SMART STABILITY – MARKET-ECONOMIC INTERACTION OF SMART HOMES FOR IMPROVED POWER NETWORK STABILITY

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ABSTRACT

In this article, the "SmartStability" concept is introduced and first results are shown. The concept is based on the exchange of electrical energy within a network of households that possess temporal flexibilities in consuming or providing energy from or to the network. The exchange is governed by a market-economic negotiation principle between the households.

Temporal flexibility is achieved by exploiting thermal capacities of the buildings themselves and those of warm water storages, and by allowing certain temperature bands. Electric and thermal energy forms are coupled by means of heat pumps and electric water boilers. The physical energy exchange takes place via the electrical grid.

The behaviour of a SmartStability network has been simulated, based on physical models of the energetic resources within each network unit, and by interlinking the individual units to form the entire SmartStability network within a multi-agent environment.

Goal of several simulation scenarios was the adaptation of the time-dependent power consumption profile of the network to a given schedule. Networks consisting of 5 to 100 houses have been simulated. The simulation results show that deviations from schedule can be reduced by approx. 50% by the market-economics-based self-optimization and the resulting intelligent operation of resources. By additionally using battery storages, the deviation from schedule can be further significantly reduced.

Keywords: smart grid, market-economic interaction, thermal storage, flexibility

INTRODUCTION

The implementation of renewable energy sources on a large scale imposes (a) technical and (b) economic challenges: (a) the fluctuating energy production needs to be handled, i.e., power needs to be consumed and stored when it is produced, and for times of little energy production storages have to be exploited. (b) Renewable energy sources and in particular energy storages are often only profitable when using federal subsidies due to the required high capital investments.

The "SmartStability" concept approaches both, technical and economic issues by establishing an interaction for the exchange of electrical energy between a number of small energy units (e.g., households) based on a market economical negotiation principle. Therefore, a distributed (or local) network of individual energy units is formed with the ability to communicate and to exchange energy via the electrical grid, similar as in [1]. The network will be able to adapt its power consumption profile *P(t)* to given boundary conditions.

The behaviour of such a network has been modelled, based on the physical behaviour of the energetic resources within the individual houses, and by interlinking the individual units within a multi-agent environment.

METHOD

For a realistic simulation of the entire SmartStability network, the individual units have to be physically correctly represented. To achieve a temporal flexibility in power consumption, the thermal capacitances and resulting time constants of selected elements within the units are exploited, and certain temperature bands are allowed. The surplus power consumption (e.g. for lighting etc.) is approximated by using standardized electric power consumption profiles.

Thermal building model

In order to represent the main part of the Swiss building stock the most common building type was chosen: a single-family dwelling with two storeys (Figure 1).

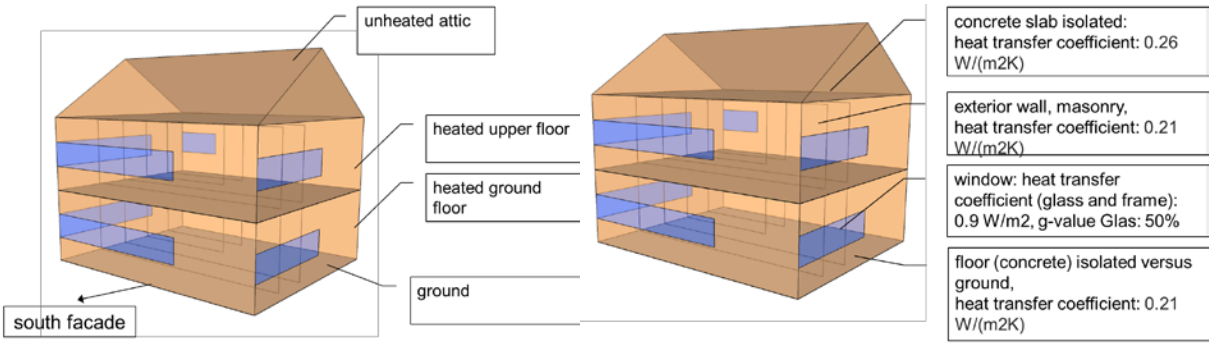

Figure 1: Building model. Left: zones; right: U values of the building envelope.

Ideally, to integrate the building model as a component within the SmartStability network the building should be reduced to a single formula. Although possible, this leads to a very simplified model and consequently to a loss of accuracy. A compromise would be to reduce the thermal behavior to several functions.

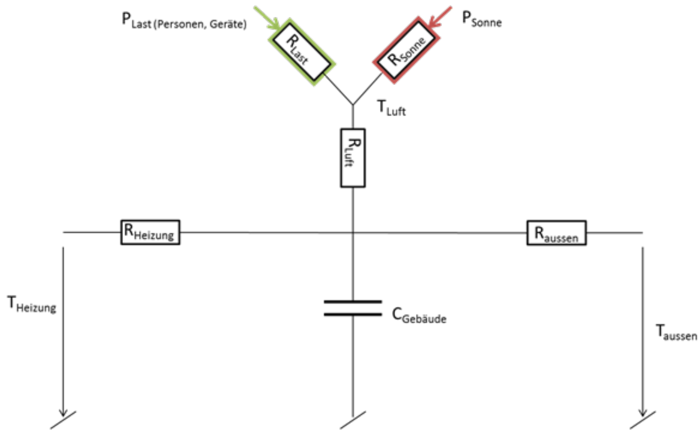

Figure 2: simplified R-C model following ISO 13790.

Therefore, some boundary conditions (e.g. temperature and radiation bins instead of weather data, no internal loads, ACH 0.7 h-1) were simplified. Our interest in the building as a thermal storage raised two questions: Firstly, how long is the heating-up time for the building from

20°C to 26°C (heat being provided by floor heating)? Secondly, how long is the cool-down time from 26° to 0°C without any heating? With these results and the heat storage capacity according to EN ISO 13786 [157 Wh/(m^{2}K)] a mathematical model has been developed.

A simplified analytical model corresponding to ISO 13790 (Figure 2) was used. The parameters were identified with the simulation data from ESP-r using the step responses for heating up (20°C to 26°C) and for cooling down (26° to 0°C). With the thermal resistance of the ground floor ($R_{Heizung}$), and of the outside walls (R_{aussen}) and thermal capacity ($C_{Gebäude}$) the dynamic behaviour of the building is described. Figure 3 below shows selected results.

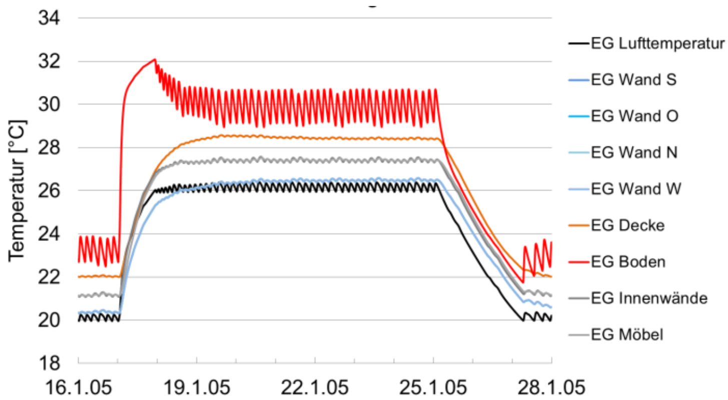

Figure 3: temperature profiles for the ground floor: air temperature, surface temperature of building elements (outside temperature: -5°C; average global irradiation < 25 W/m^2). For this example the heating-up time is 14 h, the cooling down time is 80 h.

Besides the thermal resistances and capacities, a heat-pump model transforming outdoor air-temperature into water temperature of the ground-floor heating system by using electrical power is needed. To describe a heat pump the heating curve and the coefficient of power (COP) are required. The heating curve describes the relation between outdoor and water temperature of the heating system: Lower outdoor temperatures correspond with higher water-temperatures of the ground-floor heating system. The COP = $P_{thermal}$ / $P_{electric}$ is the major parameter describing the relation between electrical input power versus thermal output power. By knowing the outdoor air temperature and the heating curve, the COP can be determined by using data from the heat-pump manufacturer.

The thermal resistances, the capacity, the heating curve and the functional description of the COP are used as parameters in the SmartStability network.

Physical modelling of energetic resources within the buildings

To develop the mathematical model of an electric water boiler, a test bed of a 3 kW, 300-liter domestic hot water boiler was chosen because such boilers are widely used. The physical boiler model on the one hand has to be simple in order to be processable in the SmartStability network simulation environment which contains a large number of individual boilers. On the other hand, the boiler model should yield precise figures regarding time constants for flexibility in turning it on or off. In the present case, a boiler model based on 8 coupled differential equations, based on heat transfer and neglecting convection, was used [2].

To verify the boiler model, a warm water boiler has been employed with temperature sensors, data logging and data measuring devices. Figure 4 shows time-resolved measurements of the water temperatures in 8 different layers, the bottom plot of Figure 4 shows the corresponding simulated temperature profiles. As can be seen, the behaviour of the real boiler and the simplified model are in an acceptable agreement.

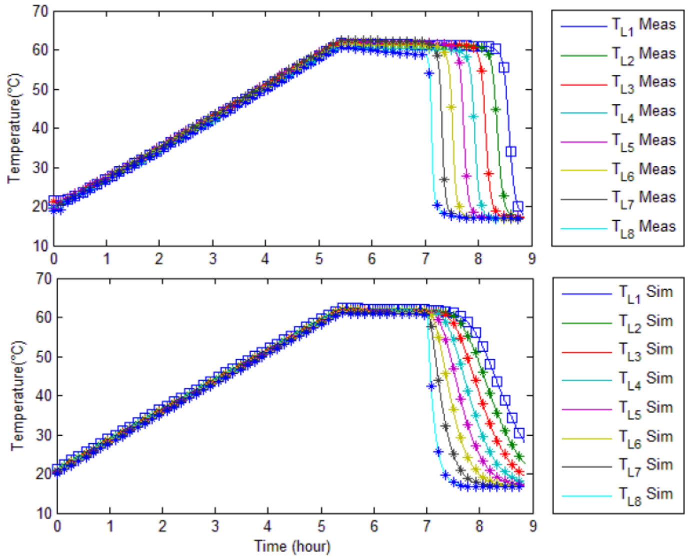

Figure 4: Measured (top) and simulated (bottom) water temperatures in different layers. The heater is on between t = 0 and 5.5 hrs; the water outflow is 0.09 l/s between t = 7 and 9 hrs.

A PV model yielding the power output of a solar panel, depending on its size, efficiency, angular orientation, geographic location, and weather conditions, has been also established. A comparison of the output of a real solar panel and the model is shown in Figure 5.

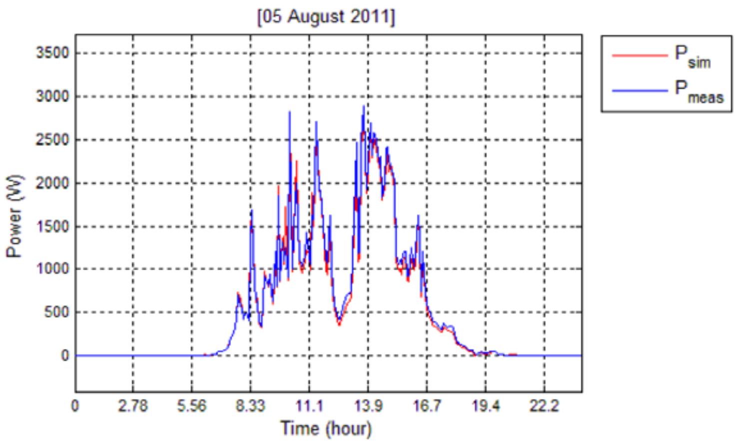

Figure 5: Measured (blue) vs. simulated (red) responses of a PV panel (3.3 kW peak power; location: Windisch, Switzerland) on a summer day with variable weather conditions.

Trading in the SmartStability network

To simulate the effects of the SmartStability network a multi-agent environment was developed. All agents in that environment are equal but two different roles are identified. All agents play the role “SmartStabilityHouse” which represents one power consumer. Each agent interprets the status of its boiler and heat pump and provides offers to the network. One agent in the network plays additionally the role of a “MarketPlaceCoordinator”. That agent is automatically determined out of the network. The coordinator receives all offers and decides which offers will be accepted and which not.

In contrast to other approaches [3, 4] the house agents offer capacity instead of power. For example, an agent offers to turn on its boiler and therefore consumes excessive power (positive capacity). Another agent may offer to turn off its heat pump and therefore does not consume power (negative capacity). Capacities are traded explicitly – not implicitly as in other approaches. Usually in other approaches, a coordinator distributes price signals and thus tries to motivate houses to turn their resources on or off. Instead trading capacity explicitly, as being used in the present approach, provides the advantage that the coordinator is able to control the resources of the houses. Of course, accepted offers are paid to the offering houses.

The trading process consists of five phases; being initiated by the market place coordinator:

1. Requesting energy demand of all SmartStability houses;
2. Calculating the power deviation from the schedule;
3. Conducting the auction;
4. Calculating the penalty fee for not matching to the schedule;
5. Announcement of the next cycle.

Figure 6 shows a visualized simulation screenshot of a SmartStability network of 5 houses. The top graph shows the target consumption (green line), the actual consumption (red line) and the deviation (thin blue line). If the network includes resources such as batteries, the deviation can be reduced to a minimum, depending on the battery dimensions. The bottom graphics shows the numbers of given (red) and accepted offers (blue).

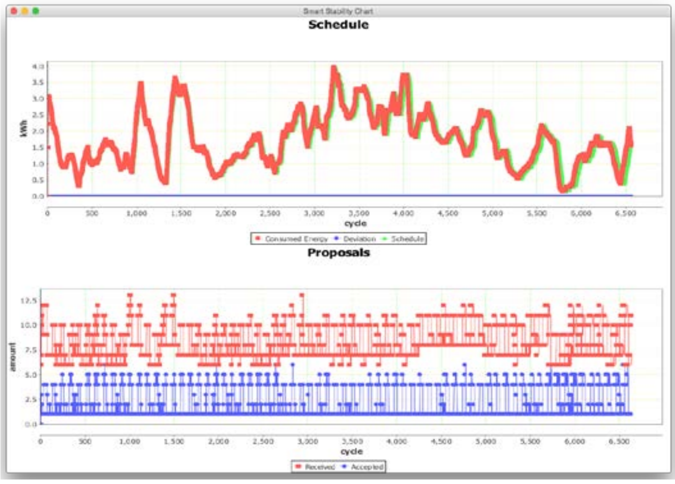

Figure 6: Screenshot of the simulation environment.

RESULTS

Figure 7 shows average deviations of the network from a given schedule for scenarios without batteries. It can be seen that reference scenarios (without trading) behave worse than with trading. Furthermore, Figure 7 relates the deviation to different network sizes. The deviation relatively decreases if more houses participate in the SmartStability network.

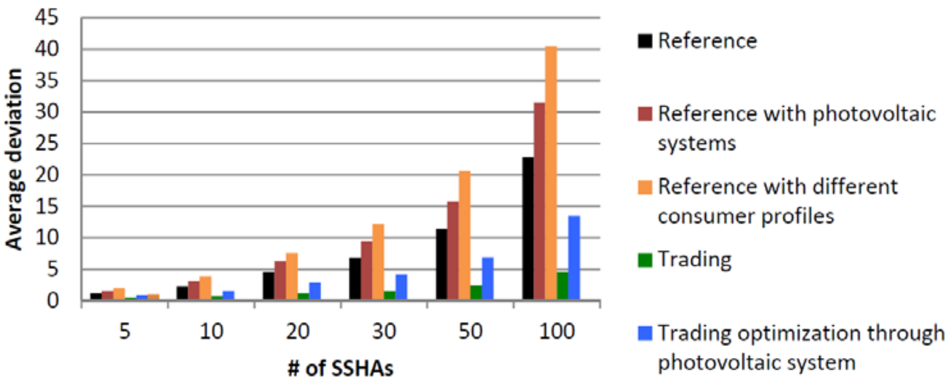

Figure 7: Average deviations from reference and trading scenarios.

Table 1 displays the deviations of several scenarios with different network sizes. In every scenario the aim was to minimize the deviation of consumed energy from a predefined schedule. In the simulation the average of 100 cycles (= 100 · 15 minutes) was chosen as a predefined schedule. The table shows that if a battery is traded then the deviation goes to zero. In those scenarios obviously the households possess enough capacity to store and shift power.

Scenario	Average deviation per cycle over a period of a year with # Households in kWh					
	5	10	20	30	50	100
Reference	1.141	2.283	4.566	6.850	11.416	22.832
Reference with photovoltaic systems	1.575	3.151	6.30	9.456	15.761	31.522
Reference with different consumer profiles	1.991	3.888	7.853	12.197	20.651	40.486
Trading	0.524	0.719	1.132	1.549	2.435	4.577
Trading optimization through PV system	0.907	1.559	2.892	4.229	6.886	13.513
Trading optimization through battery	0.0	0.0	0.0	0.0	0.0	0.0
Trading optimization through photovoltaic system and battery	0.0	0.0	0.0	0.0	0.0	0.0
Trading optimization with different consumer profiles	0.0	0.0	0.0	0.0	0.0	0.0

Table 1: Average deviation per cycle of a period of year in kWh

CONCLUSION AND ACKNOWLEDGMENT

In conclusion, it has been shown that a network of SmartStability houses is able to adapt its power consumption profile to a given schedule. Basis is the trading of capacities, based on a pure market-economic trading principle between the houses. In first instance, only the existing thermal capacities (i.e., those of the buildings themselves and of the warm water storages) have been exploited to generate capacities. Adding battery storage capacities significantly improves the adaptation of the consumption profile to a given schedule.

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