. Potential future work may further strengthen these results with a complementary quantitative evaluation. Due to the restriction of real-time execution in the prototype, the results have so-far been of limited duration. Nonetheless, the preliminary results we obtained have shown a qualitative improvement of consumption behavior, leading to reduced costs in the evaluated multi-commodity scenario under dynamic pricing. This indicates that flexible residential customers may be incentivised to activate their flexibility if energy retailers offer innovative dynamic tariffs. Developing such tariffs and integrating them into the unified framework is an essential and promising future extension of this work.

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