Domestic energy efficiency improving algorithms

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***Abstract*—Due to increasing energy prices and the greenhouse effect more efficient electricity production is desirable, preferably based on renewable sources. In the last years, a lot of technologies have been developed to improve the efficiency of the electricity usage and supply. Next to large scale technologies such as windturbine parks, a lot of domestic technologies are developed. These domestic technologies can be divided in 1) Distributed Generation (DG), 2) Energy Storage and 3) Demand Side Load Management. Control methodologies optimizing the combination of techniques raise the potential of the individual techniques. A lot of research in done in this area. This paper outlines a number of papers and deducts the general idea. Next, a three-step optimization methodology is proposed using 1) offline local prediction, 2) offline global planning and 3) online local scheduling. The paper ends with results of simulations and a field test verifying that methodology is promising.**

Keywords: Micro-generation, Energy efficiency, Microgrid, Virtual Power Plant, Smartgrid

I. INTRODUCTION

Due to increasing energy prices and the greenhouse effect more efficient electricity production is desirable, preferably based on renewable sources. In the last years, a lot of technologies have been developed to improve the efficiency of the electricity usage and supply. One of the most eye catching technologies is generation based on renewable sources like large windturbine and photovoltaic (PV) parks. Also on domestic level a lot of technologies are in development. These technologies range from PV on roofs and micro Combined Heat and Power (microCHP) [1] upto controllable appliances [2]. The technologies can be subdivided in three groups:

- **Distributed Generation (DG)** In contrast to electricity generation in a few large power plants a growing share of the electricity is generated in smaller, geographically distributed generators. DG often has a higher efficiency or is based on renewable sources. Furthermore DG lowers transportation costs due to on-site production. The DG generators range from windparks and bio-fuel plants on a megawatt level to domestic generators. Domestic generators are generators on a kilowatt level placed in or nearby houses. The advantage of these domestic generators is that they are based on renewables sources (wind, sun) or they have a increased energy-efficiency (microCHP). These generators can produce heat and/or electricity.
- **Distributed Electricity Storage** Especially with a growing amount of renewable sources in the electricity supply chain there is a growing demand for electricity storage [3]. Sometimes electricity can be produced more efficiently (e.g. at night) or only at certain times it is not needed (e.g. wind, sun) and thus needs to be stored. Large capacity electricity storage is difficult and has high losses, so distributed electricity storage may be a solution. In the PowerRouter project hardware is developed to manage domestic electricity streams and store electricity within houses [4]. Furthermore, a large scale introduction of electrical cars adds a large storage capacity since cars are only used a couple of hours per day.
- **Demand Side Load Management** Large fluctuations in the load on the grid require fast adaptable power plants (peak plants). However, these plants are less efficient [5]. Therefore, demand side load management can increase the generation efficiency by peak shaving [6] and by shifting load to more beneficial periods [7]. Parts of an appliance (e.g. the heating element of a dryer) can be temporarily switched off or the start of an appliance can be postponed [2]. About 50% of the load in houses is dedicated to refridgerators, freezers, heaters, washing machines and dryers [8]. These appliances can be managed with only a little discomfort for the residents in contradiction to lights and a television, which cannot be switched off or shifted without discomfort. Field tests in the USA have shown that optimizations with these manageable appliances already can lead to significant peak reductions [2]. Furthermore, when residents choose for a certain level of discomfort, e.g. a deviation of 0.5°C from the settled room temperature, even more schedulingfreedom is gained. Of course there has to be an incentive for the residents to accept the reduction in comfort.

Altough these three technologies already increase the energy efficiency, cooperation between the technologies and the existing infrastructure may lead to additional benefits.

In this paper a control methodology is proposed to manage the cooperation between these technologies. The methodology is based on a three-step approach to control domestic electricity and heat demand, as well as the generation and storage of heat and electricity. First, the energy usage and therefore the optimization potential for every individual house is predicted. Next, the predictions of the individual houses are aggregated and a global planning is made. In the last step, a local scheduler in every house schedules the appliances real-time, using the global planning as an input. The basic goal of this methodology is to supply all residential heat and electricity demand without loss of comfort while optimizing the overall energy efficiency. The combination of prediction, local controllers and global controllers can be extended to a Smart Grid [9] solution, controlling central power plants, non-domestic DG, non-domestic buffers and domestic imports/exports. Taking into account the continuous development of technologies mentioned above and different combinations of them in houses, the developed method has to be generic.

To verify the quality of the methodology, a simulator has been developed and used to simulate various scenarios. Furthermore, prototypes are built to study controllability of the devices in the real world and to implement first versions of the algorithms.

The remaining of this paper is structured as follows. The next section describes the optimization potentials and methods. Section III gives an overview of the related work and ends with a general idea based on the related work. Next, section IV describes the approach following from this general idea and proposes a three-step optimization methodology. Section V describes the built prototypes and section VI describes the results of simulations and prototype tests using the optimization methodology. The last section discusses these results.

II. Optimization potential

A control methodology manages the cooperation between the domestic technologies to gain maximum optimization potential. Next to improving efficiency, optimizing the behavior of the domestic technologies can (and has to) enhance the reliablity of supply [9], [10]. The objective of such a control methodology is to optimize the electricity import and export profile of (a group of) houses. The optimization objective can differ, depending on the stakeholder of the global controller. A network operator for example prefers to optimize the reliability and stability of the grid, a utility company prefers to balance demand and generation where the government likes to optimize efficiency. Although these objectives seem to be conflicting, they all come down to peak shaving. Peaks in demand are supplied by less efficient peak power plants and should therefore be lowered. Furthermore, also fluctuations in demand are supplied by these peak power plants. So, an ideal production pattern for the power plants is a constant production. These production patterns are defined by the (residantial) demand minus the distributed generation.

Fluctuations in demand are first of all caused by the stochastic nature of demand: for example, people switch their TV on when they like to watch TV. Next, the new technologies mentioned in the previous section introduce even more fluctuations. DG based on renewable sources like sun and wind has a very fluctuating production pattern and even for a large scale introduction of microCHPs a fit-and-forget strategy is not applicable [9]. The grid is designed and built for an electricity stream from power plants to houses, the transformers can not manage large electricity flows from the low voltage to the highvoltage parts of the grid. Therefore, the locally produced electricity should be used locally, i.e. within the neighbourhood without passing a transformer. Furthermore, the introduction of electrical cars is a challenge for the current electricity supply (networks) due to their higher electricity demand. So, next to a potential of using it as extra storage capacity, the introduction of electrical cars may also introduce a threat to the stability of the grid. When a lot of cars start to charge their batteries on the same time it may cause capacity problems, so charging has to be managed and/or synchronized with (local) production.

Next to different objectives, control methodologies can have different scopes: a local scope (within the house), a group of houses e.g. a neighbourhood (microgrid) or a large scale (Virtual Power Plant). Within every scope the different optimization objectives can be used.

- **Local scope** On a local scope the import from and export into the grid can be optimized, without cooperation with other houses. Possible optimization objectives are shifting electricity demand to more beneficial periods (e.g. nights) and peak shaving. The ultimate goal can be to create an independent house, which implies no net import from or net export into the grid. A house that is physically isolated from the grid is called an islanded house. Although there is no global control, it is possible to steer the import/export up to a certain level using realtime pricing signals. However, since there is no knowledge of the individual houses on a global level, the result of the pricing signals is not known and no guarantees can be given. The advantages of a local scope is that it is relatively easy, there is no communication with a global unit (privacy) and there is no external entity deciding which appliances are switched on or off (social acceptance).
- **Microgrid** In a microgrid a group of houses together optimize their combined import from and export into the grid, optionally combined with larger scale DG (e.g. windmills). The objectives of a microgrid can also be shifting load and peak shaving with as ultimate goal islanding. Advantage of a group of houses is that their joint potential is higher than for individual houses since the load profile is more flattened (e.g. startup peaks of appliances disappear in the combined load). Furthermore, multiple microgenerators working together can supply more demand than individual microgenerators since more distribution in time of the production is possible [11]. However, for a microgrid a more complex optimization methodology is required.
- **Virtual Power Plant (VPP)** The original VPP idea is to manage a large group of micro-generators with total capacity comparable to a conventional power plant. Such a VPP can replace a power plant while it has a higher efficiency, and moreover, it is much more flexible than a normal power plant. Especially this last point is interesting to react on fluctuations or to trade on the balancing market. This original idea for VPP can of course be extended to all domestic technologies. However, for a VPP also a complex optimization methodology is required.

Furthermore, communication with every individual house is required and privacy and acceptance issues may be a social problem.

III. Related work

A lot of research about *improving energy efficiency using domestic potential* is going on at the moment. It is, in general, agreed that it is both desirable and necessary to manage DG and optimize efficiency. In [9] it is stated that a fit-and-forget introduction of domestic DG will cause stabilization problems. Furthermore, the large scale introduction of renewables requires a new grid design and management. A study of the International Energy Agency concludes that, although DG has higher capital costs than power plants, it has potential and that it is possible to supply all demand with DG with the same reliability, but with lower capacity margins [10]. This study foresees that the supply can change to decentralized generation in three steps: 1) accommodation in the current grid, 2) introduction of a decentralized system cooperating with the central system and 3) most demand is supplied by DG. However, both [9] and [10] indicate that commercial attainability and legislation are important factors for the success of the introduction of DG.

Most research projects focusses in first instance on *introducing and managing (domestic) DG*. In [12] the impact of DG on the stability of the grid itself is studied, i.e. whether the oscillatory stability of the grid and transformers can be improved with DG. Their conclusion is that is is possible to improve the stability when the generators are managed correctly. The authors of [13] conclude that it is attractive to install a microCHP based on UK energy demand data.

Next to DG, energy storage and demand side load management are also research topics. One of the options is to combine windmill with electricity storage to level out the fluctuations by predicting the production and planning the amount of electricity exported to the grid [14]. In [15] and [16] Grid Friendly Appliances are described. These appliances switch (parts of) their load off when the frequency of the grid deviates too much. This frequency deviation is a measure for the stress of the grid and therefore these appliances can shift their load to periods with lower electricity demands.

A lot of *control methodologies* for DG, energy storage, demand side load management or a combination of these are described in literature. Most of the researche propose agent based methodologies. These agent based methodologies propose an agent per device [17]. The agents give their price for energy production (switching an appliance off is seen as production); via a market principle it is decided which agents are allowed to produce. Since there are a lot of agents, the information is aggregated on different levels in a hierarchical way. The research described in [8] combines all three domestic technologies: demand side load management offers 50% of the potential. To reach this, there have to be incentives for the residents to allow some discomfort. Furthermore, both electricity and heat are considered and agents use predictions to determine their cost function. The PowerMatcher described in [18] and [19] also takes the network capacities into account. This methodology is rather mature; it is a product capable of being used in field tests [20]. In this field tests, a peak reduction of 30% is reached when a temperature deviation of one degree of the thermostat is allowed. To be able to reach objectives, bussiness agents can be added that influence the biddings. Furthermore, the authors of [21] compare the results of individual (local) and overall (global) optimizations. They conclude that global optimizations lead to better results. Next, they pretend that agent based methodologies outperform non-agent based methodologies since agent based methodologies take more (domestic) information into account.

Next to agent based methodologies, there are also *methodologies not based on agents*. The research described in [22] proposes a method that is capable to aim for different objectives. For every device a cost function is determined for both heat and electricity. Using a Non Linear Problem definition the optimal on/off switch pattern is found. The authors of [23] address the problems of both agent and non-agent based solutions: non-agent based solution are less scalable and agent based solutions need local intelligence and are not transparant. Therefore, they propose a combination: aggregate data on multiple levels, while these levels contain some intelligence. The aggregation is done with a database, the control methodology is rule based. In [24] a methodology is proposed using Stochastic Dynamic Programming (SDP). The stochastic part of the methodology considers the uncertainty in predictions and the stochastic nature of (renewable) production and demand.

Most methodologies use some sort of prediction of demand and/or production. This can be predicted rather good with neural networks, as described in [25] and [26]. The predictions follow the trend rather good.

A. General idea

As can be seen in this section, there are a lot of research project investigating energy efficiency optimizations. From the research, simulations and field tests described it can be concluded that the efficiency can be improved significantly. Especially when all three types of technologies are combined. All methodologies have split up the control into a local and a global part. Furthermore, most methodologies use prediction to adapt to the production and demand patterns and an online algorithm deciding on device level. In general two different methods are used: 1) agent based using a market principle and 2) mathematical optimization methodologies.

The methodology proposed in this paper uses three steps and is split up into a local and a global part: 1) local offline prediction, 2) global offline planning and 3) local online scheduling. Because of the scalability, the global planning has a hierarchical structure and aggregates data and plannings on different levels (neighbourhood, city, etc.). Especially the three steps and the global planning differs from the rest of methodologies described in literature. Furthermore, the methodology is not agent based and uses other mathematical optimization methods or heuristics than the methodologies described. The global planning is based on Dynamic Programming, the local controller is based on cost functions and Integer Linear Programming (ILP).

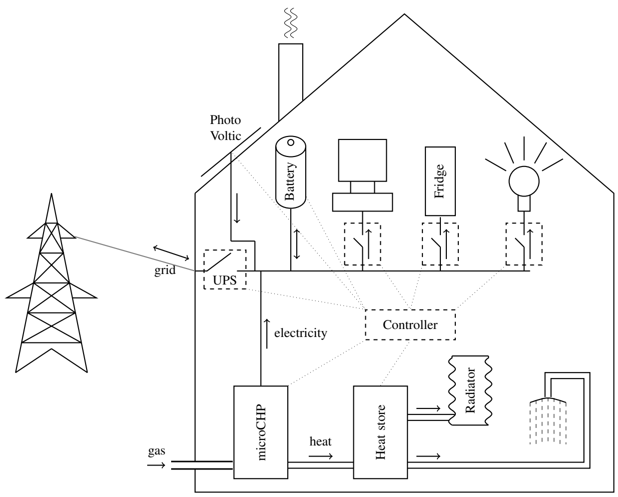


Fig. 1. Model of domestic energy streams

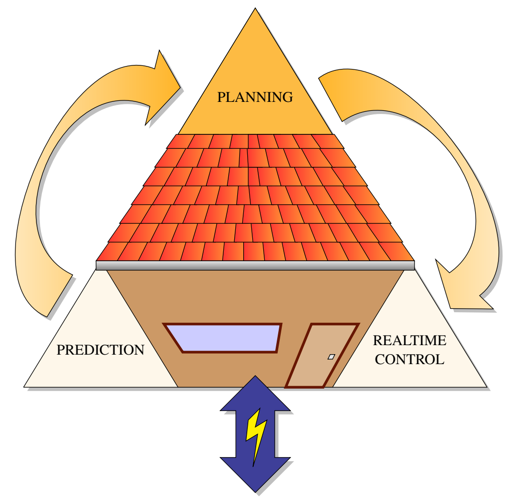


Fig. 2. Three step methododolgy

IV. Approach

Our research focuses on the development of algorithms for the control methodology. The proposed methodology is based on a three step approach: prediction, planning and realtime scheduling. The prediction and planning are offline, i.e. on beforehand a prediction and planning for a longer period are determined (e.g. a day), where the scheduling is online. This is discussed in more detail in Subsection IV-B. These algorithms have to be very flexible since there are different house configurations (type of microgenerator, buffer size, etc.), there are multiple optimization objectives and there are multiple scopes possible. The development and verification of the algorithms is split up in three steps.

1) **Algorithm development** The first step is to develop the required algorithms. These algorithms are based on analysis of the current situations, objectives, possible scopes and observations of the real-world systems and data.
2) **Simulations** These algorithms are verified with our self-built simulator [27]. This simulator can use real-world data to simulate multiple houses and verify the algorithms that decide when to start/stop the microCHP, how much electricity flows from/to the battery, how much electricity is imported/exported from the grid and which appliances to supply. With the simulations of the algorithms the optimization results are verified, e.g. it can be simulated whether it is possible to decrease the peak imports from the grid.
3) **Field tests** The third step is to develop prototypes. With these prototypes it is examined wether the algorithms are also applicable in real world situations. Furthermore, it is verified whether the stated assumptions are valid.

The current developed algorithms are flexible enough to cope with different house configurations, levels of control and optimization objectives.

A. Model

The model of a single house is shown in Fig. 1. Every house consists of (several) micro-generators, heat and electricity buffers, appliances and a local controller. Multiple houses are combined into a grid, exchanging electricity and information between the houses.

Electricity can be imported from and exported into the grid. Heat is produced, stored and used only within the house. All domestic heat and electricity devices are divided into three groups:

- **Producers** produce electricity and/or heat. All available micro-generators are modelled in this way, considering that the generation can be zero or even negative. A microCHP device produces electricity and heat, a Photo Voltaic produces only electricity where a conventional electric heater generates heat with a negative electricity production.
- **Buffers** store electricity and/or heat. When there is more energy production than consumption (and export) there is a surplus that flows into (one of) the buffers. A shortage (more consumption than production and import) flows out of (one of) the buffers.
- **Consumers** can consume electricity and/or heat. All consumers are modelled within this group, from fridges and coffeemakers to central heating and hot tapwater.

Every producer, buffer and consumer is called a device. Heat and electricity production can be coupled on device level. For example some producers produce heat and electricity at the same time, hence production of heat and electricity are coupled. A microCHP does either produce heat and electricity or nothing at all. The same holds for consuming devices, e.g. a hotfill washing machine. A more detailed description of the model can be found in [28].

Within the model, the planning horizon is discretisized resulting in a set of consecutive time intervals. The number of intervals depends on the length of the planning horizon and the length of the intervals.

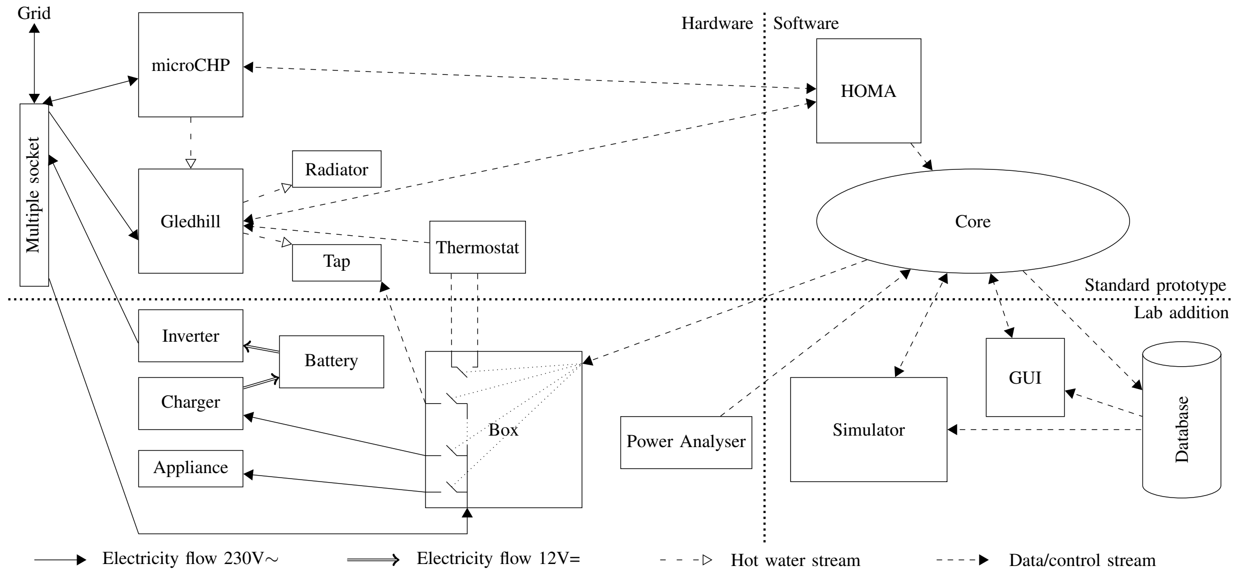


Fig. 3. Schematic of the software

B. Methodology

The goal of the local energy management methodology is to make a generic solution for different (future) domestic technologies and house configurations. Furthermore, multiple objectives are possible and the scope of the methodology can differ. That is, the methodology needs to be very flexible and generic. Since there can be global objectives (VPP) and the actual control of devices is on domestic level both a global and a local control are needed.

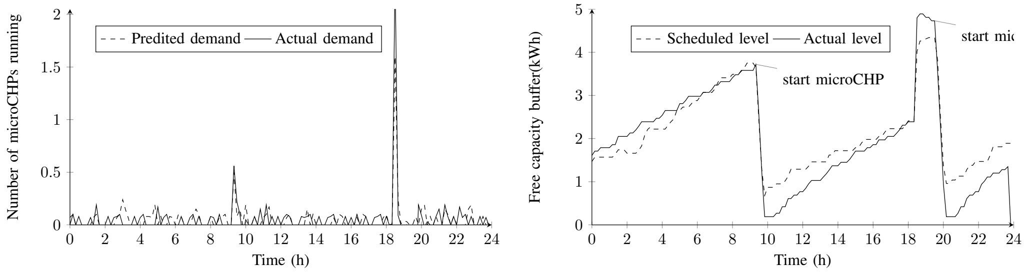
The primary functionality is to control the domestic generation and buffering technologies in such a way that they are used properly and the required heat and electricity supply is guaranteed for the house owners. The scheduling freedom of the domestic devices within these constraints can be used for optimizations. More scheduling freedom can be gained when residents are willing to decrease their comfort level. For example by accepting a temperature interval instead of a fixed temperature (scheduling freedom in heat production) or by accepting a deadline on the finish time of a washing machine instead of an exact starttime. This (small) decrease in comfort should lead to some benefits for the residents, e.g. a reduced electricity bill.

Summarising, a list of requirements for the energy management methodology is:

1) **Multiple scenarios** with **different objectives** and costs for specific devices are possible.
2) **Both a local and global controller** cooperating by responding on steering signals and send status information.
3) **Guaranteed comfort level** chosen by the resident, given the incentives.
4) **Both heat and electricity** are considered and coupled to include combined heat/electricity producers and consumers.
5) **Offline prediction and planning** to forecast net demand on beforehand.
6) **Online scheduling** possibilities for instantaneous matching of supply and demand and to respond on steering signals.
7) **Device-level** cost functions should include present and future technologies.

The proposed management methodology is divided into three steps and there is a local (within the house) and a global (combining multiple houses) part. This three-step approach is shown in Figure 2 The three steps of the methodology are:

1) **Local offline prediction** In the first step a prediction of the energy demand and production must be done for each house. This local information is necessary to decide the local production potential of the microgenerators, buffers and appliances. A neural network approach is used for this prediction [26] When the scope is not local, this information is sent to a global controller for the second step.
2) **Global offline planning** In the second step the local potential is assigned to actual plannings, based on local (domestic) and global (VPP) objectives. The planning process for only microCHPs is known to be NP-complete in the strong sense [29]. Therefore, heuristics are used for the planning. These global controllers have a hierarchical structure, they aggregate the data and optional the sends it to a higher scope controller. The global controllers determine a planning based on the information they receive (from local controllers or from lower scope global controllers) and send this information back.
3) **Local Realtime control** The last step is a local controller for online scheduling, i.e. it decides which appliances are switched on/off, etc. Whereas the first two steps can be done ofine, the devices need to be (online) controlled realtime too. In this realtime control the runs of individual microgenerators need to be (re)scheduled, if the reality differs too much from the prediction. The



(a) Predicted and actual heat demand

(b) Planned and actual buffer level

Fig. 4. Results lab tests planning and scheduling of a microCHP

local controller has no knowledge of the global state but can react on steering signals from a global controller (based on the planning). An description of the used realtime control algorithm can be found in [30].

V. Prototype

For the field tests we have two different types of prototypes, one installation in a laboratory and multiple installations in regular houses replacing the conventional heat supply. The methodologies are first tested on the laboratory installation (a real test environtment) and next they are implemented on the installations in houses.

A. Hardware prototype

The basis of the testbed is a Whispergen[31] microCHP in combination with a Gledhill[32] heatstore. The Whispergen is a Stirling engine based microCHP producing both heat and electricity. The electricity is led back to the domestic electricity infrastructure and therefore to the grid, the heat is stored in the Gledhill. The Gledhill supplies all heat demand, both for central heating and hot water taps.

In a normal situation the boiler starts when the hot water flow starts or when the thermostat gives a signal for space heating demand. Since the heat demand is supplied by the Gledhill, an extra signal is required to signal the Whispergen when it has to produce heat (e.g. when the level in the Gledhill is low). A controller giving this signal is built in the Gledhill.

HOMA Software B.V. developed monitoring and managing software that communicates with the Whispergen and Gledhill. This software logs on minute base the status of the installation. Furthermore, the software can send a request to switch on or off the Whispergen. However, the controller built in the Gledhill decides whether the request can be honored or not.

This basis testbed is installed both in normal houses and in the laboratory. In the houses it replaces the conventional installation, in the laboratory some additional hard- and software is added.

1) Additional hardware laboratory: In the laboratory configuration the Gledhill is connected to one radiator and a hot water tap. The radiator is represented by a forced heat-exchanger on the roof of the test building.

A computer controlled relay card with eight relays is used to switch on/off appliances and to generate the thermostat signal. Six relays are connected with outlets and switch the supply to the outlets on or off. The seventh relay is used to open and close a hot water tap valve and the last relay is used for the thermostat signal of the gledhill. We used a power analyzer to measure voltage, current, real and reactive load at once. This power analyzer can be connected to the PC via RS-232, so the measurement values can be logged.

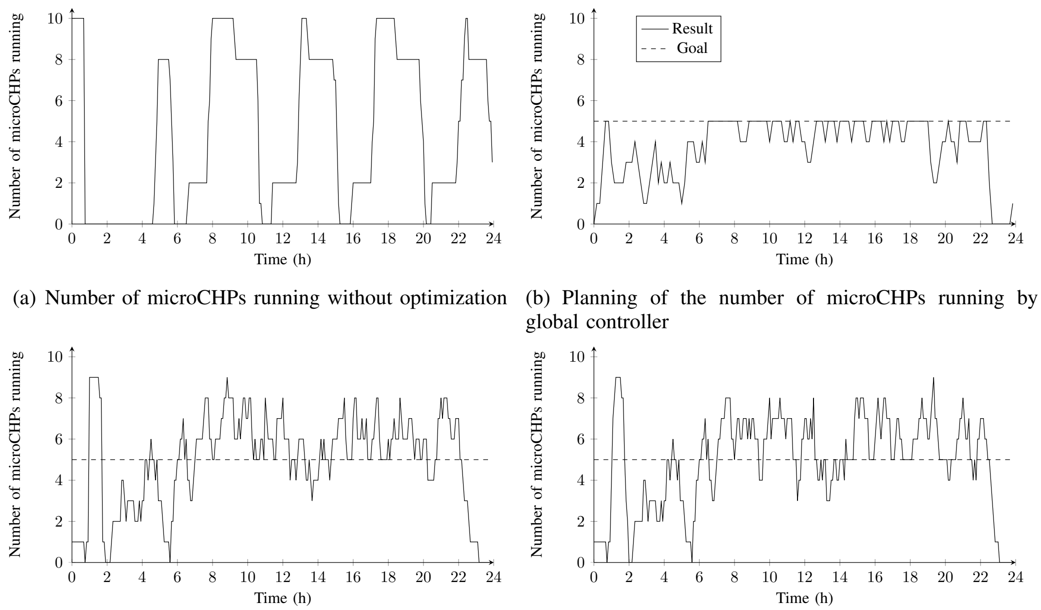
All parts of the testbed can be connected with each other with normal 230V plugs and outlets; a normal multiple socket connects all parts together.

There are two important requirements for the battery equipment:

- **Charge and discharge the battery** - the battery must be charged in case of surplus and discharged to supply shortage
- **Stabilize the 230V/50Hz**

Battery solutions exist for both separate requirements, but as far as we know there is no battery solution commercially available that can stabilize the 230V/50Hz while it is charging the battery. However, it should be possible to develop such a device. At the moment we are working together with a Dutch company that has experience with battery solutions on the development of such a battery solution. Until this solution is finished we use a battery, an inverter and a charger. The inverter inverts the 12V= from the battery to the 230V/50Hz, supplies the shortage and stabilizes the 230V/50Hz. The converter charges the battery with the surplus. With this solution the stabilization requirement is met and the battery can be charged. To prevent that the battery is continuously charged, even when there is no electricity surplus, the charger is connected to one of the controlled outlets. Disadvantage of this setup is that it is only possible to charge 360W or nothing at all. However, an electricity surplus can occur when the microCHP is running and there is a low demand.

To test the control algorithm, the islanded situation can also be emulated by connecting the prototype to the electricity grid. The amount of electricity flowing from or into the grid is the amount that should flow from or into the battery during islanded operation. In software a battery is simulated with as input this measured electricity flow, using the KiBaM battery model [33].



(a) Number of microCHPs running without optimization

(b) Planning of the number of microCHPs running by global controller

(c) Number of microCHPs running with optimization and correct heat prediction

(d) Number of microCHPs running with optimization and incorrect, realistic heat predictions

Fig. 5. Results simulation interaction local and global controller

B. Software prototype - Integration

The hardware prototype is controlled via software. This software consists of two parts for the laboratory prototype. One is the interface to all appliances (core) and the other part is for the simulations (simulation). These two parts are connected via TCP/IP to allow them to run on different computers. Furthermore, a GUI in Python is built that can connect to the core to monitor the current situation and give commands manually (switch on/off appliances, the Whispergen and the heat demand). A schematic representation of the hard- and software is given in Figure 3.

The core part of the software delivers an interface to the hardware for other programs. It can open/close the relays and can therefore manage appliances, the hot water tap valve, the central heating demand and the thermostat signal. Furthermore, it reads the values of the power analyzer every second. Finally, it connects to HOMA software, determines the status of the Gledhill/Whispergen every minute and can send requests to start/stop the Whispergen. All read information is stored into a database.

The simulation part of the software can simulate a house by switching on/off appliances and by managing the heat demand (via the core). Furthermore, the controlling algorithms are implemented in this part of the software. Information about the current and previous states required for the predictions can be queried from the core. The prediction information can be sent to a global controller via a TCP/IP connection. The local scheduler receives steering signals in the same way, can query the core for the status of the installation and can start/stop devices using the interface of the core.

A simplified combination of the core and simulation part of the software is implemented for the prototypes in the house.

VI. Results

Two different scenarios are used to verify the methodology: one field test (in the lab) using a global scope and a simulation of a global scope objective.

A. Local scope

The lab installation is used to verify whether it is possible to create a planning for an microCHP and also actually switch on/off the appliance on the preferred times. A fixed heat profile is used, i.e. the heat demand is simular for every day. Therefore, the heat demand of the previous day is used as prediction. Next, a planning is determined using a Dynamic Programming methodology. The objective for this planning is to prevent short runs (wearing of the machine) and to shift production as much as possible to daylight hours (nuisance). The planning is used as input for the schedulings algorithm. The predicted and actual heat demand are given in Figure 4(a), the planned and actual free capacity (inverse of the level) in the Gledhill is given in Figure 4(b). The runtime of the microCHP can be deducted from the free capacity, when the free capacity decreases the microCHP is running.

As aspected, the predicted heat demand is similar to the actual heat demand. Based on this rather good prediction, a planning is determined. This planned and actual free capacity are also similar and, more important, the planned and actual runtimes of the microCHP are equal. Furthermore, the microCHP is switched on by the scheduler, as can be seen since it was not required to switch on the microCHP due to the buffer level at $t = 9.3$. So, the models and assumptions are accurate enough to determine a planning and it is possible to control the microCHP.

B. Global scope

In the global scope simulation ten houses with the described microCHP installation are simulated. On a local scope the heat demand is predicted, based on this information a planning is determined and the local scheduler receives steering signals based on this planning. Two different scenarios are simulated. In the first case, the predicted demand is perfect and thus equal to the actual heat usage. In this case, the actual schedule should be similar to the offline schedule. In the second case, the predicted demand is used. Figure 5 shows the results of both the optimal offline schedule and the results of the simulation in realtime with and without steering signals.

The results show a clear difference between the results with and without steering signals. The simulated results are not equal to the planning of the global controller; the steering signals have to be tweaked. However, the communication between the local and global controller works fine. Another interesting point is the small difference between the simulations with correct and incorrect heat usage predictons. A large group levels out these individual deviations. This is why energy distributors use a limited number of average profiles for their predictions. It seems that ten houses already level out deviations up to a certain level.

VII. Acknowledgments

This research is conducted within the Islanded House project supported by E.ON UK.

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