Coordinating Smart Homes in Microgrids: A Quantification of Benefits

Matthias Huber
Technische Universität München
matthias.huber@tum.de

Florian Sänger
Technische Universität München
f.saenger@tum.de

Thomas Hamacher
Technische Universität München
thomas.hamacher@tum.de

***Abstract*—A growing number of households are seeking energy autonomy and economic benefits by installing micro-CHP and PV generators, as well as battery storage units in their so-called smart homes. An option to further increase benefits, is to install a community microgrid and coordinate smart homes intelligently. To quantify this increase, we apply numerical simulations using real-world data for household loads in a temporal resolution of 15-minutes. In systems consisting of CHP-units, the degree of electricity autonomy rises from 50 % to 80 % through installing a microgrid, allowing lucrative CHP operation. In PV-based systems, the benefits are fewer and if battery storage is installed additionally, they almost disappear completely. As a consequence, intelligently managed microgrids are as valuable option for the integration of microgeneration as long as decentralized battery storage is not profitable and thus not employed.**

***Index Terms*—Smart Grid, Microgeneration, PV, CHP, Microgrids**

I. INTRODUCTION

SEVERAL scientific authors and government institutions (see [1] and [2], among others) have argued for a decentralized and smarter supply of heat and power by microgeneration units. Reasons for this paradigm shift away from large central supply include environmental, reliability, cost and efficiency advantages, as well as the costumers' positive attitudes towards energy autonomy. The most important systems for residential heat and power supply are photovoltaic (PV) and small scale combined heat and power plants (CHP). The generation technologies can additionally be supported by a battery storage system or by an electric heater. Fig. 1 shows potential system configurations in so-called smart homes.

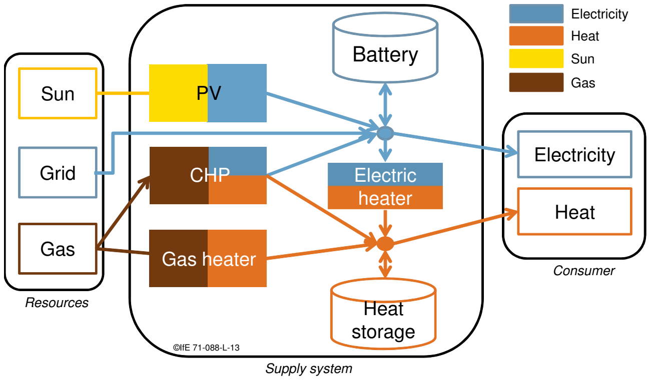

Fig. 1. Possible system components for residential heat and power supply in an individual smart home

A great deal of research has been done in the field of cost optimal scheduling of generation and storage units of smart homes. Cost-optimization mostly leads to minimal electricity consumption from the utility power grid. A huge variety of algorithms have been developed using e.g. dynamic programming [3] or particle swarm optimization [4].

In addition to this research on smart homes, more and more research is going on in the field of microgrids. Microgrids are often defined as regionally limited energy systems which can be run in on-grid or off-grid mode [5]. In [6] and [7], microgrids are defined as a "conglomeration of small generators and loads that operate as a coherent system and connect to a wider grid as a single point load". We adopt the latter definition and focus our research on grid connected microgrids that are not able to run in off-grid mode.

Research in the field of microgrid also focuses on algorithms to determine optimal scheduling of distributed resources, as e.g. a mixed integer unit commitment problem (MIP) [8] or complicate algorithms such as multi-objective chaos optimization [9]. In our paper, we apply an MIP algorithm to investigate whether the primary benefits of distributed generation (as described above) can be increased by installing micrgrids or whether advantages are low and individually operating smart homes are the better choice. We focus on one particular advantage of microgrids: the possibility of an intelligent sharing of resources scheduled by a decentralized Energy Management System (EMS), which is able to ideally schedule all generation and storage resources in the microgrid.

For this analysis, we compare the performance of 20 individually optimized operating smart homes vs. a microgrid consisting of the same 20 homes equipped with the same distributed generation and storage technologies. Fig. 2 shows the basic scenario without microgrid (a) as well as two different microgrid configurations (b,c) that are evaluated. Evaluation measures are the degree of electricity autonomy as well as the costs for energy supply.

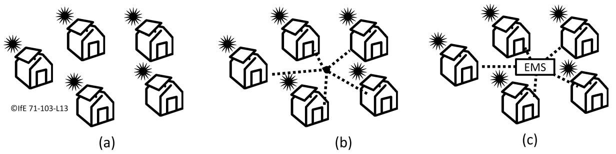

Fig. 2. Evaluated concepts: (a) smart homes are optimized individually, (b) smart homes are optimized individually but uncontrolled power exchange reduces consumption from the utility grid, (c) scheduling of distributed resources is coordinated by an energy management system (EMS)

II. MODEL FORMULATION

We model the generation of the CHP plants, heaters, and storage systems as a unit commitment and economic dispatch problem according to [10], which includes the binary state of the individual CHP plants. In this regard, we consider the production and consumption of electricity and heat in a temporal resolution of 15 minutes. We differentiate between three different system configurations according to Fig. 2. The first approach does not consider any connection between the individual smart homes, such that each smart home is independently scheduled. This leads to a cost minimization problem with variable generation costs $c_{z,v}^{var}(t)$ and start-up costs for CHP units $c_{z,v}^{up}(t)$ in every home v and each generation unit (PV, CHP, heater, electric heater) z:

$$\min c = \min \sum_{z,v,t} [c_{z,v}^{var}(t) + c_{z,v}^{up}(t)] \tag{1}$$

Furthermore, the power supply from generators $p_{z,v}(t)$, storage $p_{s,v}(t)$, and the utility grid $g_v(t)$ has to meet demand $\delta_v(t)$ according to equation 2:

$$\sum_z p_{z,v}(t) + \sum_s p_{s,v}(t) + g_v(t) \geq \delta_v(t) \tag{2}$$

The heat supply from generators $h_{z,v}(t)$ and storage $s_{z,v}$ has to meet heat demand $\zeta_v(t)$:

$$\sum_z h_{z,v}(t) + \sum_s h_{s,v}(t) \geq \zeta_v(t) \tag{3}$$

In the second approach, smart homes are connected but not coordinated. This leads to the same optimization problem as above; however, uncontrolled load and generation-leveling effects are examined in a post-processing calculation which determines the total consumption of electricity from the utility Grid: $G(t) = \sum_v g(v)$.

In a third approach, all smart homes are aggregated and coordinated by an energy management system (EMS) as depicted in Fig. 2 (c). Therefore, electric power exchange in the microgrid $f_{v,n_v}(t)$ from home v to its neighbor n_v has to be considered additionally, transforming equation (2) into equation (4). We thereby assume a fully meshed microgrid without any capacity constraints.

$$\sum_z p_{z,v}(t) + \sum_s p_{s,v} + g_v(t) + \sum_{n_v} f_{v,n_v}(t) \geq \delta_v(t) \tag{4}$$

Additional constraints consider electric and heat storage operation, start-up constraints, heat to power relation of the CHP units, as well as their minimum power output as described in [10]. The model is implemented in GAMS and solved with XPRESS.

III. DATA

The input data consists of real world time series for electricity consumption in 20 homes measured by smart meters from EON with a temporal resolution of 15 minutes (location: Altdorf, 49.39°N, 11.36°E). PV generation is modeled by [11] with time series provided by NASA [12]. The same database is used to simulate heat load with the software package TRNSYS. Required input data are irradiation, temperature, and wind speeds. The annual heat consumption was calculated to 26.000 kWh/a. All time series are synchronized values from 01.05.2009 to 30.04.2010. In Fig. 3, the leveling effect of these 20 homes is illustrated. The figure shows 20 individual load profiles for a sample week as well as the mean of those 20 samples. The leveling effect significantly reduces the peak loads from more than 6 kW in individual consumers down to less than 2 kW in average of all consumers for this week. This allows the CHP units, which have a rated power of 1 kW, to produce a high share of the electricity consumption in the community.

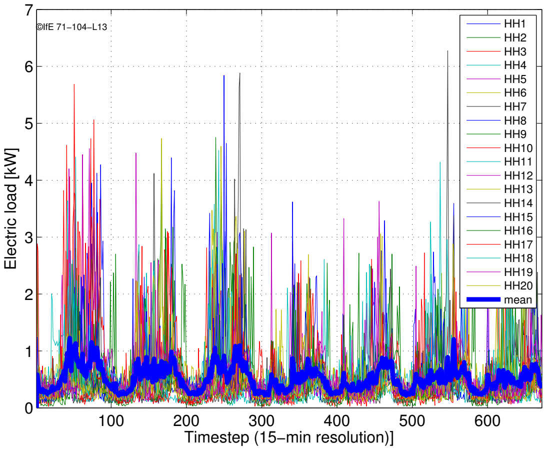

Fig. 3. Load leveling: 20 individual homes vs. their mean load over a randomly selected week.

We present an analysis of a microgrid consisting of 20 smart homes. The question about the influence of the microgrid size arises. An indicator for the effectiveness of the microgrid is the average peak load of the system. Fig. 4 illustrates the average peak load of the microgrid depending on the homes included. Beginning with around 7-10 homes, a saturation is reached. We assume that the benefits of the microgrid will only slightly increase with larger sizes from that on.

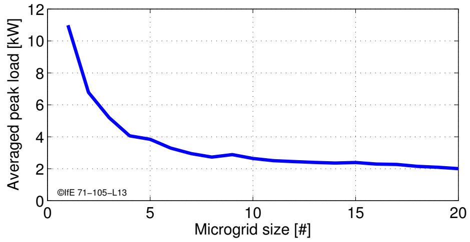

Fig. 4. Averaged peak load over network size

In order to perform simulations, further parameters concerning the employed technologies are necessary. Table I lists the major techno-economic parameters of the system components. The CHP unit has an internal combustion engine

(ICE), the price includes the complete system including a peak load boiler. The efficiency values are used in the simulations whereas cost assumptions are used to calculate economic benefits afterward. The utility price for electricity is set to 0.27 ct/kWh and to 0.07 ct/kWh for gas. Excess energy that is fed to the utility grid is not paid and no kind of subsidies are considered. CHPs are only allowed to operate if the complete heat can be used.

TABLE I

TECHNO-ECONOMIC PARAMETER ASSUMPTIONS. THE DEPRECIATION PERIOD IS 20 YEARS, INTEREST RATE IS 5 % FOR ALL TECHNOLOGIES.

Technology	Investment Costs	Efficiency
Boiler	9.000 €	99 %
CHP (1 kW_{el}, 2.5 kW_{th})	17.000 €	65 % th, 25 % el
PV	1800 €/kW	100 %
Battery	1000 €/kWh	90 % (complete cycle)
Electric heater (5 kW)	700 €	100 %

IV. SCENARIO RESULTS

In this chapter, we quantify the positive effects of a community microgrid. The analyzed smart home systems consist of the components depicted in Fig. 2, i.e. CHP, PV, battery, electric heater. The exact system composition is varied in scenarios.

The effectiveness of the microgrid and the EMS is measured by the degree of electricity autonomy and the economics of the system. We define the degree of autonomy as the share of the consumed electricity that is produced decentralized in smart homes. Environmental impacts are not evaluated as they depend on the uncertain specific CO_2-emissions of the electricity mix that a utility provides. As the decentralized system is based on either renewable or highly efficient generation technologies and grid losses are small, overall emissions are assumed to be lower with a higher degree of autonomy.

A. *Electricity autonomy*

Our first analysis investigates the impact of PV_{peak} power on the degree of electricity autonomy in separated vs. connected smart homes. In scenarios, the installed PV capacity is increased from 1 up to 10 kW_{peak} on each smart home. All three options from Fig. 2 are simulated and analyzed. The blue lines in Fig. 5 illustrate the simulation results for the PV only scenarios. An EMS does not have any influence as there are no components that are actively controlled. Thus, the connection of the systems alone (see Fig. 2 b) increases the degree of autonomy through load leveling effects. The greatest improvement from installing a microgrid is observed in a system with 2 kW_{peak} on every rooftop. The disconnected systems achieve only 25 %, whereas 31 % can be achieved in the connected ones. If 3 kWh batteries are installed in every home (red lines in Fig. 5), the EMS can be used to intelligently control all batteries as a bulk. Again, the largest advantages can be realized with 2 kW PV systems, but they are low in systems with batteries. The connection of smart homes alone allows to increase the degree of autonomy from 37 % to 38 %, using an EMS slightly further increases the value to 39 %. Summarized up, the connection of several smart homes has positive effects on the PV integration but an EMS is not required. Individual scheduling of batteries leads to almost the same degree of electricity autonomy as could be realized in an EMS controlled microgrid.

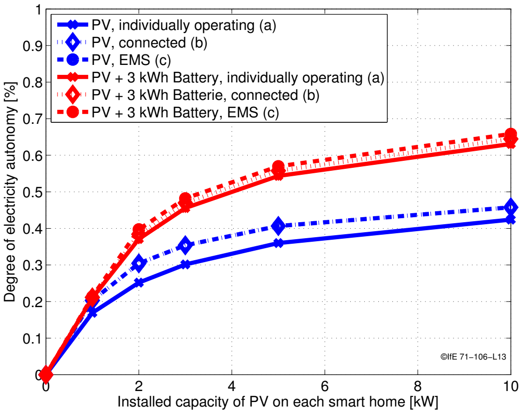

Fig. 5. Degree of autonomy achieved with PV or PV+Battery systems

The influence of the microgrid and especially of the EMS is much higher if CHP units are employed, as depicted in Fig. 6. Here, the EMS plays a crucial role: it can decide when to start and stop which CHP unit in the system. An increase in the degree of autonomy from 50 % with individual optimization to 80 % in an EMS controlled microgrid for systems without PV is observed. In an uncontrolled microgrid (b), only 64 % can be achieved. An almost complete autonomy can be achieved with CHPs and around 3 kW_{peak} PV on every rooftop. Again if battery storage is employed, the advantage of the microgrid system decreases dramatically. In large continental scale power systems, this phenomena is known as the grid vs. storage competition [13]. Our results indicate that it is also relevant for small, community scale power systems.

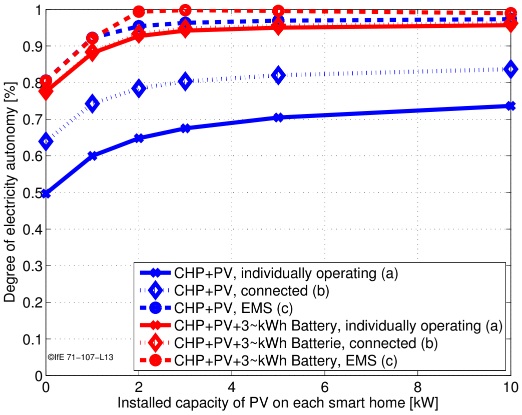

Fig. 6. Degree of autonomy achieved with CHP+PV or CHP+PV+battery systems

The reason for the positive effect of an EMS controlled microgrid consisting of small CHP units is illustrated in Fig. 7.

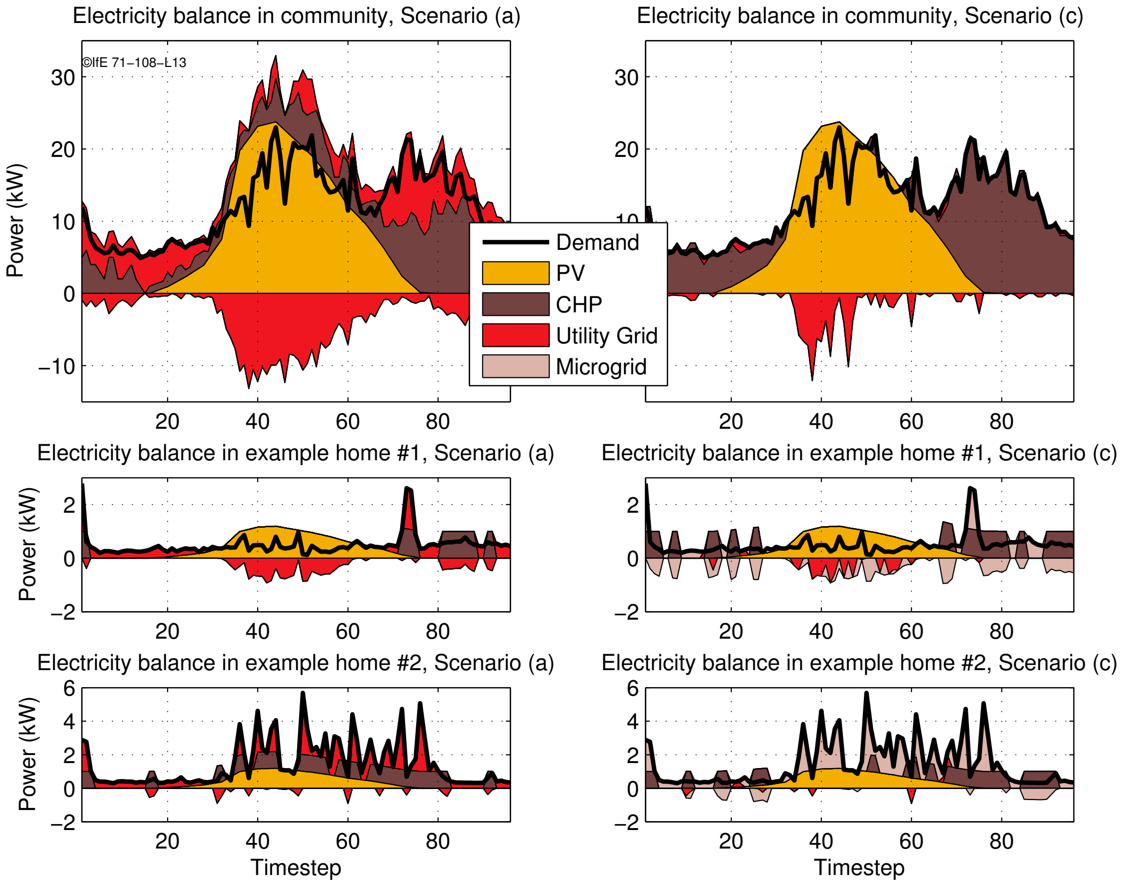

Fig. 7. Supply of electricity load in 15 min resolution. The upper two figures show the complete community, below are two examples for individual homes at the same timeframe. The figure left illustrate the situation without microgrid, the right one shows the situation if an EMC controlled microgrid is setup.

The left upper part shows the aggregated electricity generation and consumption of the 20 individually optimized smart homes for a typical day. The systems consist of a 1 kW CHP unit and 2 $\mathrm{kW_{peak}}$ PV on every rooftop. The red colored area represents the electricity that is bought from and sold (with a price of 0 in this case) to the utility grid. In many time-steps, the community buys and sells electricity at the same time. In contrast, if an EMS is used (upper right part), the excess energy of one generator can be used to supply other loads. Only excess from high PV generation that cannot be integrated in any of the smart homes is fed to the utility grid.

The annual full load hours of the CHP units increases from 2512 to 3270 (in the scenario without any PV, they increase from 3169 to 4030 hours). Without the microgrid, electricity load is often to low for profitable CHP operation in individual homes. In Fig. 7, exemplary operational schemes of individual CHPs are illustrated below the aggregated generation for both scenarios (left: individually optimized, right: EMS controlled). In home # 1, more energy from CHP can be produced if an EMS controls the generation. The overproduction in respective time-steps can be used somewhere else in the microgrid (rose colored area). In home # 2, production is not increased over the day but shifted from daytime to afternoon and night hours. Without an EMS (left), CHP power is produced during lunchtime as load is very high in home # 2 even if PV power is enough to supply the community.

B. *Economics*

Our first analysis concerning the economics of the system focuses on PV-based systems. Three different configurations are investigated: PV alone, PV+batteries, PV+electric heaters. All options are simulated with and without an EMS controlled microgrid. The results are depicted in Fig. 8. Several deductions can be drawn from these simulations:

- In a PV-alone system, the microgrid can improve the economic situation significantly.
- A 2 kW PV-System is profitable without any subsidies.
- Electric heaters are, concerning profits, a better solution to use excess electricity than battery storage.
- Storage is not yet an economic solution. Sensitivity analysis showed that storage costs have to fall below 500 €/kWh.
- If storage is applied, advantages of microgrids diminish.

In a second step, CHP units are included in the system. The strong increase in the operating hours of CHP units through an EMS is also reflected in the economics of the

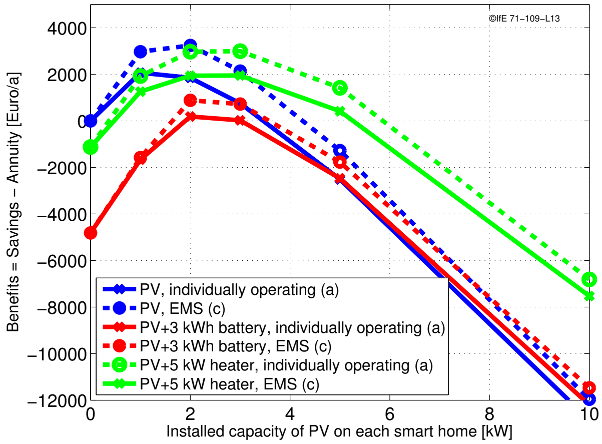

Fig. 8. Comparisons of economics of different system setups with and without an microgrid

systems as illustrated in Fig. 9. Without the EMS, CHPs are not profitable at all. CHPs alone, CHPs with PV, batteries or electric heaters, all systems have negative profit. In the EMS controlled microgrid however, the profitability increases dramatically and reaches positive value. To summarize the findings concerning systems with CHPs, we state:

- CHP units are only profitable if operated in a microgrid.
- Electric heaters are better than batteries but CHPs alone (or combined with PV) operating in a microgrid are the most profitable solution.
- Batteries are not profitable for fostering CHP integration.
- Again, advantages of microgrids diminish if storage is applied.

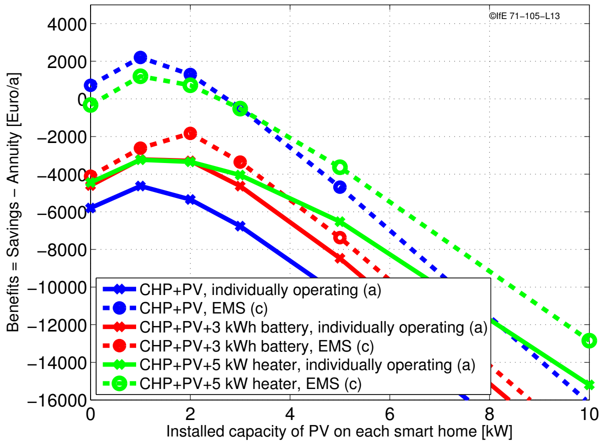

Fig. 9. Comparisons of economics of different system setups with and without an microgrid

V. CONCLUSIONS

Our numerical studies analyze the benefits of microgrids compared to individually operated smart homes. A major finding is that microgrids can increase the degree of electricity autonomy of a community as well as the profitability of microgeneration. The magnitude of positive effects depends strongly on the system configuration. The greatest effects can be achieved if small-scale CHP units are installed in every home. In such a system, the EMS can decide when to start which unit in the microgrid. This leads to an increase from 50 % to 80 % in the degree of the community's electricity autonomy and to more operational hours of CHPs. As a consequence, the dramatic increase of economic benefits renders the systems profitable. In systems with PV generation, the increase in autonomy is around 5 %(e.g., from 25 % to 30 % for 2 kW PV generators or from 30 % to 35 % for 3 kW PV generators). Nevertheless, this leads to a great increase of profit from 2000 to 3000 €/kW for a microgrid with 2 kW PV systems on every rooftop. Here, an EMS is not required; the stochastic leveling of generation and demand at the single load point from the microgrid to the utility grid is sufficient to realize benefits. This subsidy-free profit of PV systems can be further increased by installing electric heaters that use excess electricity for hot water and heating. Advantages of microgrids diminish if batteries are installed in many smart homes. As batteries are far from being profitable, microgrids seem to be an valuable option to foster microgeneration for many different system configurations in the near future.

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